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Solar Energy in Low Temperature District Heating

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***Abstract* – Solar technologies are flexible and can be used for both centralized and decentralized energy production. The main aim of this article is to compare different solar technologies and configurations for integration into the DH system. The multi-criteria analyses method is used to rank different alternatives based on several criterions. The evaluation of criterions has been based on previous studies conducted. The multi-criteria analyses allow to compare different solar system alternatives that cannot be compared directly due to differences in their scale, type of energy produced and consumed, investment levels, etc. For the particular DH system researched, the most desirable solution is the PVT panel integration with an area of 1000 m² which is aligned with the actual DH company's power consumption. However, the results are strongly impacted by the assumed investment levels, efficiency of the technologies and other assumptions that could be further analysed by the help of sensitivity analyses.**

***Keywords* – District heating; multi-criteria analyses; PV thermal panels; solar power; solar thermal energy**

Nomenclature

E_{CO2}	Specific avoided CO_2 emissions, t/MWh$_{exergy}$
DH	District heating
E_i	CO_2 emission factor, tonnes/kWh
HP	Heat pump
i	Type of energy
LCOE	Levelized costs of energy
NPV	Net present value
PV	Photovoltaic panels
PVT	Photovoltaic thermal panels
Q_i	Produced amount of energy, MWh
RES	Renewable energy sources
SC	Solar thermal collectors
T_0	Surrounding temperature
T_{source}	Heat carrier temperature
η_{exergy}	Production efficiency, MWh$_{exergy}$/m^2

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1. INTRODUCTION

Renewable energy sources (RES) continue to increase their role in the energy sector. Different renewable energy technologies become more available, economically justified and bring environmental and climate benefit to society overall [1]. The decision makers of the energy sector have a wide variety from which to choose the most suitable technology for energy production by analysing different factors such as the particular location, resource and investment availability [2], [3], demand flexibility [4] etc.

In the countries with extensive forest resources, the use of biomass for energy production continues to grow [5]. However, the principles of sustainable development and biotechnology should be considered when planning an increase in biomass plant capacities. Bioresources should be used efficiently and with maximum gains during the whole life cycle. Agricultural land should primarily be used for growing cultivated plants, not for energy crops [6]. In addition, biomass resources should primarily be used for manufacturing high value products and not for energy production [7]. Studies show [8] that the use of biomass for energy production will continue to rise. However, these resources are limited mainly due to land availability [9]. Therefore, the energy sector should implement different types of renewable energy technologies to increase the overall resilience against different unfavourable external conditions [10].

RES alternatives to biomass can include geothermal energy for heat, wind for power, solar energy for both heat and power production, etc. Figure 1 shows the overall trend for the total installed capacity increase for the solar thermal collectors (SC), photovoltaic (PV) panels and wind technologies. The total installed capacity for wind power in 2017 was around 540 GW_{el}, for SC it was 472 GW_{th} and for PV 400 GW_{el}. The growth rate is slightly decreasing for solar thermal and PV technologies when compared to 2011 [11]. However, the total installed capacities are increasing. Even though wind energy has an important role in the energy production sector overall, this research will focus on the different solar energy technologies.

Solar technologies are flexible and can be used for both centralized and decentralized energy production. Rama and Mohammad [12] analysed different SC integration opportunities in the district heating (DH) system with high and low heating network temperatures and compared it with distributed solutions. The results show that the centralized SC system brings a better economic output. An additional benefit has been achieved through heat loss reduction when the heating network temperature is lowered.

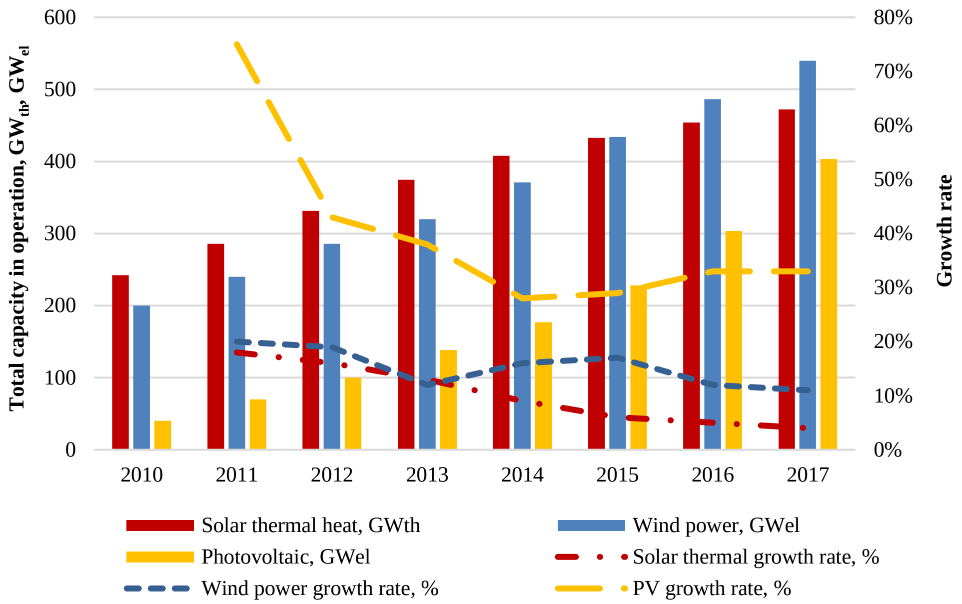

Fig. 1. Comparison of installed capacities and growth rates for different RES technologies from 2010 to 2017 [10].

Another solution for more flexible use of decentralized SC is to allow feed-in of surplus heat energy into the DH network for the heat load coverage [13]. The opposite solution for the solar thermal energy use is a large-scale solar system for DH. Such systems can cover the summer heat load and accumulate extra heat for space heating in the colder months with seasonal thermal storage. Such large-scale systems are already operating for several years in Denmark [14] and other European countries [15].

Solar power technologies have faced an important development and price reduction in recent years. Due to the continuous increase of installed PV technologies, several researchers have analysed the arising problem with a solar power overproduction and different alternatives for the surplus power utilization such as accumulation, power-to-heat or power-to-gas concepts, etc. [16].

A relatively innovative solar technology is the PV thermal (PVT) panel that can produce heat and power continuously. The superficial definition of this technology would be the assemblage of a solar panel and a solar collector in one device. The most common application of PVT is its integration in buildings (on roofs or walls) for domestic hot water, power consumption and/or space heating coverage [17]. The main gain from the PVT is a more efficient use of land or surface area, as power and heat can be produced in the same area. Good et al. [18] report different small scale and larger scale PVT projects. One of them is an innovative housing area “Suurstoffi” in Switzerland where heat for space heating and domestic hot water preparation is provided by using PVT panels (total installed PVT area 3487 m^2). The supply of heating and cooling is based on a low-temperature heat carrier that is coupled with seasonal geothermal storage. However, there is no information available on large-scale PVT system application and implementation into existing DH systems.

The main aim of this article is to compare different solar technologies and configurations for integration into the DH system. The multi-criteria analysis method [19] is used to rank different alternatives based on several criterions. The evaluation of criterions have been based on previous studies conducted [20]–[22]. The multi-criteria analysis allows the comparison of different solar system alternatives that cannot be compared directly due to their differences in scale, type of energy produced and consumed, investment levels, etc.

2. METHODOLOGY

The main steps for the research can be seen in Fig. 2. Firstly, analysis of the existing DH system is carried out to obtain information about heat demand, temperature levels, heat production efficiency and other operation parameters. The analyses are conducted for a particular DH system with an annual heat consumption of 55.5 GWh. The main input data are hourly heat production and consumption, heat supply and return temperatures, meteorological data on solar irradiation and different assumptions regarding the technological solutions. The simulation period to obtain the necessary values is one year.

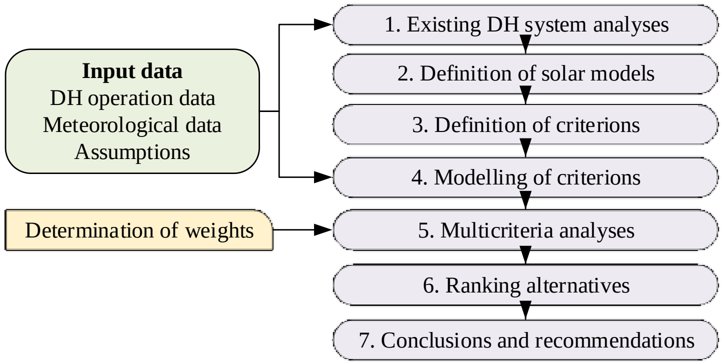

Fig. 2. Overall methodology of research.

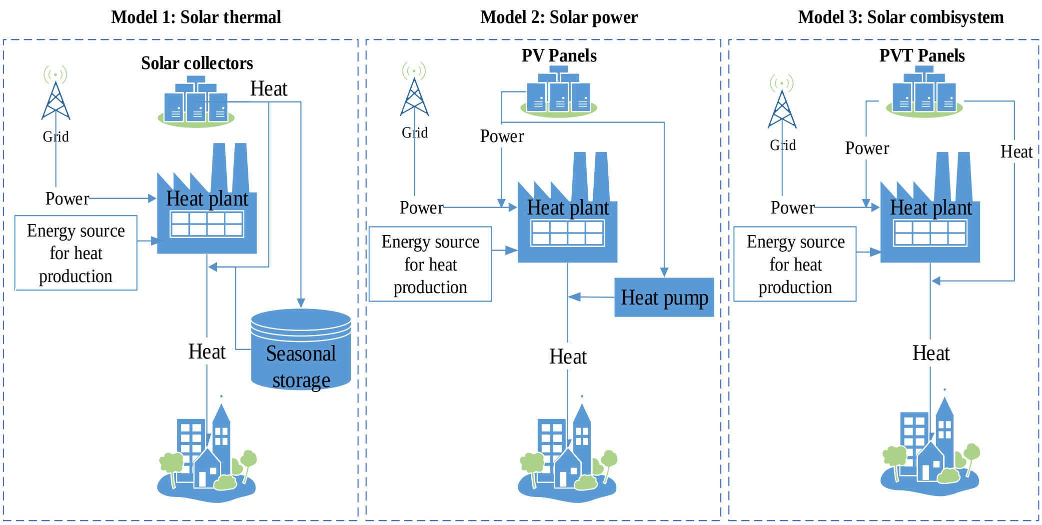

Fig. 3. Analysed solar models.

The next step of the research is the definition of the solar models. Fig. 3 shows three different configurations of the solar DH systems. Model 1 is the large-scale solar thermal model where SC generates heat. The solar heat is either used directly for the DH summer load coverage or accumulated in the seasonal storage tank. Therefore, two different scenarios are compared from this model (Table 1). Scenario 1 shows the solar thermal system with a useful solar collector area of 1 000 m^2 and all the generated heat is used directly. Scenario 2 describes the thermal system with a useful solar collector area of 20 000 m^2 and seasonal storage tank for surplus heat storage (volume of 5 000 m^3). The storage system accumulates the surplus heat during the summer period and uses it in the autumn period for space heating.

TABLE 1. OVERVIEW OF DEVELOPED SOLAR SYSTEM SCENARIOS

Scenario	Installed system	Area (panels or collectors), m^2	Capacity (thermal or power), kW
Scenario 1	Solar collector field	1 000	660
Scenario 2	Large-scale solar collector field with seasonal thermal storage	20 000	13 200
Scenario 3	PV panels	500	75
Scenario 4	PV panels with heat pump	1 000	150
Scenario 5	PV thermal panels	1 000	150
Scenario 6	PV thermal panels with heat pump	3 000	450

Model 2 describes the solar power system which primarily generates power for the heat plant operation. Scenario 3 describes the configuration when almost all of the power is used directly by the boiler house. In Scenario 4 the installed PV area is larger. When the surplus power occurs (solar power that cannot be directly used in the plant), it is either transferred to the grid or converted to heat via heat pump (HP). The decision for most suitable application of surplus power is made according to the hourly electricity market price. When the market electricity price is lower than the heat production price, than surplus power is converted to heat, if not – transferred to the grid.

Model 3 shows the combined solar heat and power system with PVT integration. In Scenario 5 almost all of the generated heat and power is used directly by the boiler house. However, Scenario 6 represents a larger solar system (3 000 m^2 of PVT panels) when surplus power occurs more often and it is utilized in the same way as in Scenario 4.

The next steps are the definition and modelling of the criterions. The criterions are defined according to the literature analyses whereby operations of different solar systems are evaluated [15]–[18]. The main criterions are the reached solar fraction, production efficiency, avoided CO_2 emissions, levelized costs of energy (LCOE), net present value (NPV) of the project, specific operation and maintenance costs, and occupied area.

The solar fraction is determined as a ratio between consumed solar energy and overall heat and power consumption of the Company. The calculations of generated and consumed solar energy are described in previous research of each solar model [20]–[22].

The production efficiency is described as exergy efficiency per solar technology surface area and calculated according to the Eq. (1):

$$\eta_{\text{exergy}} = \frac{\sum_i^n Q_i \cdot \left(1 - \frac{T_0}{T_{\text{source}}}\right)}{A}, \tag{1}$$

where

η_{exergy} Production efficiency, MWh_{exergy}/m^2;
Q_i Produced amount of energy, MWh;
i Type of energy;
T_0 Surrounding temperature;
T_{source} Heat carrier temperature.

The avoided CO_2 emissions are calculated as a specific value per each produced solar exergy MWh according to the Eq. (2):

$$E_{CO2} = \frac{\sum_i^n Q_i \cdot E_i}{\sum_i^n Q_i \cdot \left(1 - \frac{T_0}{T_{source}}\right)}, \quad (2)$$

where

E_{CO2} Specific avoided CO_2 emissions, t/MWh_{exergy};
E_i Emission factor for particular type of energy, tCO_2/MWh.

The evaluated economic criterions are NPV and LCOE that are calculated by taking into account all the costs and profits of the different solar models [20]–[22]. As the heat and power prices are not equal, it is not correct to compare LCOE power and heat systems. Therefore, the calculated LCOE has been expressed as the reference tariff of electricity or heat. The reference tariff for the PVT system is calculated according to the generated heat and power ratio.

The assumptions used for the calculations of criterions are summarized in Table 2.

TABLE 2. ASSUMPTIONS USED IN CALCULATIONS [20]–[22]

Parameter	Value	Unit
Average solar irradiance	1 366	W/m^2
Solar collector efficiency	60	%
PV panel efficiency	16	%
PVT panel thermal efficiency	40	%
PVT panel power efficiency	15	%
CO_2 emission factor for district heat, E_{heat}	264	kg/MWh
CO_2 emission factor for power from grid, E_{power}	109	kg/MWh
Surrounding temperature, T_0	20	°C
Solar heat flow temperature, T_{heat}	60	°C
Electricity price	129	EUR/MWh
Heat production tariff	45	EUR/MWh

All the criterions are weighted according to the surveys conducted among experts in the particular field. Therefore, weights differ when analysing the system development from the point of view of the DH Company and municipality (Table 3).

TABLE 3. WEIGHT FOR DIFFERENT CRITERIONS

Criterion	**Weight**	
	DH Company	Municipality
Production efficiency, MWh/m^2	0.13	0.07
Production exergy, MWh/m^2	0.13	0.07
Reached solar fraction, %	0.13	0.20
Avoided CO_2 emissions, t/MWh$_{exergy}$	0.06	0.20
Specific NPV, EUR/m^2	0.19	0.13
Normalized LCOE	0.19	0.13
Operation and maintenance costs, EUR/MWh	0.13	0.07
Occupied area, m^2/MWh$_{exergy}$	0.06	0.13

Further, all scenarios have been ranked by using multi-criteria analysis [19] from the point of view of the DH Company and the municipality, and conclusions are drawn for choosing the most suitable alternative.

3. RESULTS

One of the main parameters that determines the overall solar system operation is the produced amount of energy. Figure 4 shows the produced solar heat and power energy for each of the defined scenarios. The amount of produced exergy is calculated in order to directly compare the operation of the power and thermal systems. As can be seen, the produced amount of heat in Scenario 2 is several times higher because the large-scale system is analysed. Table 4 shows the quantification of obtained values for different scenarios.

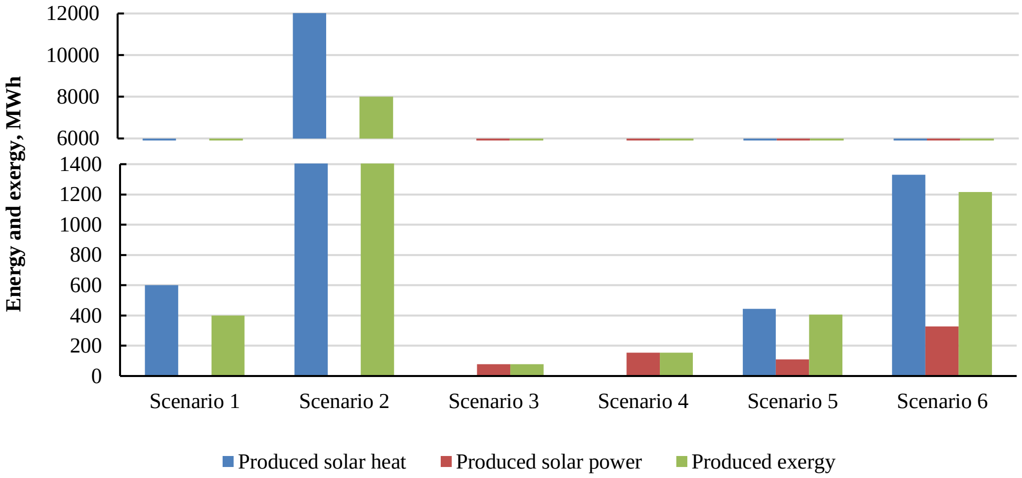

Fig. 4. Produced solar heat, solar power and exergy in each defined scenario.

Table 4 shows that in Scenario 1 all the produced solar heat (around 600 MWh per year) is consumed directly. In Scenario 2 around 155 MWh of heat is accumulated in the heat storage system, but 45 MWh are lost due to seasonal storage tank heat losses. In Scenario 3 most of generated solar power is used on site and only a small part is transferred to the grid. In the PV scenario with heat pump (Scenario 4) almost half the surplus power (14 MWh) is converted to heat. In the PVT scenarios both solar power and solar heat is generated. Scenario 5 represents the results for a smaller PVT area installation therefore only 13 MWh of surplus power occurs which are transferred back to the grid. In Scenario 6 the PVT area is larger, therefore, 136 MWh of surplus power is generated and around 77 % of that power is converted to heat via HP.

TABLE 4. OVERVIEW OF PRODUCED AND CONSUMED ENERGY IN DIFFERENT SCENARIOS

Scenarios	**Produced solar heat, MWh**	**Produced solar power, MWh**	**Consumed solar power, MWh**	**Solar power BTG, MWh**	**Consumed solar heat, MWh**	**Useful exergy, MWh**
Scenario 1	601	–	–	–	601	401
Scenario 2	12 018	–	–	–	11 973	7 982
Scenario 3	–	77	72	6	–	77
Scenario 4	–	154	125	16	42	134
Scenario 5	444	109	96	13	443	413
Scenario 6	1 329	327	191	31	1 481	1 179

3.1. Levelized Costs of Energy

To determine the economic feasibility of a solar system, the LCOE is determined which indicates how much each MWh of energy costs. Figure 5 shows the modelled values of LCOE and the reference energy costs for each scenario. The main aim of a solar system is to generate energy with minimal levelized costs according to reference tariffs. For Scenarios 1 and 2 the reference tariff is the heat production cost (assumed to be 45 EUR/MWh) and the modelled LCOE are similar to that (47 EUR/MWh in Scenario 1 and 44 EUR/MWh in Scenario 2). For Scenarios 3 and 4, the reference costs are the electricity selling price which in this research is assumed to be 129 EUR/MWh. As can be seen in Fig. 5, the LCOE of generated solar power are much lower and similar in both scenarios.

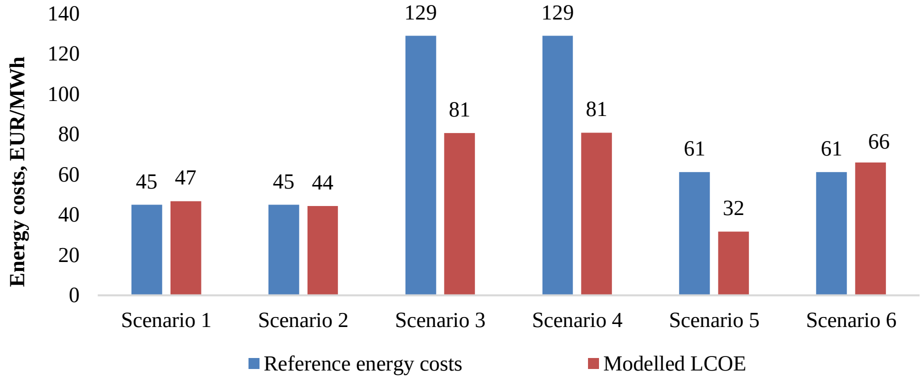

Fig. 5. Overview of modelled LCOE and reference energy costs for each scenario.

In case of PVT technologies (Scenario 5 and 6), the reference energy costs are calculated according to generated solar power and solar heat ratio (61 EUR/MWh). In Scenario 5 the

LCOE is almost half of reference energy costs, but in Scenario 6 LCOE is slightly higher than the reference costs mainly because part of the solar heat in the summer period is lost due to low heat consumption. There are also additional HP costs that increase the LCOE by around 20 %.

3.2. Avoided CO_2 Emissions

Integration of RES brings the climate benefit when fossil fuels are replaced by low carbon technologies such as solar energy. In this particular research, avoided CO_2 emissions are calculated for each solar system scenario. To compare these values, the specific avoided emissions per produced amount of exergy are used as a criterion.

The avoided CO_2 emissions are calculated as produced amount of energy multiplied by the CO_2 factor. Therefore, the CO_2 factor is strongly affecting the result. Figure 6 shows the specific avoided emissions for two different calculations methods. In the first, differenced factors are used for generated power and heat. The CO_2 factor is higher for district heat; therefore, the results are more beneficial for solar thermal systems.

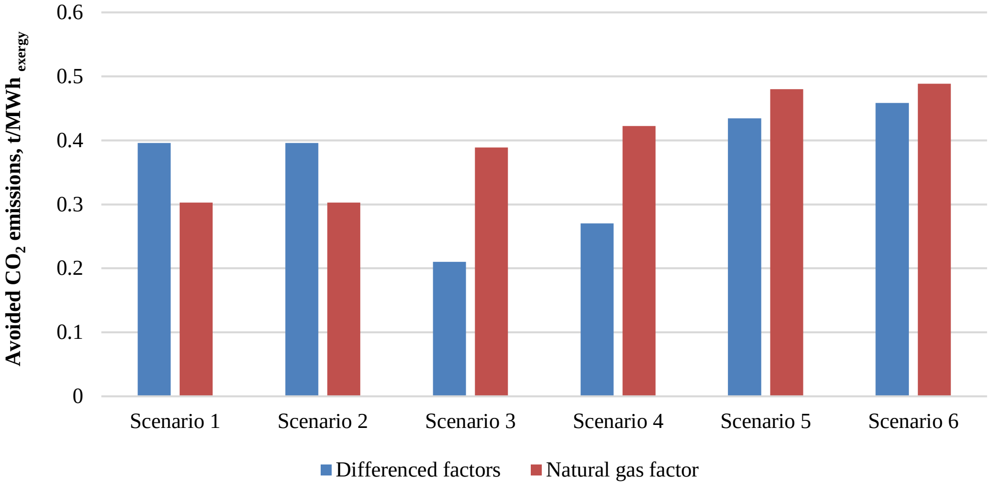

Fig. 6. Overview of specific avoided emissions for two different calculation methods – with differenced CO_2 factors and with natural gas factor.

In the other case, the natural gas CO_2 factor is applied for all scenarios by assuming that solar energy would contribute to the replacement of natural gas technologies (widely used in Latvia's energy sector) in both heating and power sectors. Fig. 5 shows that in this case, the results are changing and the PV scenarios are obtaining higher specific avoided CO_2 values.

However, with further analysis the avoided CO_2 values are calculated by using differenced CO_2 factors as this is common practice when evaluating renewable energy projects in Latvia.

3.3. Multi-Criteria Analysis Results

Table 5 shows the overview of calculated criterions for different scenarios. By analysing only the economic, environmental or efficiency aspects it is not possible to highlight one most feasible solar system scenario. Therefore, the multi-criteria analysis approach by the TOPSIS methodology has been applied to rank the analysed alternatives. The values of different criterions have been normalized and weighted according to the weights presented in Table 3 from both the DH company's and the municipality's perspective. After normalization and weighting, the scenarios are ranked as can be seen in Fig. 7.

TABLE 5. MULTI-CRITERIA ANALYSES MATRIX WITH CALCULATED CRITERIONS

Scenario	Product. effic.	Product. exergy	Solar fract.	Avoided CO_2	Spec. NPV	Normalized LCOE	OM costs	Occupied area
Unit	MWh/m^2	MWh/m^2	%	t/MWh_{exergy}	EUR/m^2	EUR/MWh_{exergy}	EUR/MWh	m^2/MWh_{exergy}
Scen. 1	0.60	0.40	3	0.17	–334	1.0	1.3	17.0
Scen. 2	0.60	0.40	57	0.17	–303	1.0	0.2	18.9
Scen. 3	0.15	0.15	0.3	0.11	240	0.6	3.9	16.2
Scen. 4	0.15	0.15	1	0.12	182	0.6	2.6	18.6
Scen. 5	0.55	0.41	15	0.20	–409	0.9	1.8	16.5
Scen. 6	0.55	0.41	32	0.21	–524	1.7	0.7	17.3

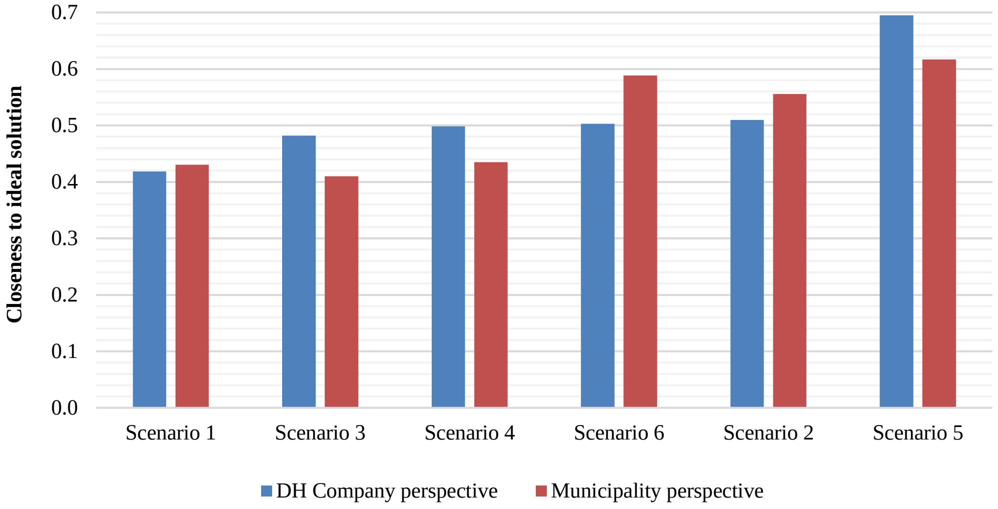

Fig. 7. Multi-criteria analyses results.

According to the multi-criteria analysis results from both the DH company's and the municipality's perspective, the most desirable solution is PVT integration by aligning the solar power capacity with the DH company's actual power consumption (Scenario 5). The lowest rank for closeness to ideal solution from the DH company perspective is for Scenario 1 which represents the heat production for summer load coverage. This is mainly due to low economic output from such technological solutions. From the perspective of the municipalities, the undesirable solution is the small PV system integration as it does not bring important impact on climate and environmental goals.

4. Conclusions

The research compares different solar energy system models for particular DH companies heat load and power consumption coverage. The analysed solar system models include PV, SC and PVT technologies with different energy storage alternatives.

The article presents novel methodology for comparing different solar system alternatives and identifies main criterions that can be used to compare different technological solutions. The results show that the developed methodology can be applied to the particular DH system to evaluate the most suitable solar energy system. The main criterions are the reached solar fraction, production efficiency, avoided CO_2 emissions, LCOE, NPV of the project, specific operational and maintenance costs, and occupied area.

For the particular DH system, the most desirable solution is the PVT panel integration with the area of 1 000 m^2 which is aligned with the actual DH company's power consumption. However, the results are strongly impacted by the assumed investment levels, efficiency of the technologies and other assumptions that could be further analysed by the help of sensitivity analyses.

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