EVALUATION OF INTEGRATION OF SOLAR ENERGY INTO THE DISTRICT HEATING SYSTEM OF THE CITY OF VELIKA GORICA

by

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In the current situation the district heating system supplies the 32% of the total thermal consumption in the City of Velika Gorica. The main issue in the district heating system is the utilization of 14 small and distributed heat plants, each providing heat to a separate and individually disconnected heating grid. Reduction of costs and CO_2 emissions can be reached with a high penetration of renewable sources. The aim of this paper is to evaluate and design the integration of a central solar heating plant with seasonal storage into the district heating system of the city. An economic assessment was made with a pessimistic and an optimistic prediction of the solar heat cost for ground mounted collectors and roof mounted collectors. The seasonal storage was chosen to be pit thermal energy storage; the system was modeled as a low-temperature district heating system with the real thermal demands of a district heating plant.

Key words: *district heating, heating demand, solar energy, central solar heating plant with seasonal storage, Velika Gorica*

Introduction

The European Union 2020 targets were set to promote a focus on a sustainable future. Until the year 2020 the EU as a whole has taken the commitment of cutting emissions of greenhouse gases by 20%, reducing energy consumption by 20% through energy efficiency, and meeting 20% of the energy needs from renewable sources [1]. Some recent researches were focused on primary energy saving and greenhouse gasses emission reduction in district heating systems by:

- using natural gas fired co-generations plants [2],
- primary energy savings using heat storage in district heating [3],
- integration of solar energy in the district heating network:
  - highlighting the advantages of solar inputs combined with thermal storage [4], and
  - installing on the roof of the buildings the solar collectors [5].

Combination of the aforesaid technologies: cogeneration, district heating network, solar field and heat storage reaches the minimum heat cost when are all included in the energy supply system [6]; showing the importance of the thermal storage [7]. Some ambitious research studied the combinations of co-generations plants with renewables energies reaching a 100% renewable energy system [8], and even analyzing heating technologies in a future with limited biomass resources, showing an advantage on the district heating instead of individual heating technologies reaching a 100% renewable energy system [9].

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The development of solar systems covering part of the thermal energy required in the residential sector is a viable option for reducing fossil fuel use and might solve an important part of the energy problems:
- shortage,
- dependency,
- high prices fluctuation,
- pollution, and
- climate change, among others [10].

Furthermore its economic costs are becoming more affordable and competitive.

Central solar heating plants with seasonal storage (CSHPSS) can cover with a high solar fraction the space heating and domestic hot water demands of big communities at an affordable price. These systems already supply heat to big communities through district heating systems in the north and center of Europe [11]. A very good example is Denmark, a country with a not high solar radiation, where a booming market for solar district heating is occurring thanks to an appropriate legal and socioeconomic framework [12]. In 2014 there were in Denmark more than 50 solar district heating plants in operation and the cost of heat produced in solar district heating systems without subsidies was lower than 0.05 € per kWh [13].

Therefore, a cost effective district heating system with large solar fraction with higher solar resources as the case study of Velika Gorica, could be economically more interesting than its current district heating system. Not only its economic cost is important as the introduction of solar energy would increase the air quality and decrease the health risk by reducing the fuel oil consumption [14].

In this paper is presented a feasibility and design study for the evaluation of a CSHPSS in a district heating system using the real consumption data from a district heating plant located in Velika Gorica, the economic assessment is made for a pessimistic and an optimistic prediction of the solar heat cost for ground mounted collectors and roof mounted collectors. Pit thermal energy storage is used as seasonal storage due to its lower investment cost. The system was modeled as a low-temperature district heating system using the model developed by Guadalfajara *et al*. [11, 12, 15].

Model of the central solar heat plant with seasonal storage

There are several examples of solar plants using seasonal storage around the world [16]. The main idea of the seasonal storage is using the excess heat produced in the summer to compensate the solar heat supply deficit during the wintertime. The model used in order to simulate a CSHPSS is the simple method proposed by Guadalfajara *et al*. [11, 12, 15].

This method is a validated method providing good results [17] and allowing the optimization of the CSHPSS. Furthermore the use of the simple method to estimate the operation of a real CSHPSS plant located in Canada, the drake landing solar community [18], which uses boreholes as thermal storages, got good results changing appropriately the heat transfer coefficient [19]. Thus this method can be adapted to estimate the behavior of CSHPSS with different seasonal storage technologies and it has motivated the use of the simple method with a pit thermal energy storage (PTES) as storage system. The simple method is based on the possibility of performing an approximate calculation on a monthly basis of the solar collector field production and the capacity of the seasonal thermal energy storage to match production and demand. Figure 1 shows the system scheme and identifies the main energy flows that appear in the simple method. The radiation received, Q_r, over the solar collector is harvested and the production of the solar field, Q_c, is calculated simulating its hourly

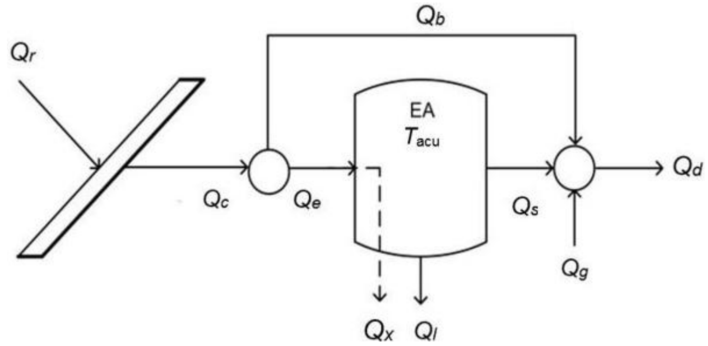

Figure 1. Energy flow chart of the simple method of CSHPSS

operation during a representative day of the month. It is considered a complete mixture in the thermal energy storage, *i. e.* without stratification. So it keeps uniform the accumulator temperature, T_{acu}, along the calculation period, which is a month in the proposed model. Thus, the solar collector performance and the heat losses, Q_l, of the seasonal storage are calculated considering the accumulator temperature at the beginning of the month. In a seasonal storage, the premise of considering constant the water temperature along the month is reasonable due to its high thermal inertia (high volume). A monthly energy balance is used to calculate the temperature in the thermal energy storage at the end of the month. This temperature of the water tank at the end of the month is used to calculate the solar collector performance at the next month.

The monthly operation of the seasonal storage has two different operation modes during the year:
– charge, and
– discharge.

The charge operation mode occurs when the production of the solar field, Q_c, is higher than the heat demand, Q_d. Then part of the produced heat will be used to attend the immediate demand, Q_b, and the surplus of the produced heat will be sent to the seasonal storage for its later consumption, Q_e. In the discharge operation mode, the heat demand, Q_d, is higher than the production of the solar collectors, Q_c, and the seasonal storage is discharged, Q_s, in first instance and if it is still not enough, then the auxiliary system, Q_g, will provide the required heat to cover the demand. The thermal energy storage operation is constrained by two temperature limits, maximum and minimum. When the limit of the minimum temperature is reached, the thermal energy storage cannot be discharged anymore and the auxiliary system provides the required heat, Q_g, to fulfill the demand. The thermal energy storage cannot be charged either over the maximum temperature. When it reaches this maximum temperature limit, part of the heat production is rejected, Q_x, to avoid overheating and equipment damage. As the thermal energy storage is warm, the heat losses to the environment, Q_l, are also calculated. The heat losses are calculated for pit thermal energy storage, its global heat transfer coefficient value is calculated to get 70-80% thermal performance in the storage using Marstal Sunstore 4 design [20]. The thermal accumulated energy in the storage is denoted by the variable EA. The model was built on the software Engineering Equation Solver [21].

Economic assessment

A specific study to do an economic assessment of solar heating plant with seasonal storage was done to estimate the solar investment and the solar heat cost, because in this study the pit thermal energy storage is evaluated due to its lower investment cost, following the work proposed by Nielsen *et al.* [22]. Pit thermal energy storage, ground mounted collectors and roof mounted collectors are evaluated. Costs of ground mounted and roof mounted solar collector, including collectors, field piping, fluid and heat exchanger can be estimated by the curves shown in fig. 2. Prices will typically be between the upper and lower line. The upper line is considered as the optimistic cost prediction and the lower line is considered as the pessimistic cost prediction.

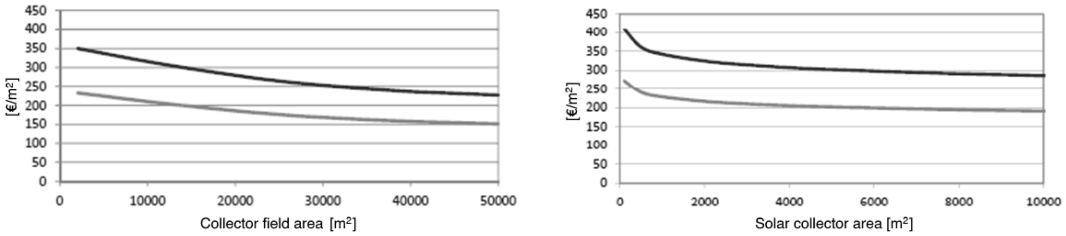

Figure 2. Cost of ground mounted collectors (left) and roof mounted collectors (right) [22]

Distance from collector field to network connection point is unknown because placement of solar field is unknown, thus it is considered to be a 10% of overrun. An overrun of 10% may cover to install a plant with a distance of 2 km from the connection point.

The investment cost for PTES vary between 40 and 250 € per m^3 depending on the size, the cost dependence on storage volume for PTES is calculated with fig. 3 [23].

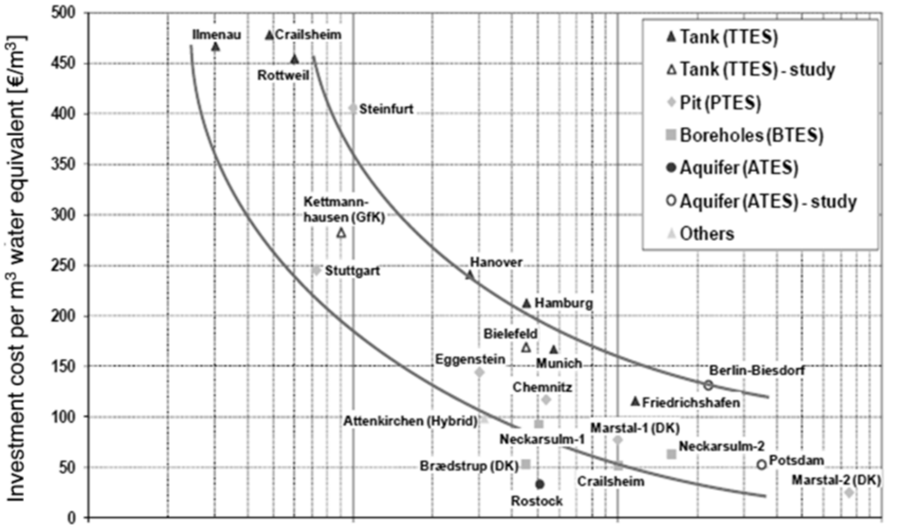

Figure 3. Specific investment cost for STES (without VAT) [23]

The volume of a storage unit increases (roughly) as the cube of the characteristic dimension and its area for heat loss increases as the square, so increasing the size reduces the loss-to-capacity ratio. So even for the cost and for the heat losses the bigger the storage is the better the system is. The expectance life time of a PTES is set up to a technical lifetime of 25 years [24].

The indirect cost of the project is estimated as an overrun of 12%. Operation costs and maintenance represents 1.5% of the total investment [10]. The cost of land has not been considered as the solar field is planned to be placed in lands owned by the city.

Case study: the City of Velika Gorica

The City of Velika Gorica, Croatia, is located 16 km south of Zagreb, and has a population of 31,553 inhabitants; the thermal consumption in the city is 197.34 GWh where the district heating system supplies the 32% of the total thermal consumption. The energy consumption in the city is analyzed using: the action plan for sustainable energy development in the city (SEAP) [25] and the provided information by the national utility company [26, 27].

Only the central part of the urban area is covered with district heating networks, which are not interconnected, with 14 heating plants and 34 boilers operated by the national utility company. Only one of the fourteen installed plants is gas operated (Vidriceva 1) bearing 60.76% of the total installed capacity, while the rest use fuel oil resulting in a high level of CO_2 emissions.

The location of the plants and the district heating networks are shown in fig. 4. Heating plant of Vidriceva 1 (number 1 in fig. 4) was analyzed.

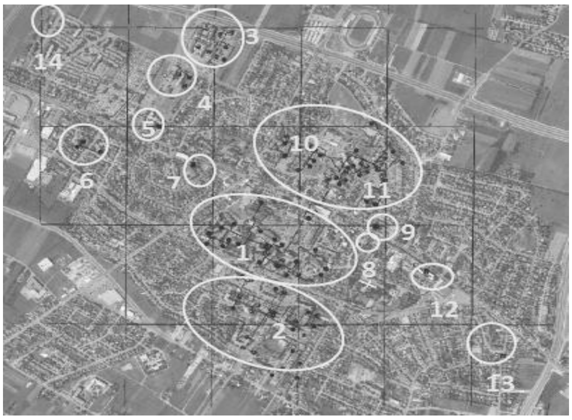

Figure 4. District heating networks in Velika Gorica [27]

The CSHPSS is modeled to supply part of the thermal demand that the district heating plant supplies [26], 49.88 GWh per year. A representative meteorological day for each month of the year is calculated using Meteonorm software [28]. The system was modeled as a low-temperature district heating system as it is one of the goals from the utility company and the city. The design variables considered are shown in tab. 1:

- area of solar collector A_{total} (or RAD, which is the ratio of the area of the solar field [m^2] divided by the annual demand in [MWh per year^{-1}]),
- volume of the seasonal storage, V (or RVA, which is the ratio of the volume of the seasonal storage [m^3] divided by the area of the solar field in [m^2]),
- efficiency curve of the solar collector (η_0, a_1, a_2), only large size solar collectors are evaluated [29],
- tilt and orientation of the solar collectors,
- mass flow rate of working fluid circulating through the solar collectors, m_s,
- specific heat capacity C_p and density of the working fluid (50% propylene glycol because the historical lowest temperature was −33 °C),
- heat exchanger efficiency of the solar field, E_{ff},
- temperature of the water supplied to the district heating network, T_{sup},
- temperature of the water returning from the district heating network, T_{ret}, and
- minimum and maximum temperatures in the seasonal storage (accumulator), T_{min} and T_{max}.

The seasonal storage is assumed as an underground pit thermal storage, its global heat transfer coefficient value is calculated to get 70-80% thermal performance in the storage using Marstal Sunstore 4 design [20], the heat loss coefficient of the lid in a pit thermal storage is $U_{acu,lid}$ = 0.19 W/m^2 °C [30], the insulation on the sides and bottom is $U_{acu,walls}$ = 0.276 W/m^2 °C and it is calculated using the measured temperatures of the surrounding zone of a PTES in Marstal [31].

Table 1. Design parameters

	Parameter	Value		Parameter	Value
Solar collector field	RAD: Ratio collector area/demand	m^2(MWh per year)$^{-1}$	Seasonal storage	RVA: Ratio volume area	m^{3}m^{-2}
	A_{total}: Area of solar collectors	m^2		V: Volume of seasonal storage	m^3
	η_0: Optic efficiency	0.827		T_{min}: Minimum storage temperature	30 °C
	a_1: Heat loss coefficient	1.118 W(m^{2}K) $^{-1}$		T_{max}: Maximum storage temperature	90 °C
	a_2: Heat loss coefficient	0.032 W(m^{2}K^2) $^{-1}$		RHB: Lid ratio length and depth	0.16 m/m
	B: Tilt	34°		$U_{acu,lid}$: Heat transfer coefficient lid	0.19 W(m^{2}K) $^{-1}$
	Θ: Orientation	0°		$U_{acu,walls}$: Heat transfer coefficient walls and bottom	0.276 W/(m^{2}K) $^{-1}$
	m_s: Mass flow rate	20 l(hm^2) $^{-1}$		EA_{max}: Max energy accumulated	MWh
	Material used	50% propylene glycol		Material used	Water
	E_{ff}: Heat exchanger efficiency	0.9	District heating	T_{sup}: Supply temperature	50 °C
Heating demand	Q_d: Annual demand	49,877 MWh per year		T_{ret}: Return temperature	30 °C

Results

There are two criteria to analyze in order to evaluate the economical and physical trends. The first criterion is based on testing different RVA values fixing the RAD value to study the behavior of the system for different storage sizes with a fixed collector area. The second criterion is based on the "critical volume" which follows the next premises:

- do not reject any heat produced, $Q_x = 0$, and
- reach the maximum usage of the accumulation installed capacity in order to do not oversize the storage.

First criterion of design

The first criterion is based on testing different RVA values fixing the RAD value to study the behavior of the system for different storage sizes with a fixed collector area. The collector area, RAD is fixed to be 0.8 in order to have a solar fraction over the 50%. It is interesting to study the effect of varying the storage volume from low values to high values. System behavior for different RVA values for a fixed collector area is shown in fig. 5. If RVA is lower than 2.7 m^3/m^2, the accumulator needs to reject energy (expressed as Q_{xy}) and the accumulator efficiency rises up linearly, then the efficiency becomes stagnant and for high values of volume (RVA = 4.2 m^3/m^2), efficiency of the seasonal storage rises down because it is oversized. Solar fraction, system efficiency and collector efficiency are rising up with similar trends for the different values of RVA. The reason is that as the seasonal storage is not full, the temperature of the stored water is lower and as a consequence the efficiency of the solar collectors increases. The system efficiency also rises due to the increase of the efficiency of the solar collectors.

The economical results for an interest rate of 3% and a fixed value of RAD = 0.8 m^2/(MWh per year) changing the storage size are shown in tab. 2. The expectance life time is set up to a technical lifetime of 25 years [24].

(1) $C_{gr;op}$ means the solar heat cost for an optimistic prediction in ground mounted collectors.
(2) $C_{gr;pess}$ means the solar heat cost for an pessimistic prediction in ground mounted collectors.
(3) $C_{roof;op}$ means the solar heat cost for an optimistic prediction in roof mounted collectors.
(4) $C_{roof;pess}$ means the solar heat cost for an pessimistic prediction in roof mounted collectors.

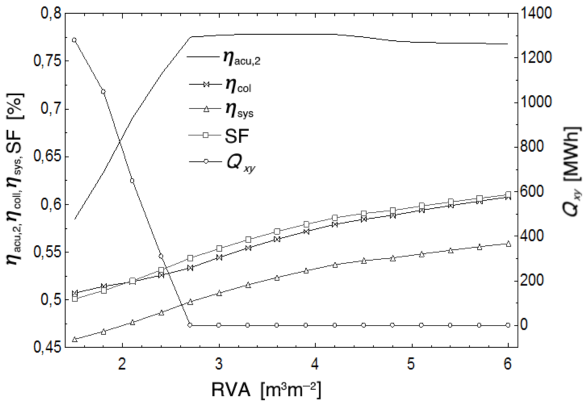

Figure 5. System trends for different RVA values with a fixed collector area

Table 2. Results of system behavior for a fixed RAD = 0.8 m^2(MWh per year)$^{-1}$

RVA [m^3m^{-2}]	V [m^3]	Q_x [MWh]	SF [%]	$C_{gr;op}$ [€ per MWh]	$C_{gr;pess}$ [€ per MWh]	$C_{roof;op}$ [€ per MWh]	$C_{roof;pess}$ [€ per MWh]
1.5	59,852	1,280	0.501	30.6	41.04	33.4	45.43
1.8	71,823	1,048	0.5098	30.94	41.2	33.7	45.52
2.1	83,793	649	0.52	31.12	41.18	33.82	45.41
2.4	95,764	310.1	0.5315	31.17	41.01	33.81	45.15
2.7	107,734	0	0.5439	31.13	40.75	33.72	44.79
3	119,705	0	0.5538	31.2	40.65	33.74	44.62
3.3	131,675	0	0.5631	31.27	40.56	33.76	44.46
3.6	143,646	0	0.5716	31.36	40.51	33.81	44.35
3.9	155,616	0	0.5792	31.47	40.5	33.89	44.29
4.2	167,587	0	0.5861	31.6	40.52	34	44.27
4.5	179,557	0	0.5907	31.84	40.69	34.21	44.41
4.8	191,528	0	0.5938	32.13	40.94	34.5	44.64
5.1	203,498	0	0.5984	32.33	41.08	34.68	44.75
5.4	215,469	0	0.6026	32.54	41.22	34.87	44.87

The economical criterion in the optimistic prediction for the collector investment is that the best storage size is the lowest possible. But if the volume, RVA, is increased a relative minimum for the solar cost is found when the RVA is 2.7 m^3/m^2 see fig. 6 (right), and it matches with the point where the accumulator does not reject energy. Thus the aforesaid critical volume criterion is found to be a possible criterion to be used [11].

For the pessimistic prediction for the collector cost, the accumulator efficiency was found to be the best criterion. The best storage size is found for RVA = 3.9 m^3/m^2 see fig. 6 (left); the solar heat cost is the lowest and it matches with the point where the accumulator efficiency starts to rise down because it is too big, 78.77 °C is the highest temperature reached in August.

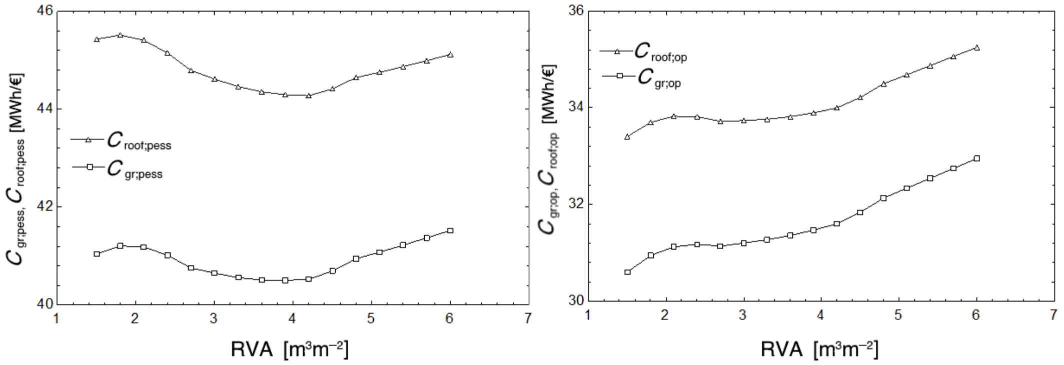

Figure 6. Solar heat cost for an optimistic (right) pessimistic (left) prediction

Second criterion of design

The second criterion is based on the critical volume which follows the next premises:

– do not reject any heat produced, $Q_x = 0$, and
– reach the maximum usage of the accumulation installed capacity in order do not oversize the seasonal storage that could be inefficient.

Increasing the area of the solar field (RAD) the critical volume RVA_c is found on the basis of the second criterion (to do not reject any heat produced and to reach the maximum usage of the accumulation capacity installed). The relationship between the critical volume and the system performances trends as a function of the collector area is shown in fig. 7.

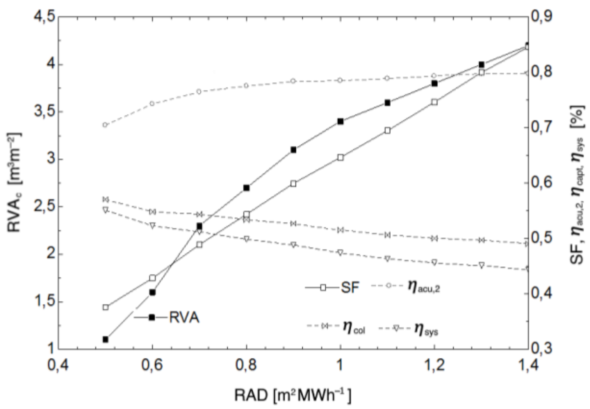

Figure 7. Trends for different solar collector area with critical volume criterion

When collector area is increased, the solar fraction rises up linearly, however the storage volume does not rise up linearly due to its cubic dimensions; it rises up faster for low values of SF and slower for high values of SF. The collector efficiency, η_{coll}, decreases linearly, because the bigger the SF is the higher the mean temperature in the accumulator along the year is. Thus the collector efficiency decreases because of the increased mean temperature in the accumulator. The thermal storage efficiency, $\eta_{acu,2}$, rises up for a SF lower than 60% and it is becoming stagnant for a SF upper than 60% (because the accumulator mean temperature is higher and counters the increasing performance due to a bigger volume). Thus the system efficiency, η_{sys}, decreases with the solar fraction. Economical results for different solar fractions are shown in tab. 3, for an interest rate of 3% and with the expectance life time set up to a technical lifetime of 25 years [24].

The solar heat cost increases with the solar fraction with different slopes for the 4 scenarios. For ground mounted collectors, the solar heat cost for a solar fraction of 37.6% varies from 28.07 € per MWh for optimistic prediction of the cost of the collectors ($C_{gr;op}$) to 38.64 € per MWh for the pessimistic prediction ($C_{gr;pess}$); and for a solar fraction of 84.6% varies from 33.42 € per MWh for optimistic prediction to 41.92 € per MWh for pessimistic prediction. For roof mounted collectors, the solar heat cost for a solar fraction of 37.6% varies from 28.92 € per MWh for optimistic prediction of the cost of the collectors ($C_{roof;op}$) to 39.32 € per MWh for pessimistic prediction ($C_{roof;pess}$), and for a solar fraction of 84.6% varies from 36.45 € per MWh for optimistic prediction to 48.58 € per MWh for pessimistic prediction. These economical results are in concordance with solar heat cost of solar plants installed in Denmark [13].

The estimated investment in the central solar heat plant with seasonal storage depending on the solar fraction and the solar field predictions is shown in tab. 4. It is shown that the higher the solar fraction is the higher the investment is.

Table 3. Results of the system behavior for different solar collector area with critical volume criterion

RAD [m^2MWh^{-1}]	RVA [m^3m^{-2}]	SF [%]	$C_{gr;op}$ [€ per MWh]	$C_{gr;pess}$ [€ per MWh]	$C_{roof;op}$ [€ per MWh]	$C_{roof;pess}$ [€ per MWh]
0.5	1.1	0.3759	28.07	38.64	28.92	39.32
0.6	1.6	0.4282	29.6	40.01	31.15	41.95
0.7	2.3	0.4889	30.65	40.62	32.78	43.67
0.8	2.7	0.5439	31.13	40.75	33.72	44.79
0.9	3.1	0.5995	31.56	40.81	34.43	45.63
1	3.4	0.6464	32.3	41.31	35.31	46.76
1.1	3.6	0.6949	32.85	41.61	35.81	47.43
1.2	3.8	0.7462	33.42	41.92	36.09	47.82
1.3	4	0.8002	34.04	42.31	36.2	47.98
1.4	4.2	0.8459	35.21	43.36	36.65	48.58

Table 4. Estimated investments depending on the solar fraction and the solar field predictions

SF [%]	$Inv_{gr;op}$ [€]	$Inv_{gr;pess}$ [€]	$Inv_{roof;op}$ [€]	$Inv_{roof;pess}$ [€]
0.3759	7,036,000	9,771,000	7,256,000	9,946,000
0.4282	8,415,000	11,490,000	8,874,000	12,060,000
0.4889	9,907,000	13,260,000	10,620,000	14,290,000
0.5439	11,180,000	14,780,000	12,140,000	16,290,000
0.5995	12,480,000	16,290,000	13,660,000	18,290,000
0.6464	13,760,000	17,770,000	15,100,000	20,200,000
0.6949	15,050,000	19,240,000	16,460,000	22,030,000
0.7462	16,450,000	20,820,000	17,820,000	23,850,000
0.8002	17,980,000	22,540,000	19,170,000	25,660,000
0.8459	19,680,000	24,430,000	20,520,000	27,470,000

A sensitivity analysis was made for different interest rates; results are shown in fig. 8. For an interest rate of 7% solar heat cost with the cost optimist prediction of ground mounted collectors is under 50 € per MWh whatever the solar fraction is and with the pessimistic prediction is under 60 € per MWh. With the same interest rate solar heat cost with the cost optimistic prediction of roof mounted collectors is under 50 € per MWh whatever the solar fraction is and with the pessimistic prediction is under 70 € per MWh.

The prices in Velika Gorica for heating (in the district heating network) in 2011 were 0.4243 Kunas per kWh which means (55.8 € per MWh), and the electricity price for 2015 was 0.1317 € per kWh (131.7 € per MWh) [32], with an increasing price trend in the last 10 years. It is expected that the prices of energy will increase in the future, in this study the solar heat cost were calculated to be the same during the 25 years of the solar heat plant expecting life time. For a reasonable solar fraction of 60% the CO_2 emissions savings replacing the natural gas are 6,140.15 tons per year.

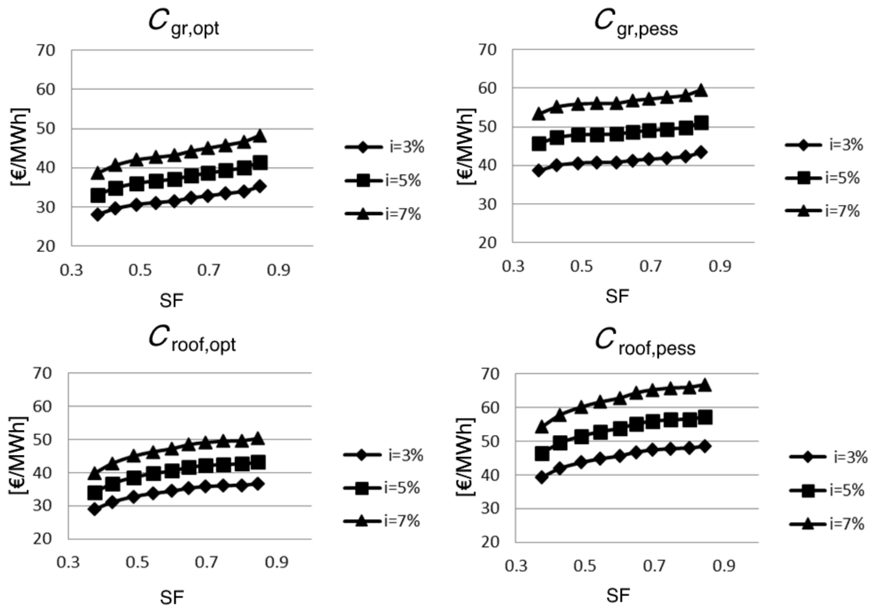

Figure 8. Sensitivity analysis for different interest rates

Conclusions

The central solar heat plant with seasonal storage optimization following an economical criterion was not found to be unique, but when the bigger is the heat demand to be supplied with solar energy, the bigger is the solar heating plant and the lower is its specific investment in the accumulator and in the solar field, which entails a lower solar heat cost.

For an optimistic prediction in the collectors cost, the best storage size was the lowest possible but a relative minimum in the solar heat cost was found when the accumulator does not reject heat. For a pessimistic prediction the accumulator efficiency was found to be the best criterion. The best heat solar cost was found when the accumulator efficiency was the highest.

For all the considered options, ground mounted collectors, roof mounted collectors, pessimistic prediction and positive prediction, the solar heat cost is lower than the current energy price in the district heating system, 55.8 € per MWh. Only in the sensitive analysis study for roof mounted collectors, pessimistic prediction and an interest rate of 7%, the solar heat cost is more expensive than the current price in the district heating system. Thus a cost effective district heating system with large solar fraction in the case study is feasible, competitive with the current system and a reliable option to consider. Furthermore central solar heat plants do not have prices fluctuation as fossil fuels energies do thus its implementation turns out to be a sensible option for long term investments.

In this study environmental profit, grants or incentives for renewables has not been considered. To consider any kind of environmental profit, grants incentives for renewables would have shown even better results for the implementation of a solar heat plant with seasonal storage.

These results are an estimation of the solar heat cost for central solar heating plant with pit thermal seasonal storage working in a stationary condition; if the utility company decides to build a solar heat plant a deeper study with dynamic simulations to know the best design parameters should be done.

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Nomenclature

a_1 – 1st order heat loss coefficient (solar collector), [$Wm^{-2}°C^{-1}$]
a_2 – 2nd order heat loss coefficient (solar collector), [$Wm^{-2}°C^{-1}$]
A_{total} – total collector area, [m^2]
C_p – specific heat capacity, [$Jkg^{-1}K^{-1}$]
E_{ff} – heat exchanger efficiency, [%]
f_{ope} – annual operation and maintenance costs, [%]
G – incident radiation, [Wm^{-2}]
i – interest rate, [%]
m_s – flow rate, [$lh^{-2}m^{-2}$]
T_{acu} – accumulator temperature, [°C]
T_{max} – maximum temperature allowed in the storage tank, [°C]
T_{min} – minimum temperature allowed in the storage tank, [°C]
T_{ref} – reference temperature, [100 °C]
T_{ret} – temperature of the water returning from the district heating network, [°C]
T_{sup} – temperature of the water supplied to the district heating network, [°C]
$U_{acu,lid}$ – heat transfer coefficient in the lid of the pit, [$Wm^{-2}°C^{-1}$]
$U_{acu,walls}$ – heat transfer coefficient in the bottom and walls of the pit, [$Wm^{-2}°C^{-1}$]
V – volume of the seasonal storage, [m^3]

Greek symbols

η_0 – optical efficiency (solar collector), [%]
$\eta_{acu,2}$ – seasonal storage efficiency, [%]
η_{coll} – solar collector efficiency, [%]
η_{sys} – system efficiency, [%]
ρ – fluid density, [kgl^{-1}]

Acronyms

CSHPSS – central solar heat plant with seasonal storage
PTES – pit thermal energy storage
RAD – ratio solar collector area/annual heating demand, [$m^2MWh^{-1}year^{-1}$]
RHB – ratio lid length and depth
RVA – ratio accumulator volume/solar collector area, [m^3m^{-2}]
SF – solar fraction

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