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Assessing the Energy Performance of Solar Thermal Energy for Heat Production in Urban Areas: A Case Study

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Received: 18 January 2019; Accepted: 19 March 2019; Published: 21 March 2019

Abstract: One of the major challenges faced in the optimization process of existing heating systems is the harnessing and integration of a higher share of renewable energy. Centralized integration at the thermic source leads to high investment costs at the first investment stage, and low values of conversion, transport, and storage efficiencies, due to high levels of heat loss from large-capacity entropic systems. This research paper presents a case study on the partially decentralized integration of thermal solar fields that are used for heat production in crowded urban areas within the optimization process of the existing heating system in the city of Oradea, Romania. A deterministic method was used as the method for the calculation of heat demand, in both stationary—hourly heat demand and dynamic regimes—annual heat demand, and the simulations within the configuration and the optimization process of the hybrid heating systems were carried out. In the case study, four representative urban areas with different thermal densities were analyzed within two working scenarios, which took into account the energy performances of the buildings inside the studied areas before thermal retrofitting, and after a usual thermal retrofit.

Keywords: renewable; solar thermal; energy; urban area; district; hybrid; heating system; efficiency; indicator; performance

1. Introduction

At present, almost 50% of the total energy that is consumed in Europe is being used for the generation of heat for either domestic or industrial purposes [1]. Around 40% of the total energy consumed is consumed in buildings; thus, buildings are responsible for generating more than 35% of the total carbon emissions in the European countries [2,3]. The vast majority of buildings are placed within urban areas, thus resulting in areas with high energy consumption densities [4]. In the current context, worldwide, there are many ways to face the challenges of sustainable development in the energy field. Efficient usage of energy and energy resources represents a major objective, focusing on the percentage increase of the use of clean and renewable energy sources (RES). Optimizing the energy balance of the urban thermo-energy sector by harnessing renewable energy sources identified within urban areas meets such requirements.

The thermal energy demand that is related to space heating and hot water preparation within residential and services sectors represents an important part of the total thermal energy demand at the district level. Such a demand is currently met, to a large extent, by the existing district heating systems [5,6].

It is a proven fact that the energy efficiency of a centralized heating system is closely linked to the energy density and surface that is covered by consumers in built-up areas, and the uniformity of this coverage. Optimizing the configuration of a district heating system in order to increase energy performance with respect to these indicators has often been approached within the technical literature, in recent times [2,7,8].

Due to the significant energy impacts of district heating systems, modelling, simulation, and analysis of such systems requires a significant degree of effort from engineers and researchers [8–12]. A great variety of methods and methodologies have been elaborated and developed, and are aimed at designing new energetic systems, and optimizing existing ones [2,9–12]. In order to select the optimal energy system, there are also numerous applications that are based on the analytical network process method [13]. Similar methods were developed that were based on fuzzy or RNA logic process, aimed at predicting and monitoring energy consumption [14–16]. Another category of analysis methods are the deterministic methods, enforced under dynamic regimes, that are compliant with the characteristics of demands in the case of new energy systems, or in the case of the existing systems with the energy consumptions and with the variable features of available energy, if renewable energy sources are taken into consideration. Such methods balance with sufficient accuracy the technological processes that are associated with the production, storage, transport, and consumption of the energy [17,18]. In most cases, the mainly used indicators are economic and environmental ones [19–24]. When comparing different types of energy equipment, one may consider fuel saving indicators, if the two forms of energy, heat and electricity, are jointly produced, as compared to installations that produce those two types of energy separately. From this perspective, the resulting optimal technology usually seems to be a cogeneration system [25]. The use of cogeneration has led to proper results in reducing fossil fuel consumption, and this has major results in reducing greenhouse gases emissions. However, from the perspective of several studies carried out within this field, it has also led to the increase of some pollutant levels, especially NO_x, within inhabited areas [26–28]. CO, CO_2, SO_2, and NO_x compounds are considered to be aggressive pollutants, and they are also the result of burning fossil fuels in order to generate heat, and therefore their reduction is also a critical objective of current worldwide energy policies.

In the future, one can expect that energy systems will include higher shares of renewable energy. Due to the fact that the connection between the efficiency of a system, both energetically and environmentally, and the use of the renewable energy sources is already proven, one of the main objectives in the district heating systems domain is currently to increase the share of renewable energy. Because the harnessing technologies for such energy require high investment costs, and they are rather limited from a technological point of view, the following objectives in the field are highlighted: optimizing the renewable energy use technologies, and the storage of the resulting thermal energy STES (seasonal thermal energy storage), and optimizing the integration of RES technologies into existing heating systems, thus resulting in hybrid heating systems.

In Romania, the current demand of thermal energy is mainly met from conventional technologies. Consequently, there is a significant potential for increasing the share of energy that results resulted from renewable heating sources, especially biomass, solar energy, and geothermal, which can all be used within alternative heating sources. The European Renewable Energy Council (EREC) has estimated that renewable energy will represent 30% of the total energy consumption at the level of the European Union until 2020, and over 50% until 2050, as compared to 2010, when the conventional heating technologies based on fossil fuels generated almost 72% of the energy consumed for heating spaces (SETIS Report).

Theoretically, the RES exploitation systems require large areas for harnessing energy, and high-capacity installations of conversion and storage. This leads to high land-use footprints. In the case of district heating systems that include technologies that are based on RES, the issue is closely connected with the systems' optimal capacity configuration, so that the RES installations will present a minimal footprint, and they will not impact each other [7], which are both aspects that represent challenges within crowded urban areas. In the case of using geothermal resources, the optimal solution seems to be achieved when consumers from high-energy density areas are connected to the centralized district heating system, and those from low-energy density areas are provided with individual heating systems based on the exploitation of renewable resources [7].

The obtained conclusions may represent input data in the case of using other types of renewable and clean energy sources. On the other hand, regarding solar systems, the existing district heating systems through the district networks may represent a sustainable alternative to managing the resulting excess energy, which is due to the variable nature of the solar resource, thus allowing for an increase in the share of renewable energy, insofar as the technological footprint does not exceed the available surfaces for mounting the collectors.

With regard to thermo-solar resources in particular, at a European level, this represents an important component in the configuration of future district heating systems. Thermo-solar systems of medium and large capacity (>100 m^2 collecting surface), efficiently integrated into the current or future district systems, already represent one of the cleanest and most innovative methods for energy optimization and the reduction of fossil fuel consumption, and implicitly, the reduction of associated CO_2 emissions. In Europe, there are several applications that are in the course of implementation, or at different monitoring stages, on this matter [29–36]. Monitoring such applications allows for significant amounts of information to be secured regarding the influence of operating conditions, and strategies on the efficiency of hybrid systems. In some applications, the annual operating efficiency of thermo-solar systems, storage systems, or hybrid heating systems is below the values of the estimated efficiency during the designing stages [29–35]. This is due to different causes, the most common being the inadequate parameter regimes and operating strategies of the hybrid heating systems. Contrary to all of these obstacles, harnessing clean renewable energies within urban areas for the production of heat remains a necessary objective that needs to be met, as it is desirable from many points of view, among which the most important are:

- The reduction of greenhouse emissions that are associated with the production of thermal energy.
- The reduction of noxious gases that impact a population's health, which are associated with the production of thermal energy within urban areas.
- Framing the building that is connected or equipped with hybrid heating systems in superior classes of energy performance.
- Offering to the final consumers who are connected to the district heating system, the possibility of being directly involved, through coparticipation, in the production and management of thermal energy (based on the feed-in principle).

2. Methodology

2.1. Problem Formulation

One of the most important indicators in the case of using renewable and alternative energy sources is the footprint of the land use. The land-use footprint [37] represents the effective share of the land that is used to capture, convert, and store the renewable energy, without the possibility of using these surfaces in other anthropic activities (i.e., farming, constructions, etc.). In the case of renewable energy resources, the real land-use footprint is not always equal to the value of the indicator, and it presents particular features that are dependent on the type of source. If, in the case of geothermal heating systems, the real footprint and its usage impact effects on other activities are rather low, due to the fact that most of their components are placed underground [37], in the case of harnessing, converting, and storing solar energy, this indicator becomes rather decisive for configuring the heating system, together with the global technical-economic efficiency of the hybrid system. In this context, the issue related to the optimization of the energy balance, by increasing the share of using solar thermal resource (RES-S), may be reduced to a function of two interdepending variables—harnessing the share of RES-S, and the efficiency of the optimized hybrid system, a function for which the land-use footprint of RES-S represents a major restriction.

2.2. The Purpose and Contribution of the Paper

The general purpose of this paper is to contribute to highlighting the possibilities of using solar energy in heat production within crowded urban areas, and to quantify the performances of the hybrid systems, in order to optimize, from a thermo-energy point of view, the existing heating systems. The specific purpose of this paper is the configuration of a case study, where some representative parameters are determined and analyzed.

In particular, the contributions of this paper are: determining the thermo-energy footprints of the analyzed reference urban areas, and the assessment of the efficiency and environmental impact of thermo-solar fields that are integrated in a decentralized manner at the level of the zonal thermal stations, within the configured case study. A major contribution of this paper is the possibility of extrapolating the secured results within a case study, by obtaining several specific performance indicators that are representative and exhaustive, but that are also closely connected to the particularities of different urban areas—thermal density, the number of consumers, the available surfaces, etc.

3. Methodology

3.1. Method Description

The method that is used is based on identifying the specific performance indicators that will accurately quantify the energy footprint of the solar resource that is harnessed within the urban areas, and this will allow for their extrapolation, in order to be reused to conduct exhaustive studies.

In order to configure the case study, the city of Oradea, situated within western Romania, has been selected. It was selected due to the fact that the urban heating is based largely on a district heating cogeneration system, and the current urban strategy representing elevated trends of modernization and optimization of the thermal energy production and transport system, as well as of the integration of identified renewable energy sources.

The configuration of the case study is presented in detail within the following subsection, and it presents the assessment of solar energy as a resource within the respective area, the configuration of the reference thermal consumers—the areas and the configuration of the hybrid heating system. Following centralization of the input data, it was decided that the four representative urban areas would be kept, and herein they are marked as A1 to A4, which are different from one another by the number of inhabitants and the thermal density. In order to quantify the energetic performance of the hybrid heating systems, and due to the fact that the trend is to thermally envelope buildings, two work scenarios were considered: Scenario 1 (S1)—before the thermal rehabilitation and modernization of existing buildings, respectively, and Scenario 2 (S2)—after the thermal rehabilitation and modernization of the existing buildings, respectively, for a common level of thermal enveloping of buildings [38,39].

The data secured in the case of the buildings located within the urban areas that were analyzed in Scenario 1, and the demands for heating and domestic hot water preparation respectively, were compared to the current rates of consumption.

The demands for heating and domestic hot water preparation have been processed mathematically, securing the thermo-energy footprint and ranked curve of the thermal energy demand, based on how the thermo-solar fields were configured, with respect to the available mounting surfaces—the land-use footprint.

Upon configuring the thermo-solar fields, the following criteria were considered:

- The efficiency of the thermal energy harness is higher than the integration of the solar fields, and it is closer to the consumption points, with the possibility of managing excess energy by delivering it to the district heating networks [40], based on the feed-in principle. In this sense, the partially decentralized integration of the solar fields at the level of the thermal points of the area have been considered.

- The available surfaces for the placement of solar collectors (i.e., on-roof terraces, roofs of parking lots, etc.).

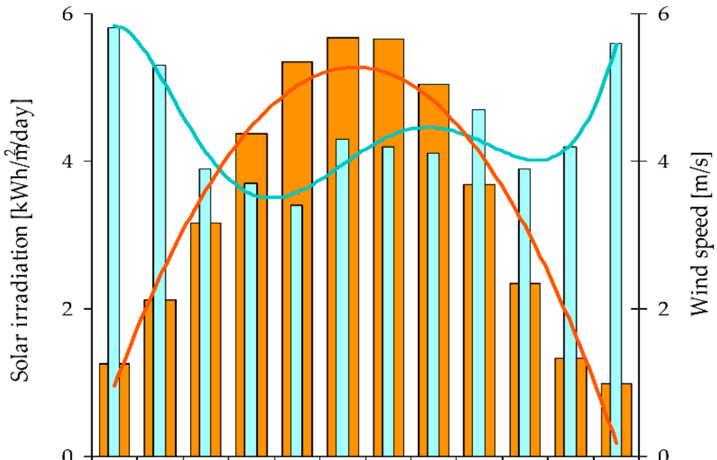
The hydraulic and technological optimization of thermo-solar systems was conducted by using the Polysun software platform (version 2016, Vela Solaris AG, Winterthur, Switzerland), with the aim being to secure the highest annual solar fractions (as close as possible to 60%) under the high global thermo-energy efficiency of the hybrid heating system, and the high yields of the thermo-collector fields, respectively.

3.2. Description of the Case Study: A Hybrid Energy System

The description of the proposed case study presents three main aspects: modelling the solar resource for the reference location, configuration of the urban areas, determining their representative characteristics, and configuration of the hybrid system of heating, respectively.

3.2.1. Solar Energy Resources

The annual average of global solar irradiation in the case of the reference location within the proposed case study is 1249.27 kWh/m^2 on a horizontal surface [41]. The average monthly values of solar irradiation and wind for the proposed location are modelled within Figure 1.



	1	2	3	4	5	6	7	8	9	10	11	12
Sun	1.25	2.12	3.17	4.37	5.35	5.67	5.66	5.05	3.69	2.35	1.33	0.98
Wind	5.8	5.3	3.9	3.7	3.4	4.3	4.2	4.1	4.7	3.9	4.2	5.6

Figure 1. Renewable energy sources-solar (RES-S)—Global insolation profile. Monthly average values.

3.2.2. The Urban Area

The area of the reference locality, the city of Oradea, located in Western Romania, has been proposed for the development of the case study [42]. The typologies of the thermal energy consumers from the reference locality are illustrated in Figure 2.

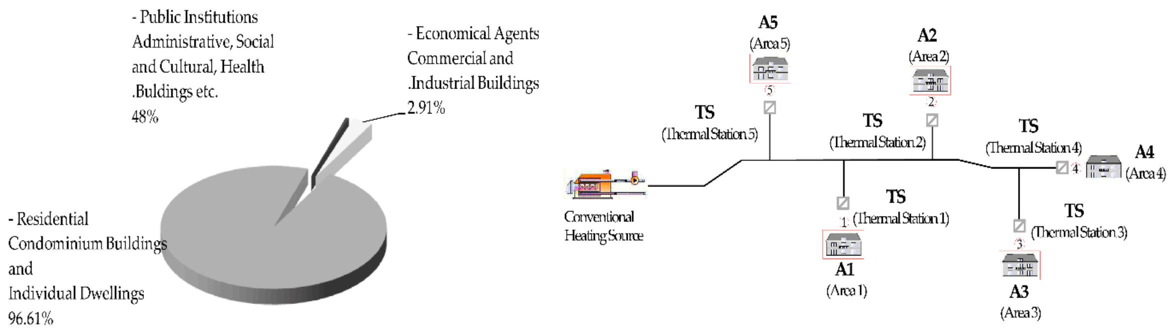
The locality is placed within an eastern European geographical area, having a moderate to cold climate, and the following climate characteristics, as per current Romanian regulations in force, are shown in Table 1.

Table 1. Characteristics of the Oradea site.

Climate Characteristics	Value	Unit
Climate Area (of winter) [43–45]	II	
Outdoor temperature calculation on a stationary regime	−15	°C
Ground temperature calculation	+10	°C
Calculation of degrees-days at an outdoor temperature of +12 °C	3150	degrees-days
Calculation of degrees-days at an outdoor temperature of +10 °C	2990	degrees-days
Conventional duration of the heating period at an outdoor temperature of +12 °C	195	days
Conventional duration of the heating period at an outdoor temperature of +10 °C	175	days
Wind Area [43]	IV	
Calculation of outdoor velocity	4	m/s
Sun Exposure Area According to the National Institute of Meteorology and Hydrology (INMH)	II	
Annual average of solar radiation	1150–1250	kWh/m^2
Annual sunshine period	2000–2100	h/year

The beginning (and duration) of the heating period is not the same for all of the buildings in the area. In the case of the centralized heating systems in Romania, the threshold values of the temperature for the beginning and the end of the heating period have been established at +12 °C, recorded for three consecutive days, and +10 °C, respectively, depending on the building's destination, as in Table 1 [44].

In order to configure the heating system, the partial thermo-energy zoning of the locality has been introduced, with the identification of zonal thermal consumers, as per Figure 2.



(**a**) (**b**)

Figure 2. (**a**) Typology of thermal consumers—buildings, in the reference locality [42]; (**b**) Simplified scheme of the district heating system within Case Study [42].

The proposed areas A_1–A_4 present constructive characteristics in accordance with Table 2. Area 5 represents a main industrial area, as analyzed within the general study, and it will be the object of a future paper.

Table 2. Areas A_1–A_4 and their characteristics [46].

Area	Thermal Density	Territorial Surface of Reference	Built Volume	No. of Consumers of DHW
-	-	m^2	m^3	pers.
A_1	very high	32,000	185,390	2755
A_2^{ref}	high	32,000	176,950	2600
A_3	medium	32,000	52,521	1048
A_4	low	32,000	23,530	277

The design of the district heating system is based on the assessment of the hourly heat demand, and the annual demand of thermo-energy (energy$_t$), respectively. The hourly heat demand represents the maximum hourly heat demand within the heating period, determined by the calculation of the outdoor temperature in a stationary regime (according to Table 1), related to the space being heated, the ventilation, and the domestic hot water system of the buildings. The hourly heat demand was determined for each of the investigated buildings, in two working scenarios, before and after the buildings' envelopes underwent thermal retrofitting [47]. The annual energy$_t$ demand included the energy$_t$ demand for space heating, ventilation, and domestic hot water preparation, during the entire year. The retrofits for the buildings were done for an average level of envelope retrofitting (according to [38,39]), in order for the buildings to be framed in a superior performance class. According to [48], the thermo-energy scale or thermo-energy classification grid for buildings in Romania sets the specific demand (i.e., consumption) values for heating, as described in Table 3.

Table 3. The thermo-energy classification for buildings [48].

Thermo-Energy Performance Class	A	B	C	D	E	F	G
-	kWh/(m^{2}year)						
Heating	≤70	≤117	≤173	≤245	≤343	≤500	≤500
Domestic hot water (DHW)	15	35	59	90	132	200	200

The annual demand of energy$_t$ was determined within a dynamic regime, using the thermo-energy computation platform [49] for each of the investigated buildings. The resulting data are presented in Tables 4 and 5, which summarize the representative working scenarios that are used in the case study.

Table 4. Work Scenario no. 1, S1.

Initial Thermo-Energy Performance (before Thermal Retrofit of Building)								
Area	Hourly Heat Demand			Thermal Density of the Area	Annual Demand of Energy$_t$	Specific Annual Demand of Energy$_t$ *	Thermo-Energy Classification	
	for Space Heating	for DHW	Total				Heating	Integrated
-	MW	MW	MW	W/m^2	MWh/year	kWh/(m^{2}year)	-	
A_1	6.711	0.868	7.579	236.84	15,441.60	304.28	C	D
A_2^{ref}	4.787	0.703	5.490	171.56	12,602.17	241.76	B	D
A_3	1.250	0.150	1.400	43.75	3575.38	297.95	D	D
A_4	0.560	0.110	0.670	20.94	1363.00	214.31	C	C
A_1–A_4	13.308	1.831	15.139	118.27	32,982.15	273.46	C	D

* reported as the built surface area.

Table 5. Work Scenario no. 2, S2.

Final Thermo-Energy Performance (after Thermal Retrofit of Building)								
Area	Hourly Heat Demand			Thermal Density of the Area	Annual Demand of Energy$_t$	Specific Annual Demand of Energy$_t$ *	Thermo-Energy Classification	
	for Space Heating	for DHW	Total				Heating	Integrated
-	MW	MW	MW	W/m^2	MWh/year	kWh/(m^2 year)	-	
A_1	3.578	0.868	4.446	138.94	9686.00	191.80	A	C
A_2^{ref}	3.038	0.703	3.741	116.91	8781.98	168.47	A	C
A_3	0.800	0.150	0.950	29.69	2819.75	235.98	B	D
A_4	0.360	0.110	0.470	12.81	1027.78	161.60	B	C
A_1–A_4	7.776	1.831	9.607	75.05	22,315.51	186.06	B	C

* reported as the built surface area.

The heat demands were assessed with the assistance of calculations and simulation software [47,49], or independently, according to the calculation methodologies described. In order to estimate the demands of domestic hot water within the reference buildings, a value of 90 L/individual/day was used in the case of dwelling buildings, and 4 L/individual/shift in the case of administrative buildings, at a delivery temperature of 50 °C. The hourly thermal energy demand was calculated for each area.

The calculation method for the annual heating demands [49] was based on heat exchange under a nonstationary regime, through opaque and transparent construction elements, and it considered the impact of heat intake due to human activity and solar radiation on the resulting interior temperature, as required under thermal comfort norms. The calculation method established the probable annual heating demands that must be provided by the heating system, in order to obtain a comfortable microclimate. The specific annual heating demand was calculated for each area. This method was selected, as it was superior to conventional methods that are used to estimate heating demands for urban consumers (for instance, the statistical method of heating characteristics, the methods of heating equivalent surfaces, etc.), so as to highlight and quantify the energy performances of urban consumers before and after thermal rehabilitation and modernization.

The annual energy$_t$ demand for space heating related to areas A_1–A_4 was reduced by ~32.3% in scenario S2 vs. scenario S1, once the building envelopes were thermally rehabilitated (i.e., modernized), respectively (see Table 6).

Table 6. Heat demands for areas A_1–A_4.

Area	**Annual Demand of Energy$_t$ (for Space Heating)**	**Optimized Annual Demand of Energy$_t$ (for Space Heating)**
	Scenario S1	Scenario S2
-	MWh/year	MWh/year
A_1	15,441.60	9686.00
A_2	12,602.17	8781.98
A_3	3575.38	2819.75
A_4	1363.00	1027.78
Total A_1__A_4	32,982.15	22,315.51

Within the case study, the thermal energy consumers represented the urban areas, as defined by: the thermal energy demand, both hourly and annually; the surface thermal density; the integrated thermo-energy class.

The thermo-energy footprint is illustrated in Figure 3 for the study areas A_1–A_4, in the case of the two work assumptions, Scenario 1 and Scenario 2—before and after thermal rehabilitation and modernization of buildings, respectively.

Under a stationary regime, the expression of the heat demand Q_h represents a linear function of the outside temperature (t_e) (see Figure 3), as follows:

$$Q_h = -a \cdot t_e + b \quad (1)$$

where the following notes have been made:

$a = G \cdot V_c$, respectively $b = G \cdot V_c t_{int} - (Q_S + Q_{int})$, where the G-factor is defined as a "weighted" coefficient of the thermal insulation of all buildings within the study areas [42].

where:

V_c represents the built-volume, in m^3; t_{int} = the indoor temperature of the designed house; Q_S = the solar input, in kW; Q_{int} = the internal input, in kW.

For the case study analyzed, the weighted coefficient of thermal insulation G has the following values:

- for Scenario 1 (S1): $G = 1.6 \times 10^{-3}$ W/(m^{3}K);

- for Scenario 2 (S2): G = 0.9 × 10^{-3} W/(m^3K).

The ranked curve represents the decrease of the hourly energy demands on the entire period of a year. It is obtained by classifying all daily load curves. By overlapping all load curves, the 'mountain' load of the system was obtained. By intersecting it with a perpendicular plane, the power levels and the associated time periods were identified, resulting in the shapes from Figure 4. In Figure 4, the ranked curves of the thermal energy demand for heating and domestic hot water preparation (DHW) are graphically represented, in the case of the two working scenarios, scenario S1 and scenario S2, respectively.

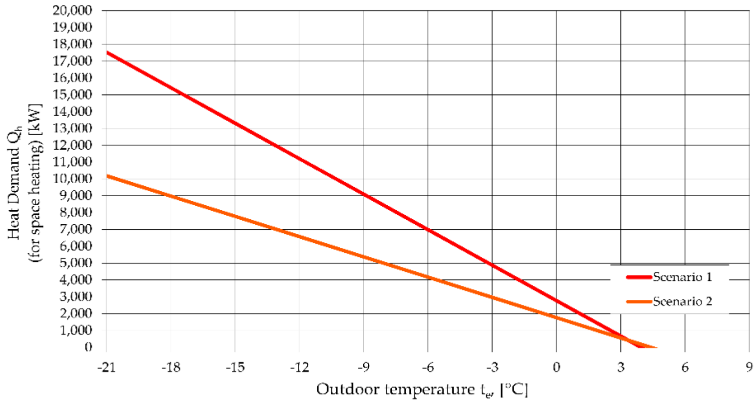


Figure 3. Thermo-energy footprints of the reference urban areas for the study scenarios under a stationary regime.

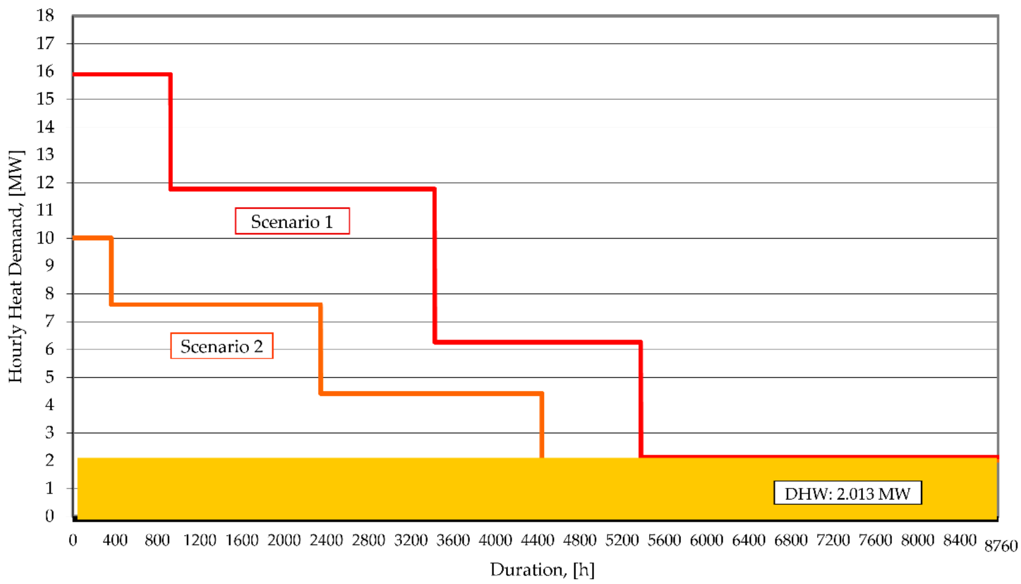


Figure 4. Ranked curves of the annual $energy_t$ demands of the urban areas for the study scenarios under a transitory regime [42].

The significant impacts of the thermal rehabilitation and modernization of building envelopes on the energy footprints of their areas are presented in Figures 3 and 4.

The thermal energy consumption would decrease in Romania, following the completion of thermo-energy rehabilitation and modernization works on existing buildings, and at the same time, the reduction of the polluting emissions associated with the improvement of hygiene conditions and the interior thermal comfort, respectively, could be achieved. In the context of the case study for buildings located within areas A_1–A_4, the hourly heat demand for space heating was decreased by 41.5% compared to its initial value. Also, the value of the annual demand of $energy_t$ for space heating decreased by 32.3%, compared to the initial value (see Tables 4 and 5), considering the fact that the existing buildings were thermally retrofitted (i.e., thermally insulated) at an average level (according to [38,39]).

3.2.3. The Solar-Assisted Heating System Configuration

The hybrid heating system assumes the use of solar energy in order to produce heat, by integrating solar-based systems in a decentralized way in the existing heating system, in a complementary mode to the conventional sources.

The hydraulic integration of the thermo-solar systems was conducted at the level of the thermal stations (TS) existing within the area. The case study aims at the A_1–A_4 reference areas, with the initial and final thermo-energetic characteristics, as per Tables 4 and 5, which are characteristics that have led to the work scenarios S1 and S2. The temperature values of the thermal agent of the heating network are set forth below: in the case of Scenario S1, 90/60 °C, and 70/40 °C in the case of Scenario S2. The integration mode of the thermo-solar fields at the level of the thermal stations TS of the areas is presented in Figure 5.

In order to compare the secured indicators between areas with different characteristics, the following assumption was considered: the reference system for the configuration of the hybrid heating system was a thermo-solar system consisting of 5000 thermal collectors, having a gross surface of 10,000 m^2, and a thermal energy storage system with a nominal volume of 4000 m^3. Solar collectors with a gross surface area of 2 m^2 were chosen, in order to simplify their assembly work within crowded urban areas, on roofs of buildings, over car parks, etc. The system had a solar fraction output of 60% for the area with the lowest thermal density (A_4 area) within the initial scenario of energy efficiency (S1). The land-use footprint in relation to the annual solar fraction achieved ($\%\alpha_a$—the equivalent surface [50]) was verified in situ within the study case, and an evaluation of existing surfaces without any other usefulness, and therefore available for mounting solar thermal fields, mainly on buildings' roofs and over car parks, was made.

The operating regime in the heating system contained variable flow. The volumetric flow within the solar collector field was automatically set, including the function of the temperature in the storage tank, and the temperature in the collector's field, respectively.

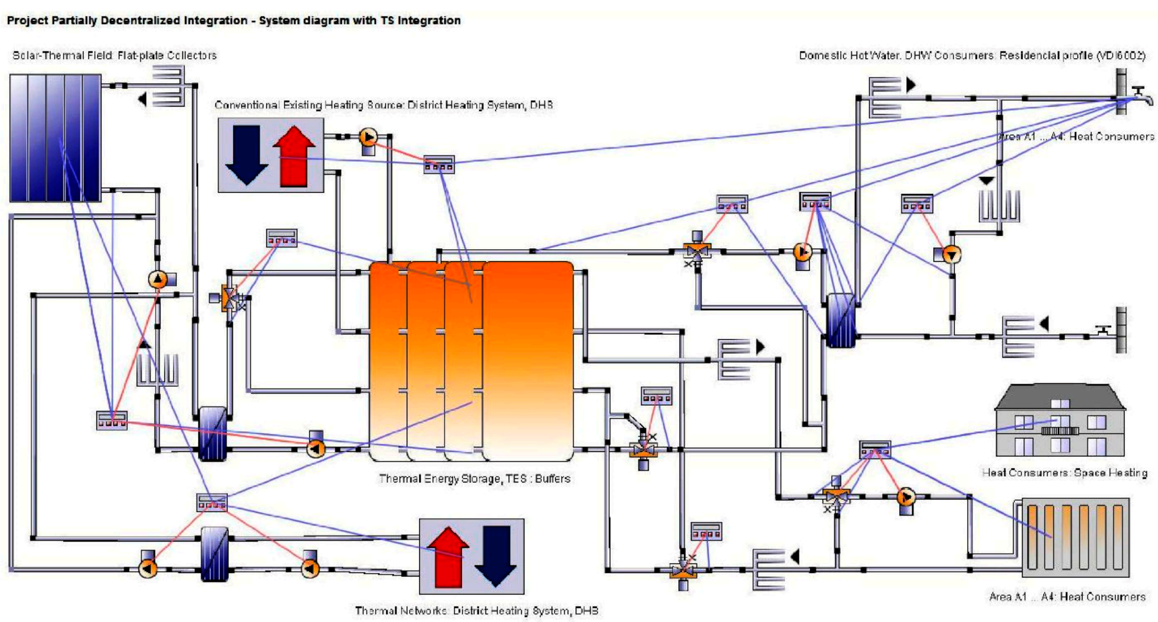


Figure 5. Optimized hybrid heating system with the integration of area thermal stations (TS). Hydraulic scheme of the principle [51].

In order to achieve the virtual frame for the simulations for the hydraulic system configured in Figure 5, an automation and control system was attached, according to Table 7.

Table 7. The control algorithm attached to the hybrid heating system.

Automation	Automation Input (Sensors)			Automation Output (Actuators)		
	-	Value	Unit	-	Value	Unit
Solar loop pump — Variable flow	Collector temperature	Temperature output	°C	On/Off pump	Solar loop pump: On/Off	%
	Thermal storage tank temperature	Inferior level	°C	On/Off pump	Solar loop pump: On/Off	%
	Temperature collector input	Temperature input	°C	Pumping capacity	Solar loop pump: Volumetric flow	L/h
	Collectors efficiency	Collectors	kWh	Pumping capacity	Solar loop pump: Volumetric flow	L/h
Auxiliary heating system	Temperature sensor switches on	Thermal energy storage (TES): Layer 11	°C	On/Off auxiliary heating	Auxiliary heating: On/Off	%
	Temperature sensor switches off	TES: Layer 9	°C	On/Off pump	Auxiliary heating pump: On/Off	%
	Volumetric flow	Designed volumetric flow	L/h	Volumetric flow control	Auxiliary heating pump: Volumetric flow	L/h
Thermal storage tank	Temperature sensor	Solar loop: TES temperature input	°C	On/Off switch	3-way electrovalve solar loop: deviation circuit	-
	Temperature sensor	TES: Layer 10	°C			
District heating network	Temperature sensor	TES: Layer 3	°C	On/Off switch	Pump: On/Off	%
	Temperature sensor	Temperature collector output	°C	On/Off switch	Discharge pump: On/Off	%
	Temperature sensor	Temperature collector output	°C	On/Off switch	Discharge pump: On/Off	%
	Temperature sensor	Discharge: Return temperature setting	°C	-	-	-

The thermal storage layers index used for the control algorithm (Table 7) were designed according to the 12-layer model of thermal stratification in the storage tank.

The solar collectors used were flat-plane collectors, with the following coefficients: η_0 = 75–80% (corresponding to the laminar and turbulent flow conditions), k_1 = 3.5–4.0 W/(m^{2}K) (in the absence and in the presence of wind, respectively), and k_2 = 0.02 W/(m^{2}K^2). The solar collectors had a mounting angle of 45°, and the values of solar irradiation were adjusted accordingly within the virtual simulation framework. The efficiency curves that were secured based on the Hottel–Whillier–Bliss equation, for the collectors used in the case study, are shown in Figure 6. Solar collectors with a gross area of 2 m^2 were chosen, in order to simplify the assembly work within crowded urban areas, on buildings' roofs, over car parks, etc.

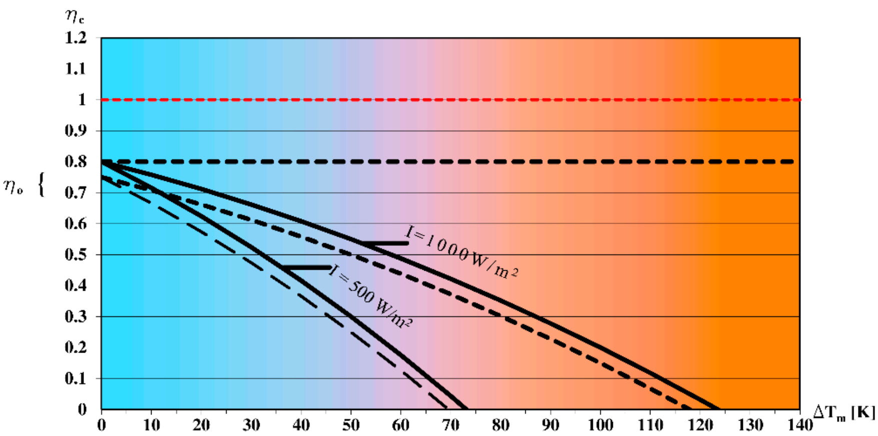


Figure 6. Yield curves of the flat-plane collector, depending on the operation temperature regime within the case study.

4. Results and Discussion

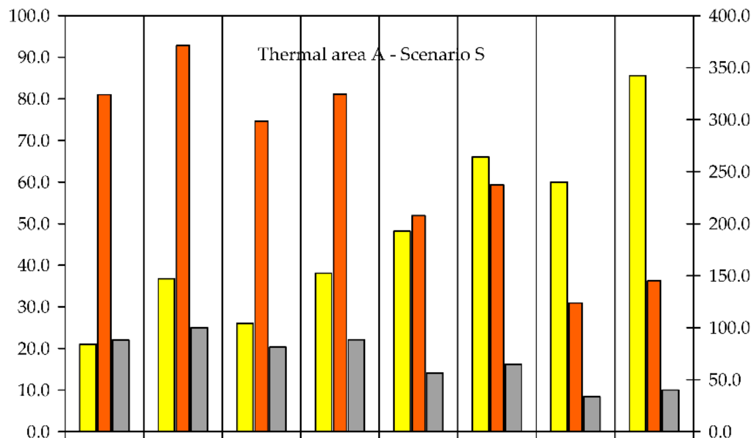
The most representative values obtained for areas A_1–A_4 within the case study for heat demand in the hybrid heating system are presented as follows.

4.1. Processing the Preliminary Data Related to the Urban Area Heat Demand

The thermo-energetic balance indicators secured for areas A_1–A_4 within the established hypotheses are centralized in Table 8.

The diagram presented in Figure 7 illustrates, in a comparative manner, the performance indicators that are achieved for the hybrid heating systems from areas A_1–A_4 within the two work scenarios, S1 and S2.

The annual efficiency of the thermo-solar collectors' field is defined as the ratio between the annual amount of useful heat that is supplied to the served thermic system, and the aperture area of the collectors' field. Delivering thermal energy in the district heating network, based on the feed-in principle, is limited to the level of excess energy management, which is due to the differences between the variable features of the solar resource and the consumption profile. Since the collector's field surface is similar in both cases, one can see in Figure 7 that the solar fractions achieved in area A4 were much higher, but also that the stagnation periods of the thermo-solar system and the resulting excess energy were also higher. On the other hand, this resulted in high operating temperature values, and a decrease of operational efficiency for the solar collectors. The assumption of the same area of the solar collectors' field being integrated into urban areas with different thermal energy densities was introduced, in order to compare similar investments in urban areas with different energy densities, within a gradual energy retrofit process for urban localities.



	A1 - S1	A1 - S2	A2 - S1	A2 - S2	A3 - S1	A3 - S2	A4 - S1	A4 - S2
Annual solar fraction, %	21.0	36.8	26.0	38.1	48.2	66.0	60.0	85.6
Annual solar collectors yield, %	22.0	25.0	20.3	22.1	14.1	16.1	8.4	10.0
Annual efficiency of the collectors field, kWh/(m² yr)	323.9	371.2	298.4	324.5	207.8	237.1	123.8	145.0

Figure 7. Performance indicators of the solar system. Comparative graphs for A_1–A_4.

Table 8. Indicators of the thermo-energy balance A_1–A_4.

Indicators of Thermo-Energy Balance A_1			**Unit**	**Value**	
-			-	**Scenario 1**	**Scenario 2**
Annual demand of energy$_t$ (in buildings)			MWh/year	15,441.60	9686.00
Annual solar fraction		α_y	%	21.0	36.8
Solar collector field	Total area	S	m^2	10.000	
	Aperture area	A	m^2	9.000	
Annual global yield of the solar collector		η_c	%	22.0	25.3
Annual efficiency of the solar collector field		Ef_a^c	kWh/(m^2 year)	323.9	371.2
Exergetic components of the thermo-energy balance		Q_{sol}	MWh/year	2914.9	3341.0
		$Q_{feed\text{-}in}$	MWh/year	103.5	166.6
		Q_{aux}	MWh/year	10,997.9	5725.6
Indicators of thermo-energy balance A_2			**Unit**	**Value**	
-			-	**Scenario 1**	**Scenario 2**
Annual demand of energy$_t$ (in buildings)			MWh/year	12,602.17	8781.98
Annual solar fraction		α_y	%	26.0	38.1
Solar collector field	Total area	S	m^2	10,000	
	Aperture area	A	m^2	9000	
Annual global yield of the solar collector		η_c	%	20.3	22.1
Annual efficiency of the solar collector field		Ef_a^c	kWh/(m^2 year)	298.4	324.5
Exergetic components of the thermo-energy balance		Q_{sol}	MWh/year	2685.9	2920.3
		$Q_{feed\text{-}in}$	MWh/year	117.8	208.6
		Q_{aux}	MWh/year	7640.2	4750.7
Indicators of the thermo-energy balance A_3			**Unit**	**Value**	
-			-	**Scenario 1**	**Scenario 2**
Annual demand of energy$_t$ (in buildings)			MWh/year	3575.38	2819.75
Annual solar fraction		α_a	%	48.2	66.0
Solar collector field	Total area	S	m^2	10,000	
	Aperture area	A	m^2	9000	
Annual global yield of the solar collector		η_c	%	14.1	16.1
Annual efficiency of the solar collector field		Ef_a^c	kWh/(m^2 year)	207.8	237.1
Exergetic components of the thermo-energy balance		Q_{sol}	MWh/year	1869.8	2133.8
		$Q_{feed\text{-}in}$	MWh/year	167.4	291.5
		Q_{aux}	MWh/year	2006.7	1100.4
Indicators of thermo-energy balance A_4			**Unit**	**Value**	
-			-	**Scenario 1**	**Scenario 2**
Annual demand of energy$_t$ (in buildings)			MWh/year	1363.00	1027.78
Annual solar fraction		α_a	%	Reference ~60.0	85.6
Solar collector field	Total area	S	m^2	10,000	
	Aperture area	A	m^2	9000	
Annual global yield of the solar collector		η_c	%	8.4	10.0
Annual efficiency of the solar collector field		Ef_a^c	kWh/(m^2 year)	123.8	145.0
Exergetic components of the thermo-energy balance		Q_{sol}	MWh/year	1114.2	1303.9
		$Q_{feed\text{-}in}$	MWh/year	202.7	352.8
		Q_{aux}	MWh/year	643.7	220.2

The background colours correspond to the graphic representations in Figure 7.

4.2. Impact Indicators of the Solar-Assisted Heating System and Preliminary Data Related to the Urban Area Heat Demand

The results of the comparative analyses conducted after developing the case study for the proposed areas A_1–A_4 (initial energy performances of the thermal consumers versus the final energy performances of the thermal consumers), in accordance with the established hypotheses, are centralized in Tables 9 and 10, and graphically illustrated within the comparative diagrams presented in Figures 8 and 9.

Table 9. Areas A_1–A_4. Components of the thermo-energy balance.

Area	Scen.	Solar Thermal Energy, Annually Delivered into the System	Thermal Energy Annually Delivered into the System by an Auxiliary Conventional Heating Source	Solar Thermal Energy Annually Delivered into the District Heating Network	Maximum Quantity of CO_2 Emissions Annually Avoided (ref. Natural Gases)
		(orange)	(purple)	(yellow)	(grey)
-	-	Q_{sol}	Q_{aux}	$Q_{feed\text{-}in}$	Em_{CO2}
-	-	MWh/year	MWh/year	MWh/year	kg CO_2/year
A_1	S1	2914.9	10,997.9	103.5	597,554.5
	S2	3341.0	5725.6	166.6	684,905.0
A_2	S1	2685.9	7640.2	117.8	550,609.5
	S2	2920.3	4750.7	208.6	598,661.5
A_3	S1	1869.8	2006.7	167.4	383,309.0
	S2	2133.8	1100.4	291.5	437,429.0
A_4	S1	1114.2	643.7	202.7	228,411.0
	S2	1303.9	220.2	352.8	267,299.5

The background colours correspond to the graphic representations in Figure 8.

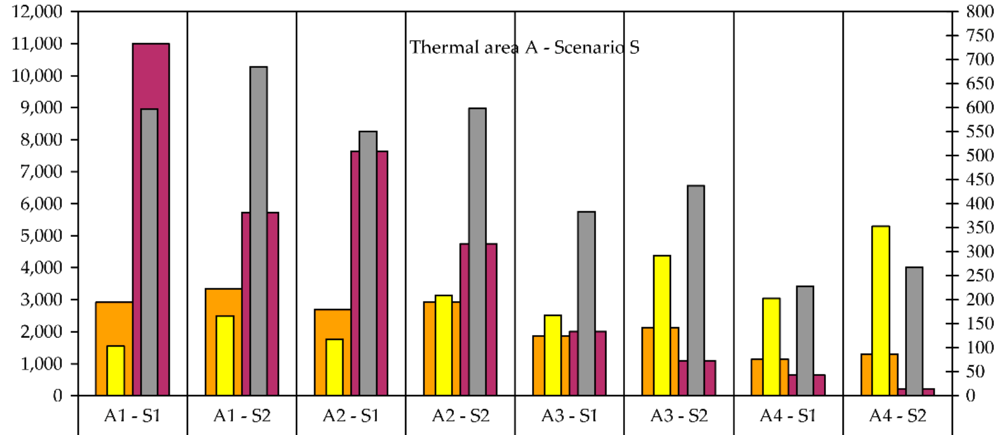
Table 10. Areas A_1–A_4. Indicators of thermo-energy performance.

	Indicators of Thermo-Energy Performance	Unit	Area							
			A_1		A_2		A_3		A_4	
			Scenario							
			S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2
	Specific annual heat demand, Q_{sa}	kWh/(m^2 year)	304.3	190.9	241.8	168.5	317.8	250.6	214.3	161.6
(purple)	Conventional primary energy indicator E_{conv}	kWh/(m^2 year)	216.7	112.8	146.6	91.1	178.4	97.8	101.2	34.6
(grey)	Emissions equivalent indicator * Em_{CO2}	kg_{CO2}/(m^2 year)	11.8	13.5	10.6	11.5	34.1	38.9	35.9	42.0
(yellow)	Indicator of primary energy from renewable energy sources (at the thermal station TS) Eres-TS	kWh/(m^2 year)	57.4	65.8	51.5	56.0	166.2	189.7	175.2	205.0
(orange)	Indicator of primary energy from renewable energy sources (at the consumers) Eres-C	kWh/(m^2 year)	55.4	62.6	49.3	52.0	151.3	163.8	143.3	149.5

* natural gases as a reference. The background colours correspond to the graphic representations in Figure 9.

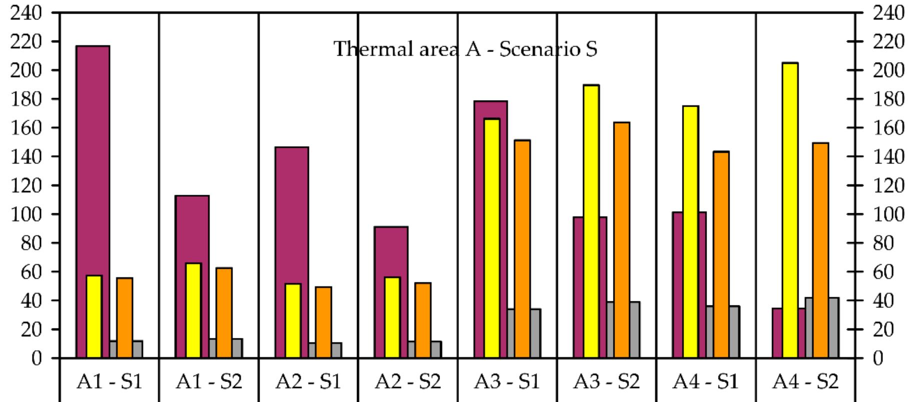
Eres-TS and Eres-C (kWh/m^{2}year) are indicators of primary energy from renewable energy sources, determined in the first case, at the level of the thermal stations (TS), and in the second case, at the level of the consumers (C). Their values (according to Table 10 and Figure 9, respectively) are closely related to the annually harnessed solar energy, relative to the heated surfaces. Thus, the low values of the Eres-TS and Eres-C indicators within the first two cases (areas with high-energy densities) represent a consequence of the introduced hypothesis: the assumption of the same area of solar collection integrated in urban areas with different thermal energy densities. One of the conclusions is that the same thermal solar collector surface, implemented in urban areas with different densities, records the values of these efficiency indicators as being lower and the energy density of the area as being is higher, and thus the annual solar fractions achieved are higher.

The performance indicators achieved after developing the case study, as presented in Table 11 for the proposed areas A_1–A_4, have been divided into the number of consumers involved (persons). The specific performance indicators have been secured in relation to the number of consumers and implicitly to the energetic density of the proposed areas. In this regard, the resulting data can be used as input data for future technical–economic studies as required, for the implementation of thermo-solar systems within the proposed configurations for similar urban areas.



	A1 - S1	A1 - S2	A2 - S1	A2 - S2	A3 - S1	A3 - S2	A4 - S1	A4 - S2
Qsol, (MWh/yr)	2,914.9	3,341.0	2,685.9	2,920.3	1,869.8	2,133.8	1,142.2	1,303.9
Qaux, (MWh/yr)	10,997.9	5,725.6	7,640.2	4,750.7	2,006.7	1,100.4	643.7	220.2
Qfeed-in, (MWh/yr)	103.5	166.6	117.8	208.6	167.4	291.5	202.7	352.8
EmCO2 (to/yr)	597.5	684.9	550.6	598.6	383.3	437.4	228.4	267.3

Figure 8. Areas A_1–A_4. Balance components.



	A1 - S1	A1 - S2	A2 - S1	A2 - S2	A3 - S1	A3 - S2	A4 - S1	A4 - S2
Econv, kWh/(m² yr)	216.7	112.8	146.6	91.1	178.4	97.8	101.2	34.6
EmCO2, kgCO2/(m² yr)	11.8	13.5	10.6	11.5	34.1	38.9	35.9	42.0
Eres-TS, kWh/(m² yr)	57.4	65.8	51.5	56.0	166.2	189.7	175.2	205.0
Eres-C, kWh/(m² yr)	55.4	62.6	49.3	52.0	151.3	163.8	143.3	149.5

Figure 9. Energy performance indicators. Areas A_1–A_4.

Table 11. Areas A_1–A_4. Specific indicators.

Area	No. of Consumers	Specific Indicators Achieved					
-	-	Scenario 1			Scenario 2		
		q_{aux}	q_{sol}	$q_{feed\text{-}in}$	q_{aux}	q_{sol}	$q_{feed\text{-}in}$
-	pers.	kWh/(year·pers.)			kWh/(year·pers.)		
A_1	2755	3992.0	1058.0	37.6	2078.3	1212.7	60.5
A_2	2600	2938.5	1033.0	45.3	1827.2	1123.2	80.2
A_3	1048	1914.8	1784.2	159.7	1050.0	2036.1	278.1
A_4	277	2323.8	4022.4	202.7	794.9	4707.2	1273.6
Area	**No. of Consumers**	**Maximum specific quantities of CO_2 emissions *, annually avoided**					
-	pers.	kg/(year·pers.)					
A_1	2755	216.9			248.6		
A_2	2600	211.8			230.3		
A_3	1048	365.8			417.4		
A_4	277	824.6			965.0		

* as a reference at natural gases.

5. Conclusions

This paper presents a case study within a research project, referring to the partial integration of thermal solar fields for heat production in urban areas as a part of the optimization process of the existing heating system in the city of Oradea, Romania. A deterministic method was used as the method of determination of heat demand under both stationary (hourly heat demand) and dynamic regimes (annual heat demand), and simulations within the configuration and optimization process of the hybrid heating systems were carried out using the Polysun Solarthermal Software (version 2016, Vela Solaris AG, Winterthur, Switzerland).

In the case study, representative areas with different thermal densities are analyzed within two working scenarios that take into account the energy performances of the buildings. Based on the proposed and achieved performance indicators, it is recommended that thermal–solar energy, under a hybrid system, even within crowded areas, is used for optimizing the existing heating systems with partial integration of the solar systems at the level of the thermal stations, with short- or medium-term storage, and with the management of excess energy based on the feed-in principle, in the case of Oradea, Romania. By determining the specific performance indicators, in relation to the number of consumers, the resulting data can be used as the input data for future technical–economic studies for similar urban areas. Moreover, by integrating systems that harness renewable energies within crowded urban areas, pollutant emission levels should drop significantly, resulting in the depollution of urban areas.

Due to various economic and social issues, renewable and alternative energy sources are poorly harnessed in crowded urban areas. In the future, the study of both integration modes is also recommended: partially decentralized, with integration at the thermal stations, versus decentralized, with integration at the consumer site, both from economic and social perspectives.

Author Contributions: Conceptualization, T.M.Ș.; Data curation, T.M.Ș., L.M.M. and G.D.; Formal analysis, L.M.M., G.D., A.C. and D.L.M.; Investigation, T.M.Ș.; Methodology, T.M.Ș.; Resources, T.M.Ș.; Supervision, A.C. and D.L.M.; Validation, A.C. and D.L.M.; Writing—original draft, T.M.Ș.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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