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Energy Saving Potential of Industrial Solar Collectors in Southern Regions of Russia: The Case of Krasnodar Region

Svetlana Ratner [1,2], Konstantin Gomonov [1,*], Svetlana Revinova [1] and Inna Lazanyuk [1]

1 Department of Economic and Mathematical Modelling, Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya Street, Moscow 117198, Russian; ratner-sv@rudn.ru (S.R.); revinova-syu@rudn.ru (S.R.); lazanyuk-iv@rudn.ru (I.L.)

2 Economic Dynamics and Innovation Management Laboratory, V.A. Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, 65 Profsoyuznaya Street, Moscow 117997, Russian

* Correspondence: gomonov-kg@rudn.ru; Tel.: +7-495-433-4065

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Abstract: Industrial low-temperature processes are a promising sector for the introduction of solar collectors, which can partially, and in some cases, completely, replace traditional heat supply technologies. In Krasnodar Region (Russia), it is shown that the energy-saving potential when introducing industrial solar collectors only at food industry enterprises can make up 16%–17% of the total amount of thermal energy produced in the region annually. The global market of industrial solar collectors is currently developing almost without any government incentives, only due to market mechanisms, which indicates the commercial attractiveness of the technology. According to the predicted estimates, levelized cost of energy produced by industrial solar collectors in the southern regions of Russia may amount to 3.8–6.6 rubles per kWh. Even though the forecast estimates are higher than current tariffs, the economic feasibility of using solar collectors in the industry increases significantly if it is not possible to connect to centralized heating networks, as well as in the case of the seasonal load of industrial facilities. As a measure of state incentives for the development of industrial solar collectors in Russia, we offer state co-financing of demonstration projects of Russian manufacturers. This will increase the level of awareness of the population and businesses about the capabilities of this technology. Also, it will increase the technical competencies and innovative potential of companies involved in the production and installation of solar collectors.

Keywords: heat supply of industrial processes; renewable energy; solar collectors; economic efficiency

1. Introduction

In recent decades, renewable energy has developed enormously throughout the world. The transition to renewable energy sources is considered both in academic and business societies as an essential step towards the formation of a circular economy and achieving sustainable development goals [1,2].

The average annual growth rate of installed capacity of renewable energy sources (RES) in the period from 2009-2018 amounted to 8.4% [3], and, starting from 2015, net capacity additions for renewable power are higher than for fossil fuels and nuclear all together [4]. The average annual growth rate of energy generation based on renewable energy sources in the period from 2009–2017 amounted to almost 6% (Figure 1). At the end of 2017, investments in renewable energy-based electricity generation for the first time in history exceeded investments in traditional types of electricity generation (including nuclear energy), most of which came from countries with developing economies [5]. In 2018 global investment in RES (including large hydropower plants) reached USD 288.9 billion. Despite an

11% decrease compared to 2017, that was the fifth year in a row that investment exceeded USD 230 billion [4].

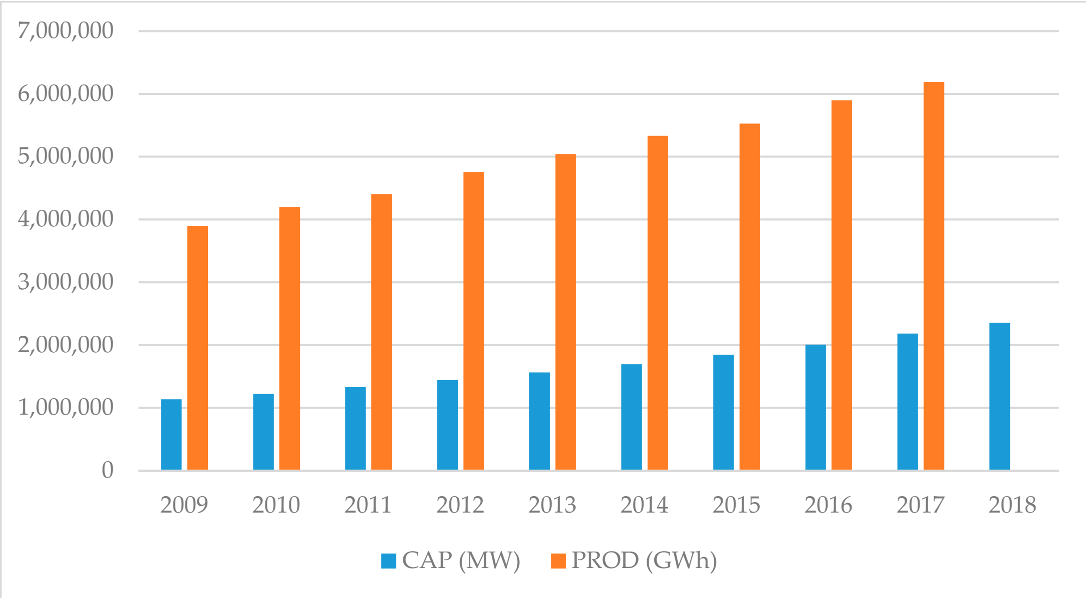

Figure 1. Total renewable energy capacity and production in the world. Source: authored based on The International Renewable Energy Agency data [3].

Today, almost all countries of the world have goals at the state level for the development of renewable energy [5–8]. However, despite significant progress in electricity generation, the introduction of renewable energy technologies in the heat supply and heat generation sector, including for industrial needs, is still slow, despite the fact that these types of final energy consumption have the most significant shares in the global energy balance. Thus, according to REN21 statistics of 2016, 51% of all energy consumed in the world is spent on heat supply, and this sector contributes nearly 40% of global energy-related CO_2 emissions [4]. The share of modern renewables in final heat consumption globally is only 9.8% and distributed between the following modern technologies [5]:

1. *Biogeneration:* boilers using solid biomass; the use of biogas in central heating systems; the addition of biogas to the gas supply grid; the direct use of biogas for cooking.

2. *Solar collectors:* used for heating water and, to a lesser extent, heating buildings. In recent years, the scale of use in central heating systems and industry has increased significantly [5].

3. *Geothermal energy:* used in central heating systems, for swimming pools, greenhouses, as well as in industry. All three technologies together contribute 8% in final heat consumption.

4. *Heating with renewable electricity:* the use of electricity generated by solar panels, wind farms, etc., for the operation of heat pumps in the residential, commercial, and industrial sectors. In 2016, this sector contributed 1.8% of the final heat consumption.

The use of solar energy in the heat supply of buildings in the residential and commercial sectors has a rather long history and is well studied in the literature [9–11], while the use of solar energy in industrial production is currently only developing. The primary constraint so far is the impossibility of providing round-the-clock heat supply to the production process using solar energy. To overcome this technical barrier, it is necessary to install additional equipment like heat storage systems, which significantly increase the cost of the entire solar installation [11–13]. The high initial cost of acquiring and installing equipment (solar collectors and heat storage systems) is the second most crucial constraint, which is especially essential for small and medium enterprises that do not have a sufficiently large volume of current assets [12]. At the same time, government support measures for the development of this type of renewable energy sources are not yet widespread. So, in 2018, according to REN21 [4], already 135 countries of the world carried out various government policy measures aimed at supporting renewable energy in the electricity generation sector, while incentive measures for renewable energy technologies in the heating sector were introduced in only 20 countries.

Currently, the use of solar energy is most developed in the food industry [14], primarily because most of the production processes associated with food processing are low-temperature (Table 1). So, for example, processes such as various types of drying, cleaning, washing, heating water, pasteurization, and sterilization do not require temperatures above 250 °C, which can easily be achieved using various types of solar collectors. The second most common user of solar collectors is the textile industry, in which many production processes (such as cleaning, drying, washing, pressing) do not require high temperatures [15–17].

Table 1. Industrial processes are potentially suitable for the use of solar collectors as heat supply equipment [14–17].

Sector	Industrial Process	Temperature Range, °C
Chemicals	Biochemical reaction	20–60
	Distillation	100–200
	Compression	105–165
	Compression	110–130
Foods and beverages	Blanching	60–100
	Scalding	45–90
	Evaporating	40–130
	Cooking	70–120
	Pasteurization	60–145
	Smoking	20–85
	Cleaning	60–90
	Sterilization	100–140
	Tempering	40–80
	Drying	40–200
	Washing	30–80
Paper and paperboard manufacturing	Bleaching	40–150
	De-inking	50–70
	Cooking wood in a chemical solution	110–180
	Drying	95–200
Fabricated Metal	Chromating	20–75
	Degreasing	20–100
	Electroplating	30–95
	Phosphating	35–95
	Purging	40–70
	Drying	60–200
Rubber and Plastics	Drying	50–150
	Preheating	40–70
Textile industry	Bleaching	40–100
	Coloring	40–130
	Drying	60–90
	Washing	50–100
	Fixing	160–180
	Pressing	80–100
Wood industry	Steaming	70–90
	Pickling	40–70
	Compression	120–170
	Cooking	80–90
	Drying	40–150
Mining	Cleaning	~60
	Electro-winning	~50
	Other processes	~80
Agriculture	Drying	80
	Water heating	90
Automobile industry	Water heating	90
	Cleaning	120
	Other processes	~50

Depending on the required temperature level of the production process, various types of solar thermal collectors are used, from the most straightforward and cheapest air flat-plate collectors, suitable for temperatures up to 100 °C to the more complex Fresnel collector or parabolic trough collectors for temperatures up to 400 °C [14–17].

This study aims to review the current state of the world market of industrial solar collectors and assess the possibilities of their application in individual industrial sectors of the Russian Federation. The rest of the paper is organized as follows: in Section 2 we describe materials for the study and basic methodology; Section 3 gives a brief overview of the research background and particular main trends and status-quo of industrial solar collectors in the world and in Russia; in Section 4 we present the results of calculations for estimation of the expected economic efficiency of industrial solar collectors in the southern regions of Russia and estimation of the potential for their use in the Krasnodar Region; Section 5 discusses the results of the study and gives some policy recommendations; the final section concludes the study and discusses its added value for academic literature.

2. Methods

The information base of the study was the analytical materials of the project of the World Energy Agency "Integration of Solar Heat into Industrial Processes" (IEA SHC Task49 / IV SHIP), materials of the REN21 expert network and the analytical agency Solar and Wind Energy. The current state and the trends in the development of solar heat in Russia was studied based on the data of Austrian Institute for Sustainable Technologies (IFA Solar Heating and Cooling Program), and the data of Russian Litvinchuk HVAC Marketing Agency (http://www.litvinchuk.ru/), which specializes in research for heating, air conditioning, and cooling systems markets. The data for assessing the potential of using solar collectors in the industry of the Krasnodar Region were obtained from the statistical collection "Krasnodar Territory in Figures, 2016" [18] and open data from the Federal State Statistics Service, presented on the official website in the section Technological Development of Economic Sectors / Energy Efficiency (https://www.gks.ru/folder/11189).

The traditional approach is widely used to calculate the economic efficiency of industrial solar collectors in Russian scientific literature (see, for example, [11,19]). This approach is based on calculating the payback period of equipment T (years) through the cost of replaced energy, the cost of energy produced by the solar collector, and the coefficient of efficiency of conversion of solar energy into thermal energy (the conversion factor) by the formula:

$$T = \frac{C_{SC}}{S_p \eta C_{th}} \tag{1}$$

where

S_{SC}—cost of heat generated by the solar collector (rubles/m^2);

C_{th}—cost of replaced energy (rubles/kWh);

S_p—the total intensity of solar radiation in the plane of the solar collector (kWh/m^2);

η—the conversion factor of solar energy into heat.

This approach gives the most accurate results in the case of calculating the economic efficiency of a particular solar collector installed in a certain way in a specific geographic location but is poorly suited for predicting and assessing the economic potential of using solar collectors on a scale of the industrial sector of the region. Firstly, it does not take into account changes in the value of money over time (discount coefficient), and secondly, it requires data on the exact locations of all industrial facilities on which the installation of solar collectors is planned. When calculating the regional potential for such a region as the Krasnodar Territory, with an area of 76,000 square km and a length from north to south of more than 320 km, and from west to east of more than 350 km, this approach creates significant computational difficulties [20] and at the same time does not give any advantages over less accurate methods, since it still leads to the need for data averaging.

Therefore, in this study, we used an approach based on the construction of a linear regression model based on statistics on the performance of flat solar water collectors in different regions of the world presented in the source [15]. The explanatory variable (proxy) in the model is the level of solar insolation. Further, the calculated value of the productivity of the solar collector was substituted into the formula *LCOE* (levelized cost of energy) [21,22]:

$$LCOE = \frac{I_0 + \sum_{t=1}^{T} A_t \cdot (1+r)^{-t}}{\sum_{t=1}^{T} SE \cdot (1+r)^{-t}}, \tag{2}$$

where

I_0—the unit cost of equipment, taking into account the installation (euro /m^2);

A_t—equipment maintenance cost in year t (according to [23] is assumed to be equal 0.25%–0.5% depending on the type of collector);

SE—the amount of energy produced in year t;

T—the life cycle of equipment (years);

r—discount rate, reflecting the change in the value of money over time (for calculations in euros, as a rule, it is assumed to be equal to 3%).

Values I_0 and T were taken as average for equipment of a similar class, A_t as the average value of labor costs in countries with a comparable standard of living and wages, and r as the average inflation rate in Russia over the past five years.

One can quickly notice that the advantage of our approach is, on the one hand, simplicity, and, on the other hand, taking into account essential factors affecting the economic efficiency of the solar collector, such as the costs of its installation and maintenance, the life cycle of the solar collector, and the change in the cost of money over time. Schematically, the logic of our study is reflected in Figure 2.

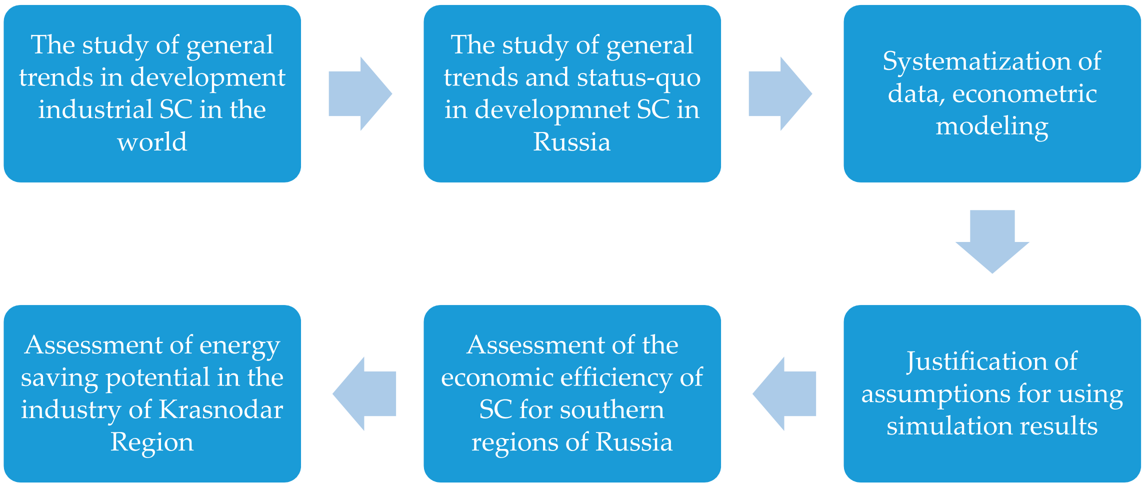

Figure 2. The general algorithm of the study.

Thus, to achieve the main goal of the study, we needed to solve the following two problems: 1) to analyze the structure of industrial production in the region and assess the volume of low-temperature industrial processes, and, possible demand for industrial solar collectors; 2) to determine under what conditions a transition of low-temperature industrial processes to solar energy can be economically feasible.

3. General Trends in Development Industrial Solar Collectors in the World and Russia (Research Background)

3.1. Industrial Solar Heat Worldwide

Solar Heat for Industrial Processes (SHIP) is a fast-growing new global market [15,23]. According to the data of Austrian Research Institute for Sustainable Technologies AEE INTE, which is at the current moment the leading European research center for hybrid heating systems, the number of industrial solar installations at the end of 2018 (the latest statistics) is estimated as 741 systems with a total collector area of more than 662,000 square meters. Moreover, if earlier the leaders in this market were technologically developed countries, in recent years several promising projects have been implemented in the territories of developing countries, from small demonstration plants to large-scale systems with a capacity of 100 MWth (Figure 3). In 2017, 124 systems were installed in the industrial sector with a total collector area of more than 190,000 square meters, and in 2018 another 108 industrial new solar systems with a total area of more than 54,000 square meters were commissioned (Table 2).

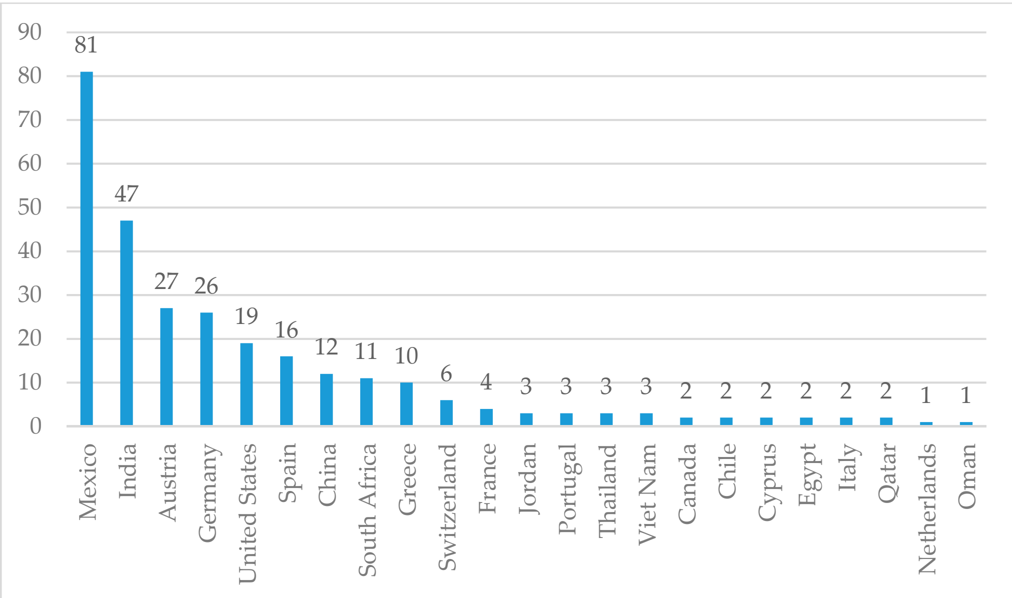

Figure 3. The number of industrial collectors with a capacity of at least 700 kW in different countries of the world in March 2019 [23].

Table 2. Statistics of installations of industrial solar collectors by country in 2017–2018, [15,23].

Country	2017			2018		
	Number of New Collectors	Gross Area, m^2	The Average Area of Collector, m^2	Number of New Collectors	Gross Area, m^2	The Average Area of Collector, m^2
Oman	1	148,000	148,000	-	-	-
Mexico	36	6411	178	51	6,898	135
India	36	15,313	425	10	3964	396
China	19	11,534	607	15	28,813	1921
Austria	2	1758	893	3	435	145
France	2	2052	1026	2	5,543	2772
Afghanistan	1	3260	3260	-	-	-
Jordan	1	1254	1254	-	-	-
Germany	-	-	-	9	1589	177
Spain	-	-	-	3	1218	406
Others	12	2971	114	15	5193	346
Total	**124**	**192,580**		**108**	**53,654**	

The information on the most significant industrial solar collectors is presented in Table 3.

Table 3. Largest industrial solar collectors in the world. Source: authored based on data from [15] and https://www.solarthermalworld.org.

Name of the System (Country)	Gross Area, 1000 m^2	Capacity, MWth	Type of Industrial Processes	Type of Collector
Miraah (Oman)	148	100	Heavy oil production	Parabolic through
Gaby Copper mine (Chile)	39.3	28	Copper mining	Flat plate
Qier Solar (China)	13	9	Dyeing fabrics	Flat plate
Prestage Foods Factory (USA)	7.8	5	Sanitation	Flat plate
Heli Lithium (China)	3.3	2.3	Lithium-ion Battery Manufacturing	Evacuated tube
Kabul Meat Factory (Afghanistan)	3.26	2.2	Meat processing	Parabolic through
Polyocean Algal Industry Group (China)	2.2	1.5	Seafood processing	Evacuated tube
Japan Tobacco International (Jourdan)	1.25	0.7	Cigarette production	Frenel

In February 2018, the world's largest 4-block solar power plant Miraah with a capacity of 100 MWth was commissioned. The heating system supplies steam (660 tons daily) to the Amal field in southern Oman. Steam is used in the production of viscous and heavy oil. The system consists of parabolic solar collectors placed in a greenhouse in order to protect against wind and sand. The greenhouse turned out to be a successful and economical solution, as it allows reduction of the cost of cleaning and washing the collectors, as well as makes them lighter and less resource-intensive [15]. The second-largest industrial solar thermal plant was installed in Chile in June 2013 near the copper ore mine. Its capacity is 27.5 MWth [23].

The largest 2.3 MWth solar power plant in China was commissioned in 2017 to supply steam to one of Heli Lithium Industry's plants (producing lithium-ion batteries for electric forklifts). Vacuum tube collectors with a total area of 3300 m^2 are installed at the power station. Another large power plant with a capacity of 1.5 MWth, also using tubular vacuum collectors (total area of 2200 m2), is located in Qingdao in Shandong province in eastern China and supplies heat to the seafood processing company Polyocean Algal Industry Group [15].

At the end of 2017, the first parabolic collector was installed to heat a meat processing plant in Afghanistan. The total area of the collector was 3260 m^2. In Jordan, a Fresnel collector with a capacity of 700 kWh (total area of 1254 m^2) for direct steam generation for the needs of the Japanese tobacco factory Japan Tobacco International has been installed [15].

Since the market for industrial solar collectors is still very young, a complete system of statistical accounting of its structure and dynamics has not yet been formed. The complete detailed information is currently collected in the framework of the project of the World Energy Agency "Integration of solar heat into industrial processes" (IEA SHC Task49 / IV SHIP), carried out jointly by experts from 16 countries during 2015–2018. During the interview, experts collected information on 308 industrial heat collectors out of the 741 known. Figure 4 shows the distribution of the recorded 308 objects by size [23]. The first group includes the two largest solar thermal power plants (more than 21 MWth), which are also described in detail in Table 3. To the second group belongs 33 heating plants with a capacity of 0.7 to 21 MWth (or a total area of 1000 to 2999 m^2), followed by a group of 57 heating systems with a capacity of 0.35 to 0.7 MW (area from 500 up to 1000 m^2). The most significant number, 139 heating systems with a capacity of less than 0.35 MW (or a total area of less than 500 m^2) represent the fourth group of industrial solar power plants; the fifth group includes small heating systems with an area of up to 100 m^2, which includes 77 systems.

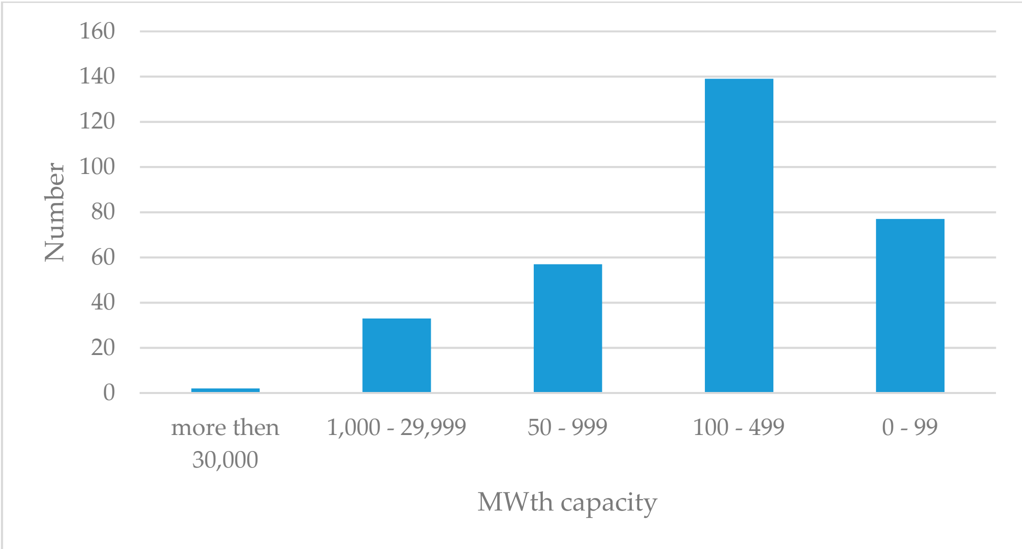

Figure 4. Distribution of industrial solar installations by size [23].

In the food industry 112 solar collectors are currently used, 31 in the beverage industry, and 24 in the textile industry (Figure 5). However, even though these industries are leading in the number of installations of solar collectors, the mining industry is the undisputed leader in the volume of their use (collector area and capacity) (Figure 6).

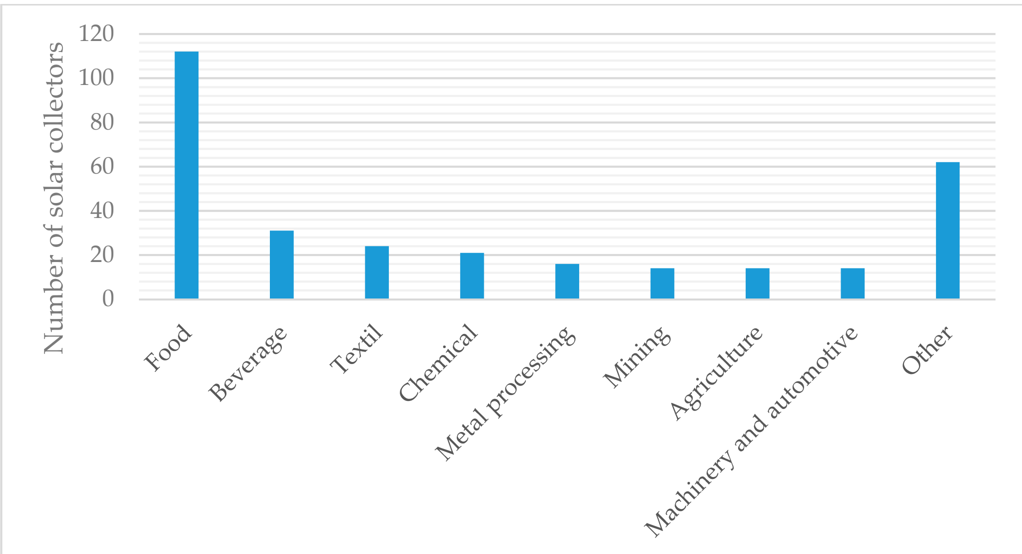

Figure 5. Distribution of industrial solar installations (numbers) by application [23].

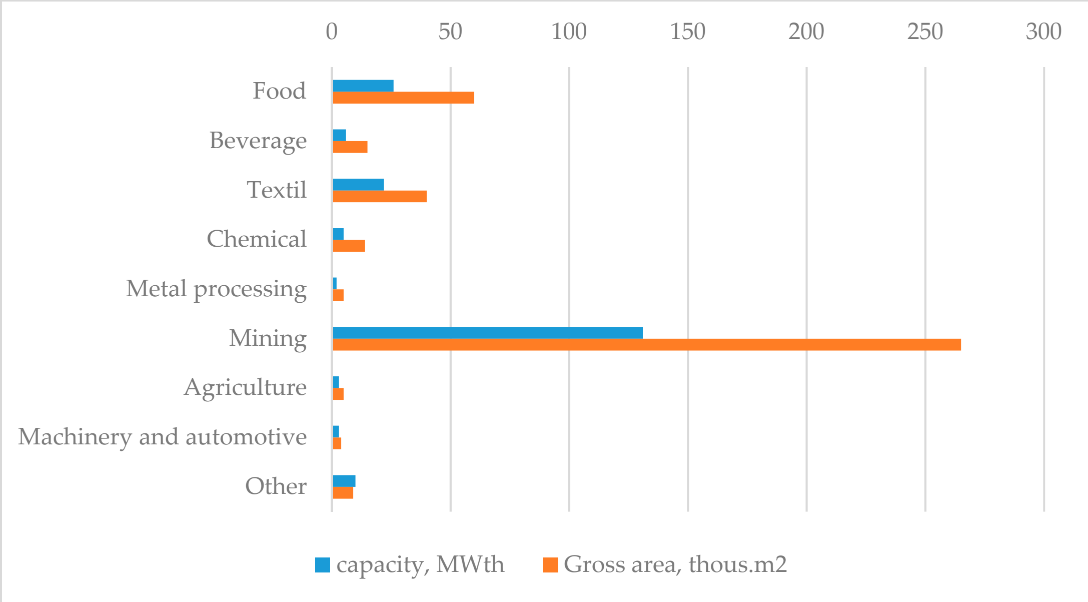

Figure 6. Distribution of industrial solar installations (capacity, gross area) by application [23].

Currently, the leaders in the cumulative area and capacity of installed industrial solar collectors are Oman, China, Chile, USA, Mexico, and India (Figure 7). Other countries are significantly inferior to them in the development of the SHIP market. With the exception of the United States, the leading countries in terms of the development of solar collectors in the industry are rapidly developing industrial countries in which the industrial sector mainly generates the growth in demand for thermal energy. For example, the growth of thermal energy consumption in the industrial sector of India in the period from 2010 to 2015 increased by more than 30% [24,25].

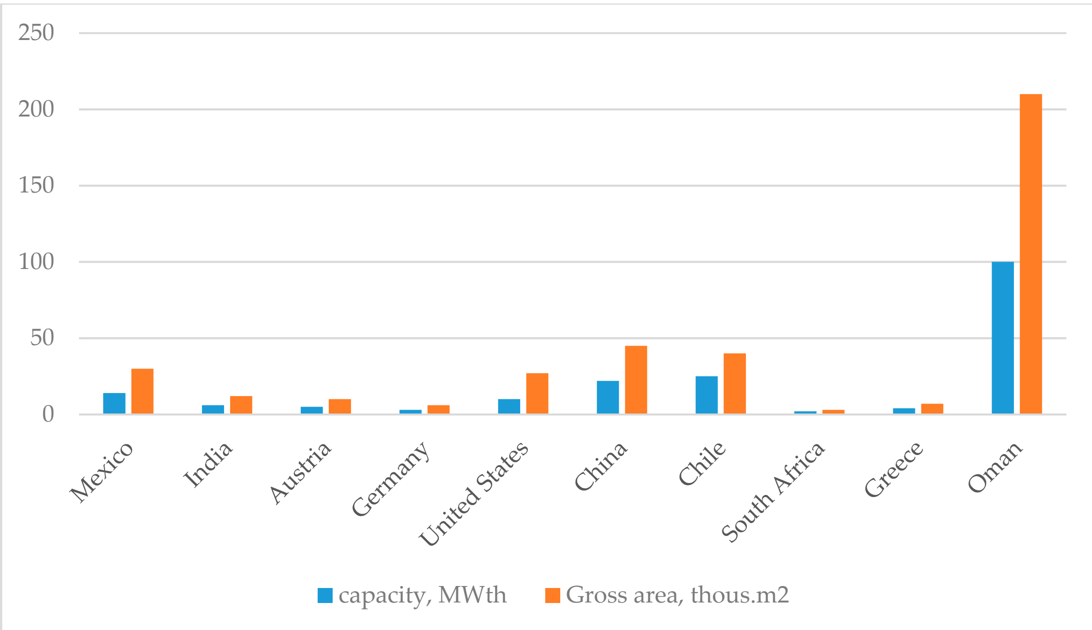

Figure 7. Cumulative area and cumulative power of installed solar collectors in the leading countries [23].

As for the types of commonly used solar collectors, they are flat plate collectors (139), followed by parabolic (58) and evacuated trough collectors (46). However, in terms of total area, parabolic collectors are superior to flat and vacuum (Figure 8).

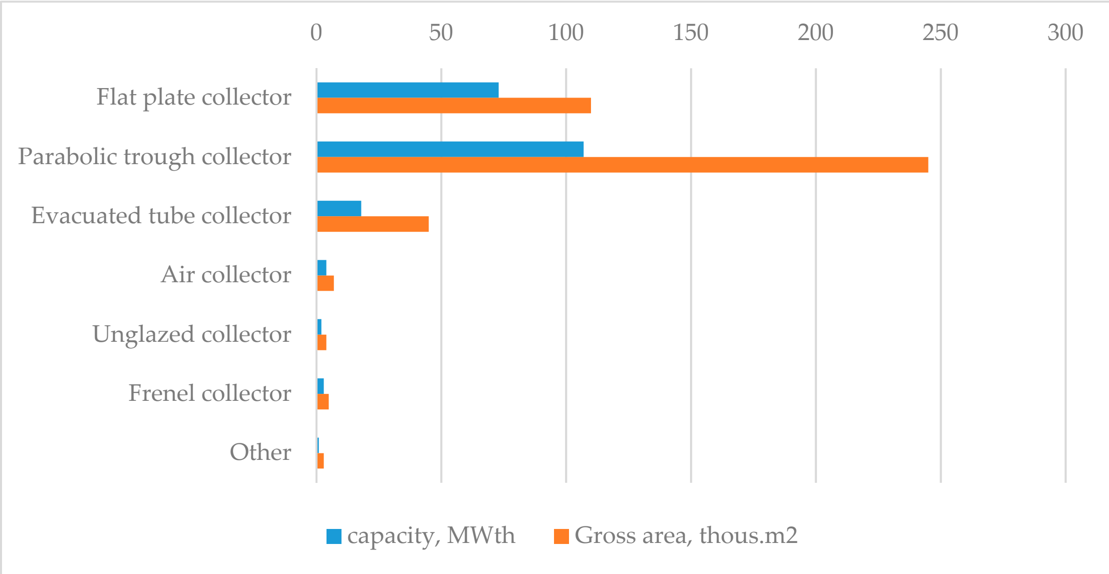

Figure 8. Distribution of industrial solar collectors by type [23].

The largest manufacturers of flat solar collectors are Chinese companies: Sunrain (annual turnover of more than 600 million US dollars), BTE Solar, Five Star, and others [26]. The list of leading companies among manufacturers of solar collectors in 2017 also includes the Austrian company Greenonetec and the German Bosch Thermotechnik (according to the data of analytical agency Sun&Wind Energy http://www.sunwindenergy.com/solar-thermal/2017-ranking-worlds-largest-flat-plate-collector-manufacturers. In addition to these countries, the production of solar collectors on a large scale is also established in Greece, Italy, Turkey, Australia, Mexico, Bulgaria, Poland, and India. In the production of solar collectors, relatively simple technologies are used that do not require special licensing and are relatively easy to copy; therefore many manufacturing companies co-finance projects with state support for the development of industrial solar collectors to expand their sales market [27,28].

In South Africa there is the system of incentives for demonstration projects on the use of high-power solar collectors in the food and textile industries, aimed at raising awareness about the possibilities of using this technology and developing the production of power equipment [5,29]. Industrial solar collectors have also received support in Tunisia as part of the Prosol industrial development program, launched in 2010 with financial support from the Italian Ministry of the Environment and the United Nations Environment Program. Benetton Textile Mill is a demonstration project, in which 1000 m^2 of flat plate solar collectors were installed on the roofs of production facilities in 2016. The success of the project allows for the replication of the technology in other sectors of industry to achieve the national goal of 14,000 m^2 solar collectors by the end of 2020 [5].

3.2. Status-Quo of Solar Heat in Russia

There are no official statistics on the solar heat supply in Russia; therefore, estimates of international organizations on solar collectors are based on an expert method based on a survey of leading Russian specialists in this field [11]. Dynamics of development of the solar heat supply in Russia in the period from 2013 to 2017 (last statistics) are presented in Figure 9. The predominance of flat plate solar water collectors (FPC water) in Russia is explained by the fact that the amount of heat generated by them per unit area in the winter is significantly higher than the amount of heat generated by vacuum collectors.

The fact that snow and frost on the surface of flat solar collectors can be removed faster than from vacuum collectors is also essential.

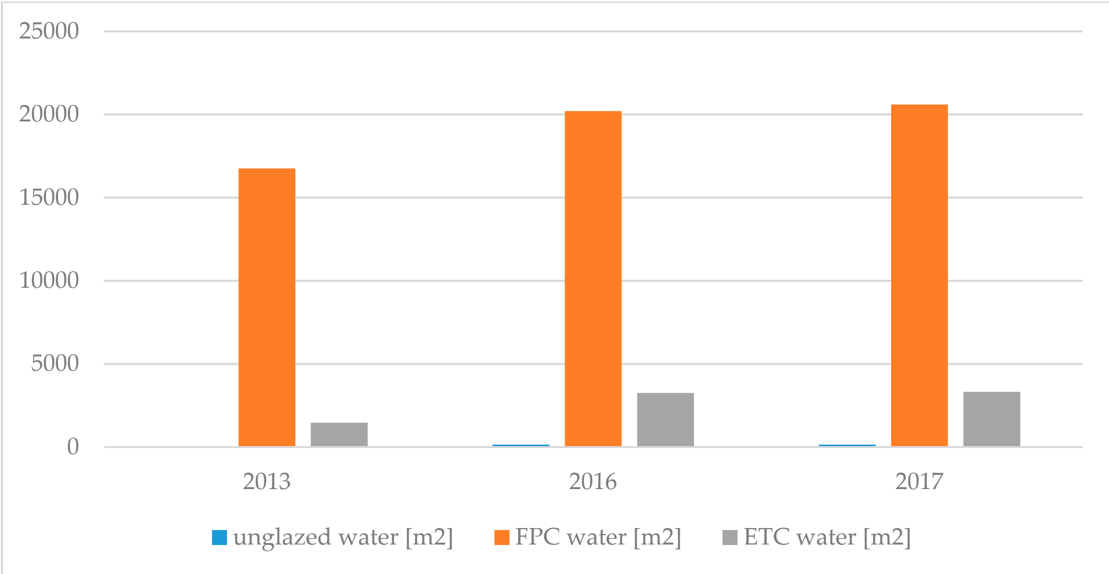

Figure 9. Gross area of solar collectors (for all applications) in Russia.

According to Austrian Institute for Sustainable Technologies estimates, at the end of 2017, the largest share of solar collectors was in the district heating sector (Figure 10). This is explained by lower unit costs for its construction and operation since equipment such as tanks, pumps, and chemical water treatment plants are already available in the regular boiler room. The same is true for well-qualified personnel. The share of solar collectors in the industry is only about 3.8% (about 900 m^2).

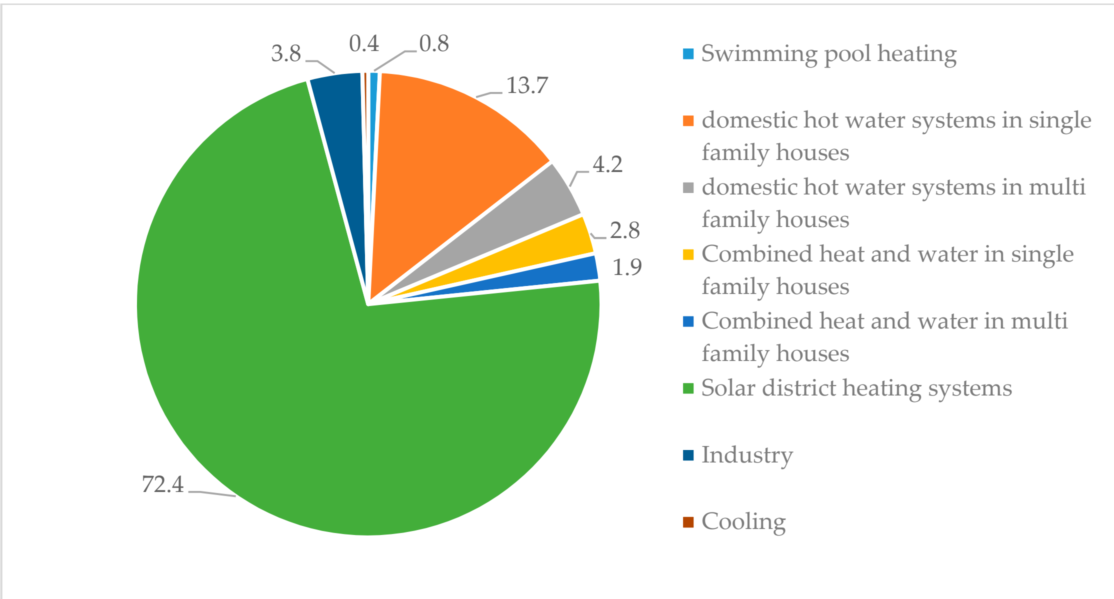

Figure 10. Distribution of solar collectors in Russia by application [11].

The largest number of solar collectors is operated in the southern regions of Russia: Krasnodar, Stavropol, Astrakhan, and Volgograd regions, as well as in the regions of the Far Eastern Federal District with a fairly high level of solar radiation and a high percentage of decentralized heat supply. They are the Republic of Buryatia, Khabarovsk, and Primorsky regions. In the Krasnodar Territory, as a region with a highly developed tourist infrastructure, more than half of all solar collectors are installed for the hot water supply of hotels and other tourist facilities. In Buryatia, most solar collectors are involved in industry. In the boiler house in the city of Narimanov (Astrakhan Region) the largest solar collector in Russia, with an area of 4400 m^2 and manufactured by Buderus (Germany), is used for hot water supply.

A significant obstacle to the wider distribution of solar collectors in Russia is the low awareness of the population about the capabilities of this technology, as well as the lack of service companies that provide turnkey solar collector installation services [30].

4. Results

4.1. Assessment of the Economic Efficiency of Industrial Solar Collectors in Russia

The economic efficiency of industrial solar collectors, as well as other solar energy conversion devices, primarily depends on the level of solar insolation (irradiation), which determines their performance (specific solar yield, kWh/m^2-a). Other significant factors are the initial cost of the collector itself, the costs of its installation and maintenance, and the life cycle of the solar collector. All these factors, as well as the discount coefficient, are taken into account in the indicator levelized cost of energy, which is the most common in a comparative assessment of the economic efficiency of various energy technologies. In other words, it reflects the average cost of a unit of energy produced using the specific generating device for the entire period of operation of the equipment [21,22]. Despite some criticism [31], this metric is currently the most widely used in the literature [22,32,33].

According to IEA SHC Task49/IV SHIP experts, the LCOE value for large-scale solar collectors used for the hot water supply of residential houses ranges from 2 euro cents (in 2016 prices) per kWh of thermal energy in India to 14 euro cents in Austria, Denmark, Canada, and France [15]. This significant difference is determined mainly by the cost of labor in these countries. Assuming that the cost of the installed industrial solar collector, similar in quality and performance, is approximately equal to the cost of the collector used for hot water supply (from 200 to 1160 euros per m^2), and the temperature of water heating in them is comparable to the temperature necessary to provide heat for low-temperature industrial processes, we can estimate expected the LCOE for industrial collectors in Russia. To this end, we will construct a model of paired linear regression based on the performance of large-scale solar collectors used to heat water at a certain level of solar radiation, given in the source [15] for 62 capitals of the world. We consider the level of solar insolation (X) as a factor, and as the dependent variable (Y) we take the performance of the average large-scale solar collector with a horizontal panel for hot water supply. Using the least-squares method implemented in STATISTICA 10.1, we obtain the model, presented in Table 4.

Table 4. Dependence of performance (specific solar yield, kWh/m^2-a) of the average large-scale flat plate solar collector on horizontal irradiation.

Parameters of Linear Regression Model	Value
Solar insolation, kWh/m^2-a	0.389 ***
const	41.719 **
R^2	0.97
P(F-stat)	0.0001

***—1% significance level, **—5% significance level.

Given the high statistical quality of the constructed model, it can be used to predict the expected performance of the solar collector anywhere in the world. So, for example, for the level of solar insolation in Sochi (average annual horizontal irradiation of 1365.1 kWh/m^2), we obtain the expected productivity of the solar collector 573.24 (kWh/m^2). Substituting the predicted estimates of collector productivity in the model (Table 4, Figure 11), and using the lower estimates for the volume of initial specific investments in the purchase and installation of equipment from the source [15], we obtain LCOE estimates for the cost of energy produced using industrial solar collectors in the region of Sochi, in the range of 0.052–0.09 euros per 1 kWh or 3.8–6.6 rubles/kWh (when converting euros to rubles at the rate of 1 euro = 73 rubles).

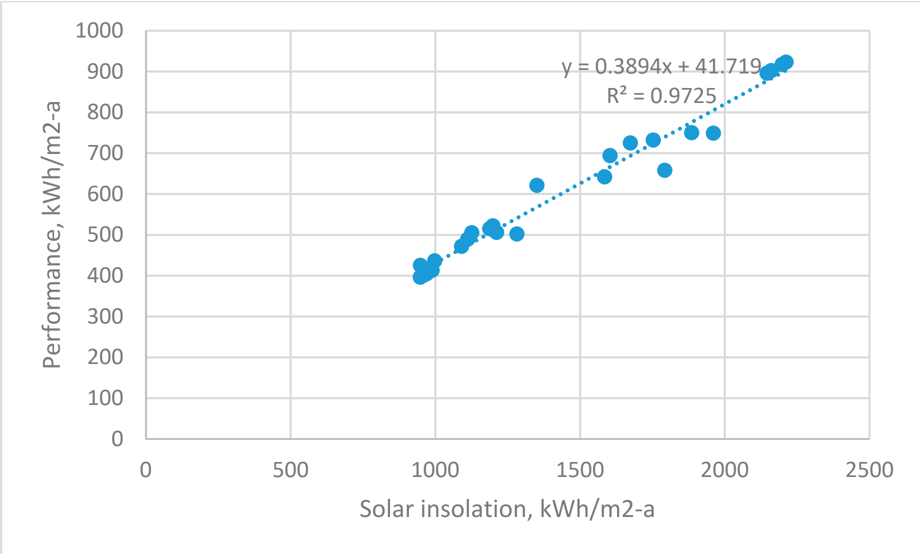

Figure 11. Linear regression model.

The use of lower estimates of specific investments is because the cost of labor in Russia is much lower than in developed European countries. If, as estimates of specific investments we take the values of these indicators as equal to France, Canada, or Denmark (as the highest), then the LCOE will range from 5.4 to 8.03 rubles/kWh.

Both the upper and lower estimates of the cost of thermal energy produced by solar collectors are higher than when using traditional hydrocarbon technologies for thermal energy production in the chosen region [34]. In the district heating zone, the tariff for thermal energy at the beginning of 2020 was only 1.5–2 rubles/kWh. However, with the rise in price of hydrocarbon sources and the introduction of taxes on greenhouse gas emissions (which is currently being discussed in the world expert community as a necessary measure to achieve the goals of the Paris Climate Agreement) [35–38], the commercial attractiveness of new technologies can significantly increase in those regions of Russia, where the average annual level of solar insolation is relatively high, and the need to provide energy for low-temperature industrial processes is quite large. Also, the economic feasibility of using solar collectors increases significantly if it is impossible to connect to centralized heating grids, as well as in the case of the seasonal load of industrial facilities (for example, in enterprises for the production of canned vegetables, sugar beet processing, etc.) One of these regions, where the development potential of industrial solar collector technology is large enough, is the Krasnodar Region.

4.2. Assessment of Energy-Saving Potential in the Industry of Southern Russia (for Example, the Krasnodar Region)

The southern regions of Russia not only have suitable natural and climatic conditions for the efficient use of solar collectors in various types of economic activities but are also regions with developed industrial sectors in which low-temperature production processes predominate. Therefore, for example, in the structure of thermal energy consumption in the industry of the Krasnodar Territory during 2010–2015 (Figure 12) the production of food, including drinks and tobacco, steadily occupies the fifth position, following only the chemical and metallurgical industries, the production of electricity, steam, and water, as well as the production of petroleum products [18].

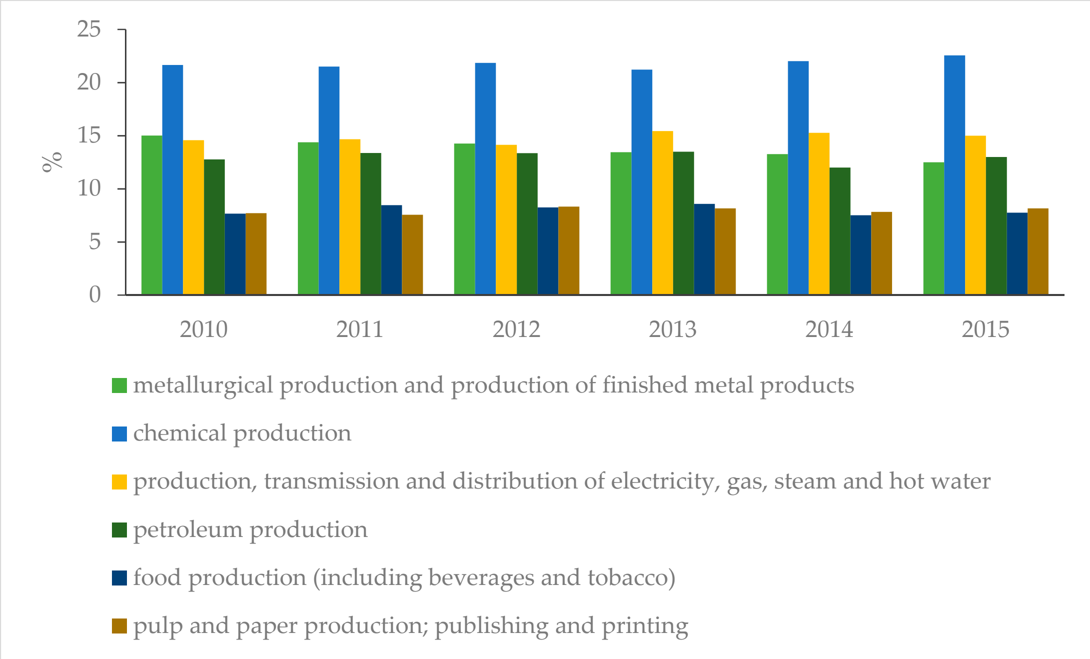

Figure 12. Industries in the Krasnodar Region leading in the consumption of thermal energy. Source: Statistical Digest Industrial "Production in Russia—2016", Part 5.4 "Consumption of certain types of fuel and energy resources by type of economic activity" https://gks.ru/bgd/regl/b16_48/Main.htm [18].

Note that at least two more of the above leading industries are also potential applications of solar collectors (chemical and petrochemical production).

However, even if we evaluate the energy-saving potential when introducing solar collectors only for food industry enterprises, we get an approximate estimate of 2,612,000 Gcal per year (detailed calculations are given in Table 5).

Table 5. An assessment of thermal energy consumption by food industry enterprises of the Krasnodar Region.

Goods	Specific Consumption of Thermal Energy, Thousand kcal per ton/Thousand per Deciliter [1]	Production Volume, Thousand Tones/Thousand Deciliter [13]	Total Thermal Energy Consumption, Thousands kcal
Sugar form sugar beet	1376.3	1505.2	2,071,606,760
Bread and Bakery	285.7	303.4	86,681,380
Milk	250	309.5	77,375,000
Cheese and cheese Products	752	65	48,880,000
Vegetable oil	348	512	178,176,000
Butter	1365.6	10.1	13,792,560
Alcohol	1539.4	17,870.5	27,509,847.7
Beer	2156.9	20,200	43,569,380
Meat	155.7	76.6	11,926,620
Meat products	351.9	65.2	22,943,880
Compound feed	30.3	975.7	29,563,710
	Total		2,612,025,138

[1] According to the Federal State Statistics Service http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/ru/statistics/economydevelopment/#.

At the current moment, the production of thermal energy in the region is ensured by the operation of four thermal power plants and 2848 boiler houses. In 2017 5,316,500 Gcal of thermal energy were produced by power plants and 10,394,200 Gcal were produced by boiler houses, from which 76% use natural gas as a primary fuel [39]. The average capacity factor of boiler houses in the region is 68%. The average level of boiler house wear is 70%, and in some municipalities it reaches more than 80%. The vast majority of boiler houses (boiler room equipment) and heating grids were built more than 20–25 years ago, which means not only a low level of their technical condition but also high backwardness of existing capacities from modern analogues designed for the production and transmission of thermal energy [40,41]. The technical backwardness of the regional heat supply system has a significant impact on the energy intensity of the economy. The energy intensity of the Krasnodar Territory is 1.5 times higher than the global average and 2-2.5 times higher than in developed countries. Maintaining high energy intensity indicators compared with the world average is a limiting factor for the economic growth [41].

Considering that the total volume of thermal energy produced in the region in recent years is about average 15,711,700 Gcal, the introduction industrial solar collectors only in food industry enterprises can bring energy saving up to 16–17% of the total amount of thermal energy produced in the region annually and have a positive impact on improving the energy efficiency of the region's economy.

Another positive effect for the economy of the region may be the creation of new jobs in the industry of manufacturing and maintenance of solar collectors. Given the estimates of the average productivity of solar collectors in the region obtained in the previous paragraph (573.24 kWh/m^2), it is possible to calculate the area of solar collectors needed to convert the industrial processes listed in Table 5 to solar energy. According to our calculations, the required number of solar collectors is estimated at 5,300,000 m^2. The study [23] claims that in countries with low labor costs and advanced automated production of solar collectors, on average systems with a total of 87 m^2 solar collector area have to be installed per full-time job. With this assumption, we can estimate that the potential for creating new jobs in production, installation, and maintenance of solar thermal systems is around 61,000.

5. Discussion and Policy Applications

As our analysis demonstrated, the market for industrial solar collectors is a rapidly growing segment of the global market for renewable energy technologies, which is currently developing with minimal government support measures, mainly due to market mechanisms. This indicates the commercial attractiveness of the technology, especially in countries with a high level of solar insolation and well-developed industries characterized by seasonality and a significant proportion of low-temperature processes.

For the southern regions of Russia, the use of industrial solar collectors can be considered a commercially viable alternative to the construction of new boiler houses and heating grids in the case of the creation of new enterprises for processing agricultural products in areas where there are no central heating systems and poorly developed heating grids. Also, the installation of solar collectors can be considered an investment-attractive option for the modernization of worn-out and outdated equipment of traditional boiler houses of industrial enterprises, which allows partially replacing hydrocarbon sources. In both cases, the development of industrial solar collectors will help to reduce the energy and carbon intensity of the Russian economy [42,43] and increase the share of renewable energy in the country's energy balance. This will help the country to fulfill its obligations under the Paris Climate Agreement [35,44].

It is also crucial that the use of solar collectors instead of hydrocarbon alternatives for the heat supply of industrial processes has a positive impact on the environment not only at the stage of direct operation of the solar collector but throughout the entire life cycle, including the stages of extraction and processing of raw materials for production of solar collectors, the stage of their production, the stages of transportation and installation, as well as disposal after use [45]. Thus, the use of solar collectors not only helps to approach the achievement of the goals of decarbonization of the economy, but also is fully integrated into the concept of transition to a circular economy.

Nevertheless, despite the relatively high level of commercial attractiveness and environmental efficiency, the development of solar collectors in Russia, in our opinion, needs certain measures of state support. Given the fact that the general concept of government incentives for development of renewable energy in Russia is aimed primarily at developing national production of equipment for renewable energy sources [46], it is advisable to direct measures of state support for the development of solar collectors not only to create effective demand (for example, through the system of purchase and installation subsidies for the solar collector), but, first of all, aiming to support existing Russian manufacturers of solar collectors with their technologies and competencies in this field. The creation and expansion of effective demand for solar collectors through customer subsidies can lead to the occupation of the domestic market with products of world leaders that can compete in price due to large-scale production [47]. Based on international practices, several types of government incentives can be proposed: (i) the government co-financing of demonstration projects of Russian manufacturers; (ii) the introduction of property tax benefits for enterprises using solar collectors in industrial processes; and (iii) the introduction of accelerated depreciation on solar collectors for industrial enterprises [48,49]. Also, the Russian practice of stimulating innovative production is rich in positive examples of the development of new enterprises through obtaining the status of a resident of the Skolkovo innovation cluster.

An analysis of the official websites of leading Russian manufacturers of solar collectors (JSC VPK NPO Mashinostroeniya (Moscow), LLC Novy Pole (Moscow), LLC Altenergiya (Krasnodar Region), ANDI Group (Moscow), GreenSun Technologies (Vladivostok)) shows that all of them (except the Novy Pole company, which has created its own brand and a whole line of products) need serious adjustments to their marketing strategy, development of after-sales services, and diversification of product sales channels. Given this situation, the co-financing of demonstration projects can be proposed as the most likely effective form of state support.

6. Conclusions

In our study, we investigated the prospects for the development of solar collectors in the industry of the southern regions of Russia. As a basis for calculating the demand for industrial solar collectors, we considered the structure of heat supplies and the industrial production of a specific territory. It was shown using the example of the Krasnodar Region that the potential for energy savings in the region's industry due to the introduction of solar collectors is at least 16–17% of the total volume of thermal energy produced. Converting such a volume of thermal generation to solar energy will require the installation of 5,300,000 m^2 of solar collectors, which will create more than 60,000 new jobs in the region.

The economic efficiency of solar collectors is still insufficient to compete with conventional boiler houses operating on cheap hydrocarbon fuels (expected average LCOE 3.8–6.6 rubles/kWh comparing current tariffs 1.5–2 rubles/kWh in a district heating area). However, the installation of solar collectors may well be considered as an investment-attractive option for the modernization of worn-out and outdated equipment of traditional boiler houses of industrial enterprises, which allows partially replacing hydrocarbon sources and lowering the carbon intensity of the Russian economy. As a measure of state incentives for the development of industrial solar collectors in Russia, we offer state co-financing of demonstration projects of Russian manufacturers. This will increase the level of awareness of the population and businesses about the capabilities of this technology, as well as increase the technical competencies and innovation potential of companies involved in the production and installation of solar collectors.

The results of our study can be useful in developing and improving federal and regional programs for the development of renewable energy in Russia and improving the energy efficiency of the Russian economy, as well as the industrial policy of the Russian Federation. They allow policymakers to more clearly classify the industrial enterprises that are most suitable for the introduction of solar collectors and to introduce more effective incentives for the development of this type of renewable energy. Also, these results can be used to calculate the required size of subsidies (or carbon taxes) which allow balancing the economic efficiency of solar collectors with the current hydrocarbon thermal generation technologies in the region.

The results of our study may be applicable outside of Russia. The proposed "demand-side" approach and algorithm for developing a regional strategy for increasing energy efficiency and the reduction of carbon intensity in the industrial sector can be used in other countries and regions.

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Abbreviations

RES	renewable energy sources
LCOE	levelized cost of energy
FPC water	flat plate solar water collectors
ETC water	evacuated tube collector
SHIP	solar heat for industrial processes
MWth	megawatts thermal

References

1. Olabi, A. Circular economy and renewable energy. *Energy* **2019**, *181*, 450–454. [CrossRef]
2. Donia, E.; Mineo, A.; Sgroi, F. A methodological approach for assessing business investments in renewable resources from a circular economy perspective. *Land Use Policy* **2018**, *76*, 823–827. [CrossRef]
3. Renewable Energy Statistics 2019. Available online: https://www.irena.org/publications/2019/Jul/Renewable-energy-statistics-2019 (accessed on 13 December 2019).
4. REN21. Renewables 2019 Global Status Report. Paris: REN21 Secretariat. Available online: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf (accessed on 13 December 2019).
5. Renewable Energy Policies in a Time of Transition. IRENA, OCED/IEA and REN21. 2018. 112 P. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_IEA_REN21_Policies_2018.pdf (accessed on 13 December 2019).
6. Nicolli, F.; Vona, F. Energy market liberalization and renewable energy policies in OECD countries. *Energy Policy* **2019**, *128*, 853–867. [CrossRef]
7. Erdiwansyah Mamat, R.; Sani, M.; Sudhakar, K. Renewable energy in Southeast Asia: Policies and recommendations. *Sci. Total Env.* **2019**, *670*, 1095–1102. [CrossRef] [PubMed]
8. Ratner, S.; Nizhegorodtsev, R. Analysis of renewable energy projects' implementation in Russia. *Therm. Eng.* **2017**, *64*, 429–436. [CrossRef]
9. Energy Efficiency Market Report 2017. OECD/IEA, Paris. 2017. 142 P. Available online: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/energy-resources/Energy_Efficiency_Marketing_Report_2017.pdf (accessed on 13 December 2019).
10. Schmitt, B. Classification of Industrial Heat Consumers for Integration of Solar Heat. *Energy Procedia* **2016**, *91*, 650–660. [CrossRef]
11. Butuzov, V. Solar Heat Supply: World Statistics and Peculiarities of the Russian Experience. *Therm. Eng.* **2018**, *65*, 741–750. [CrossRef]
12. Kumar, L.; Hasanuzzaman, M.; Rahim, N. Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review. *Energy Convers. Manag.* **2019**, *195*, 885–908. [CrossRef]
13. Schramm, S.; Adam, M. Storage in Solar Process Heat Applications. *Energy Procedia* **2014**, *48*, 1202–1209. [CrossRef]
14. Farjana, S.; Huda, N.; Mahmud, M.; Saidur, R. Solar process heat in industrial systems – A global review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2270–2286. [CrossRef]

15. Weiss, W.; Spörk-Dür, M. Solar Heat Worldwide. Global Market Development and Trends in 2017. Available online: https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2018.pdf (accessed on 13 December 2019).
16. Chang, K.; Lin, W.; Leu, T.; Chung, K. Perspectives for solar thermal applications in Taiwan. *Energy Policy* **2016**, *94*, 25–28. [CrossRef]
17. Suresh, N.; Rao, B. Solar energy for process heating: A case study of select Indian industries. *J. Clean. Prod.* **2017**, *151*, 439–451. [CrossRef]
18. Statistical Digest Industrial "Production in Russia – 2016", Part 5.4 "Consumption of certain types of fuel and energy resources by type of economic activity. Available online: https://gks.ru/bgd/regl/b16_48/Main.htm (accessed on 14 December 2019).
19. Frid, S.; Kolomiets, Y.; Sushnikova, E.; Yamuder, V. Effectiveness and prospects of using different solar water heating systems under the climatic conditions of the Russian Federation. *Therm. Eng.* **2011**, *58*, 910–916. [CrossRef]
20. Gridasov, M.; Kiseleva, S.; Nefedova, L.; Popel', O.; Frid, S. Development of the geoinformation system Renewable sources of Russia: Statement of the problem and choice of solution methods. *Therm. Eng.* **2011**, *58*, 924–931. [CrossRef]
21. Ueckerdt, F.; Hirth, L.; Luderer, G.; Edenhofer, O. System LCOE: What are the costs of variable renewables? *Energy* **2013**, *63*, 61–75. [CrossRef]
22. Reichenberg, L.; Hedenus, F.; Odenberger, M.; Johnsson, F. The marginal system LCOE of variable renewables–Evaluating high penetration levels of wind and solar in Europe. *Energy* **2018**, *152*, 914–924. [CrossRef]
23. Weiss, W.; Spörk-Dür, M. *Solar Heat Worldwide. Global Market Development and Trends in 2018*; AEE-Institute for Sustainable Technologies: Gleisdorf, Austria, 2019.
24. Wang, H.; Chen, W. Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe. *Appl. Energy* **2019**, *238*, 1563–1572. [CrossRef]
25. Sahoo, N.; Mohapatra, P.; Sahoo, B.; Mahanty, B. Rationality of energy efficiency improvement targets under the PAT scheme in India–A case of thermal power plants. *Energy Econ.* **2017**, *66*, 279–289. [CrossRef]
26. Huang, J.; Tian, Z.; Fan, J. A comprehensive analysis on development and transition of the solar thermal market in China with more than 70% market share worldwide. *Energy* **2019**, *174*, 611–624. [CrossRef]
27. Imtiaz Hussain, M.; Ménézo, C.; Kim, J. Advances in solar thermal harvesting technology based on surface solar absorption collectors: A review. *Sol. Energy Mater. Sol. Cells* **2018**, *187*, 123–139. [CrossRef]
28. Shafieian, A.; Khiadani, M.; Nosrati, A. A review of latest developments, progress, and applications of heat pipe solar collectors. *Renew. Sustain. Energy Rev.* **2018**, *95*, 273–304. [CrossRef]
29. Oosthuizen, D.; Goosen, N.; Hess, S. Solar thermal process heat in fishmeal production: Prospects for two South African fishmeal factories. *J. Clean. Prod.* **2020**, *253*, 119818. [CrossRef]
30. Svetlana, R.; Yuri, C.; Larisa, D.; Anna, P. Management of Energy Enterprises: Energy-efficiency Approach in Solar Collectors Industry: The Case of Russia. *Int. J. Energy Econ. Policy* **2018**, *8*, 237–243.
31. Loewen, J. LCOE is an undiscounted metric that distorts comparative analyses of energy costs. *Electr. J.* **2019**, *32*, 40–42. [CrossRef]
32. Fan, J.; Wei, S.; Yang, L.; Wang, H.; Zhong, P.; Zhang, X. Comparison of the LCOE between coal-fired power plants with CCS and main low-carbon generation technologies: Evidence from China. *Energy* **2019**, *176*, 143–155. [CrossRef]
33. Bruck, M.; Sandborn, P.; Goudarzi, N. A Levelized Cost of Energy (LCOE) model for wind farms that include Power Purchase Agreements (PPAs). *Renew. Energy* **2018**, *122*, 131–139. [CrossRef]
34. Administration and City Council of Krasnodar. Tariffs for Housing and Communal Services. Available online: https://krd.ru/upravlenie-tsen-i-tarifov/elektronnyy-sbornik-1-07-2013/analytic_info/informatsiya-ob-urovne-tsen-i-tarifov-na-tovary-i-uslugi-v-gorode-krasnodare-za-2019-god/informatsiya-ob-urovnyakh-tsen-i-tarifov-na-tovary-i-uslugi-po-munitsipalnomu-obrazovaniyu-gorod-krasnodar-za-1-kvartal-2019-goda/tarify-na-uslugi-zhilischno-kommunalnogo-khozyaystva/ (accessed on 14 December 2019).
35. Klimenko, V.; Klimenko, A.; Mikushina, O.; Tereshin, A. To avoid global warming by 2 °C—mission impossible. *Therm. Eng.* **2016**, *63*, 605–610. [CrossRef]
36. Orlov, A.; Grethe, H.; McDonald, S. Carbon taxation in Russia: Prospects for a double dividend and improved energy efficiency. *Energy Econ.* **2013**, *37*, 128–140. [CrossRef]

37. Liobikienė, G.; Butkus, M. The European Union possibilities to achieve targets of Europe 2020 and Paris agreement climate policy. *Renew. Energy* **2017**, *106*, 298–309. [CrossRef]
38. Saheb, Y.; Shnapp, S.; Johnson, C. The Zero Energy concept: Making the whole greater than the sum of the parts to meet the Paris Climate Agreement's objectives. *Curr. Opin. Environ. Sustain.* **2018**, *30*, 138–150. [CrossRef]
39. Ratner, S.; Iosifov, V.; Ratner, M. Optimization of the regional energy system with high potential of use of bio-waste and bioresources as energy sources with respect to ecological and economic parameters: The Krasnodar Krai case. *Reg. Econ. Theory Pract.* **2018**, *16*, 2383–2398. [CrossRef]
40. Ratner, S.V.; Ratner, P.D. Regional Energy Efficiency Programs in Russia: The Factors of Success. *Region* **2016**, *3*, 68–85. [CrossRef]
41. Ministry of Fuel and Energy Complex and Housing and Communal Services of the Krasnodar Territory. State Program of the Krasnodar Territory Development of the Fuel and Energy Complex. Available online: http://www.gkh-kuban.ru/kcpvcp19.html (accessed on 14 December 2019).
42. Matraeva, L.; Solodukha, P.; Erokhin, S.; Babenko, M. Improvement of Russian energy efficiency strategy within the framework of green economy concept (based on the analysis of experience of foreign countries). *Energy Policy* **2019**, *125*, 478–486. [CrossRef]
43. Matraeva, L.V.; Goryunova, N.A.; Smirnova, S.N.; Babenko, M.I.; Erokhin, S.G.; Solodukha, P.V. Methodological approaches to the assessment of energy efficiency within the framework of the concept of green economy and sustainable development. *Int. J. Energy Econ. Policy* **2017**, *7*, 231–239.
44. Berezin, A.; Ratner, S. Policy transition to low-carbon economy in Russia: State support measures. In Proceedings of the 13th International Days Of Statistics And Economics Conference Proceedings, Prague, Czech Republic, 5–7 September 2019; Libuše Macáková, MELANDRIUM, 2019 Fügnerova 691 274 01 Slaný IČO: 48709395. ISBN 978-80-87990-18-6.
45. Kylili, A.; Fokaides, P.; Ioannides, A.; Kalogirou, S. Environmental assessment of solar thermal systems for the industrial sector. *J. Clean. Prod.* **2018**, *176*, 99–109. [CrossRef]
46. Boute, A.; Zhikharev, A. Vested interests as driver of the clean energy transition: Evidence from Russia's solar energy policy. *Energy Policy* **2019**, *133*, 110910. [CrossRef]
47. Ratner, S.V.; Klochkov, V.V. Scenario Forecast for Wind Turbine Manufacturing in Russia. *Int. J. Energy Econ. Policy* **2017**, *7*, 144–151.
48. Gawel, E.; Lehmann, P.; Purkus, A.; Söderholm, P.; Witte, K. Rationales for technology-specific RES support and their relevance for German policy. *Energy Policy* **2017**, *102*, 16–26. [CrossRef]
49. Huntington, S.; Rodilla, P.; Herrero, I.; Batlle, C. Revisiting support policies for RES-E adulthood: Towards market compatible schemes. *Energy Policy* **2017**, *104*, 474–483. [CrossRef]