Proyecto Fin de Carrera

Evaluation of integration of solar energy into district heating system of the City of Velika Gorica

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Abstract

Evaluation of integration of solar energy into district heating system of the City of Velika Gorica

In the current situation the City of Velika Gorica (the "**City**"), located in Croatia, faces several key issues regarding its thermal energy consumption. The thermal consumption of its 31,500 inhabitants is 197.34 GWh where 20% is supplied by firewood, 2% by electricity, 15 % by fuel oil, 31% by natural gas and 32% by the district heating system. In the district heating sector the main issue is the utilization of 14 small and distributed heat plants, each providing heat to a separate and individually disconnected heating grid. Of the fourteen installed plants only one is gas operated bearing 60.76% of the total installed capacity, while the rest use fuel oil resulting in a high level of CO_2 emissions as well as the distribution losses due to a high-temperature district heating and an old distribution system. Other issues are the high thermal energy consumption of roughly 200 kWh/m^2 in the residential sector and 190 kWh/m^2 on average for public buildings. Reduction of costs and CO_2 emissions can be reached with a high penetration of renewable sources and decreasing the energy consumption with better insulation.

The aim of this project is to evaluate the integration of solar energy into the City to produce Domestic Hot Water and Space Heating. The first part of this project contains an analysis of the current situation in the City and a studio of the thermal and electricity needs of the City. Second, a studio of the available solar resources and possible technologies to use is presented (concentrating solar power, CSP, photovoltaic, PV, thermal, photovoltaic-thermal, PVT, seasonal thermal energy storage, STES, heat pumps, HP, and biomass boiler). Third, three proposed scenarios for the use of solar energy in the City have been analyzed: (i) producing Domestic Hot Water (DHW) for a residential-scale use; (ii) water preheating in a district heating plant; and (iii) a Central Solar Heating Plant with Seasonal Storage for a district-scale use. In all aforesaid scenarios, an economic assessment is made.

The potential energy savings in the production of DHW with solar energy for buildings no connected to the district heating system, were 12.96 GWh in the entire City. The obtained economic results have been: i) DHW production is profitable and its estimated solar heat cost was 0.0458 €/kWh, lower than the current production energy prices; ii) the water preheating of a district heating plant with solar energy, is feasible and its estimated solar heat cost was 0.027 €/kWh, lower than the energy prices in the current production system; iii) the solar heat cost of a solar heating plant with seasonal thermal storage has been shown to be competitive with the current cost for heating in the district heating system, 55.8 €/MWh.

A district heating system centralized is better than distributed, the bigger the central solar heating plant is the lower its solar heat cost is, a low-temperature district heating system is better than a high-temperature district heating system and the feasible and profitable scenario of the solar introduction in the City were the main conclusions in this project.

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1 Introduction

Nowadays one of the main problems of society is the depletion of fossil fuels and their environmental impact that causes the greenhouse effect (the globally averaged temperature over land and ocean surfaces for 2014 was the highest among all years since record keeping began in 1880, according to two separate analyses made by NASA National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration (NOAA) scientists). Furthermore energy consumption is increasing drastically due to new areas of application and a variety of uses. The main solution to this issue is based on the reduction of consumption of fossil fuels and their substitution with other type of clean and sustainable energy as renewable energies.

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].

One of the most suitable renewable energies is the solar energy, because solar energy is environmental friendly so it may be supplied with a lower environmental impact than conventional energies, it is inexhaustible and its economic costs are becoming more affordable and competitive.

Considering the reasons explained above, the goal of this project is to evaluate the integration of solar energy into the district heating system of the City of Velika Gorica (Croatia) in order to respond to the energy proposal made by the City in the framework of the Sustainable Energy Action Plan (SEAP) [2] of Velika Gorica and as part of the project Beyond Energy Action Strategies (BEAST) [3], where the main goal is the reduction of consumption of fossil fuels to reduce the greenhouse gas emissions and the introduction of renewable energies in the energy supply system.

Firstly the current situation in the City is analyzed. Action plan for sustainable energy development in the City (SEAP) [4] and the provided information by the national utility company [5] are used in order to know the existing problems. In the district heating sector the main issue found out is the utilization of 14 small and distributed heat plants, each providing heat to a separate and individually disconnected heating grid. Only one of these fourteen installed plants is gas operated, bearing 60.76% of the total installed capacity, while the rest are fuel oil operated, resulting in a high level of CO_2 emissions. Moreover the heating grid presents very high distribution heat losses due to a high-temperature of the district heating working fluid (hot water) and an old distribution system. In the residential sector the main issue is a very high specific consumption of 200 kWh/m^2.

Secondly the energy consumption in a district heating plant was studied with the data of the hourly gas consumption for three years provided by the national utility company. This data were processed with MATLAB [6] to obtain the monthly consumption in the district heating plant. Energy certificates of public buildings and residential buildings were studied to obtain the thermal and electricity needs in order to create an example template with the average energy consumptions.

Once energy consumption was obtained, a studio with available solar resources along the year was made with Meteonorm software [7]. Technical feasibility of the different available technologies to transform the solar energy into thermal and electrical energy was studied too, among them:

- Concentrating solar power, CSP, to produce electricity and thermal energy.
- Flat plate thermal collectors, to produce thermal energy.
- Photovoltaic panel, PV, to produce electricity.
- Photovoltaic-thermal collector, PVT, to produce thermal energy and electricity.

- Heat pumps, HP, to help to optimize the inlet and outlet temperature of the solar energy system.
- Biomass boiler, to produce electricity and thermal energy.
- Seasonal thermal energy storage, to reduce the thermal energy mismatch between supply and demand.

Fourthly three proposed scenarios for the use of solar energy in the City, were analyzed.

(i) Domestic Hot Water (DHW) production for a residential-scale use. F-chart method [8] and the Engineering Equation Solver, EES software [9], were used in a building as a template example.

(ii) Preheating of the working fluid (hot water) in a district heating plant. For this purpose an own model was created inspired in the work developed by Guadalfajara et al. [10] using EES software.

(iii) A Central Solar Heating Plant with Seasonal Storage for a district-scale use using the model developed by Guadalfajara et al. [10], [11], [12], with some variations in respect to the thermal seasonal storage.

In all the mentioned scenarios an economic assessment has been made. The production of DHW with solar energy for the buildings no connected to the district heating system has been shown to be profitable and its potential energy savings were 12.96 GWh in the entire City. For a representative building the solar heat cost in the production of DHW was 0.0458 €/kWh, cheaper than its current production, and CO_2 emissions savings were 5266 kg per year.

The water preheating, of the district heating networks which were not possible to be connected in the same district heating network or the seasonal thermal energy storage was unworthy, has been shown to be feasible and its solar heat cost was 0.027 €/kWh, cheaper than the energy prices in the current production system.

The solar heat cost of a solar heating plant with seasonal storage, in a criterion of do not reject energy and reach the maximum usage of the accumulation installed capacity was lower than the current energy price in the district heating system, 55.8 €/MWh, for all the studied options: ground mounted collectors, roof mounted collectors, pessimistic prediction and positive prediction of the solar field cost. Only in the sensitive analysis studio for roof mounted collectors, pessimistic prediction of the solar field cost and an interest rate of 7 %, the solar heat cost was more expensive than the current system.

The central solar heating plant with seasonal storage optimization following an economical criterion was not found to be unique; it depends on the prediction of the solar field 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, thus the best heat solar cost was found when the accumulator efficiency was the highest.

In all the scenarios the hybrid collectors have been evaluated and have been shown to be profitable. Its use in relation to the flat plate thermal collectors should be considered depending on the energy price estimation, the higher the electricity price was the more recommended was the use of the hybrid collectors. Although for large-scale applications as central solar heating plant, the use of big size thermal collectors was better because of its lower cost per square meter and its better thermal performance.

A district heating system centralized is better than distributed, the bigger the solar heating plant is the lower the solar heat cost is and a low-temperature district heating system is better than a high-temperature district heating system were the main conclusions in this project. Furthermore the solar heat cost in all the studied scenarios has been shown to be cheaper than the current system. As the conventional energy prices were expected to be increased in the future, the use of the solar energy in the City is a reliable option to consider because the solar heat cost is constant for the expectance life time of the solar installations.

Environmental profit, grants or subsidies for renewables have not been considered. To consider any kind of environmental profit, grants or subsidies for renewables would have shown even better results for the implementation of the solar energy in the City.

Estimations of the solar cost in all the proposed scenarios have been done in this project, if the company or the City decide to implement the solar energy deeper studios with dynamic simulations to know the best design parameters should be done.

This project has been carried out with an Erasmus+ grant, in the Department of Energy, Power Engineering and Environment in the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia. To be held in Zagreb and as part of the project Beyond Energy Action Strategies (BEAST), true data collection and an approach to the needs of the City was done. The tools used for the drafting and data management have been Word and Excel.

2 Energy current situation

The city of Velika Gorica is the largest and most populated city in Zagreb County, Croatia. The Zagreb County surrounds – but does not contain – the nation's capital Zagreb. The municipality has a population of 63517 inhabitants (2011) in 329 square kilometers having a population density of 193 inhabitants per square kilometer and consists of 58 settlements [13]. The city Velika Gorica, located 16 km south of Zagreb, is the largest settlement with a population of 31553 and occupying an area approximately of 10 squares kilometers with a population density of 1,053 inhabitants per square kilometer. Next are presented the main features of the energy current situation in the City. More detailed information can be found in Appendix A.

2.1 Energy consumption in the building sector

The energy consumption in the building sector in Velika Gorica is analyzed using the action plan for sustainable development of energy (SEAP) in Velika Gorica [4]. The building sector consists of public buildings, residential buildings, commercial building and service activities.

The total heat[1] consumption in 2008 in the City for the building sector were 197.34 GWh. 7.89 GWh in the public buildings, 153.03 GWh in the residential buildings and 36.43 GWh in commercial building and service activities. A very high specific consumption is shown in Table 1, providing one of the City main issues.

	Energy consumption: buildings sector by sub-sector				
	Total area [m^2]	Heat consumption [kWh]	Electricity consumption [kWh]	Specific thermal consumption [kWh/m^2]	Specific electricity consumption [kWh/m^2]
Public buildings	39,291	7,878,534	1,757,291	200.5	44.7
Residential buildings	791,968	153,031,838	30,906,134	193.2	39.0
Commercial buildings and service activities	202,400	36,432,000	10,120,000	180.0	50.0
Total	1,033,659	197,342,372	42,783,425		

Table 1 Energy consumption: Building sector by sub-sector in the City

[1] Energy required for domestic hot water consumption is considered in the heat consumption.

The total electricity consumption in the City for the building sector was 42.78 GWh, 1.76 GWh in the public buildings, 30.91 GWh in the residential buildings and 10.12 GWh in the commercial buildings and service activities. According to the results of the energy analysis in the building sector in the City, in absolute terms the most energy-consuming subsector is the residential buildings where this project will be more focused on.

The structure of energy sources used for heating the building sector is composed of district heating 32%, natural gas 31%, firewood 20%; fuel oil 15%; and electricity 2%, see Figure 1.

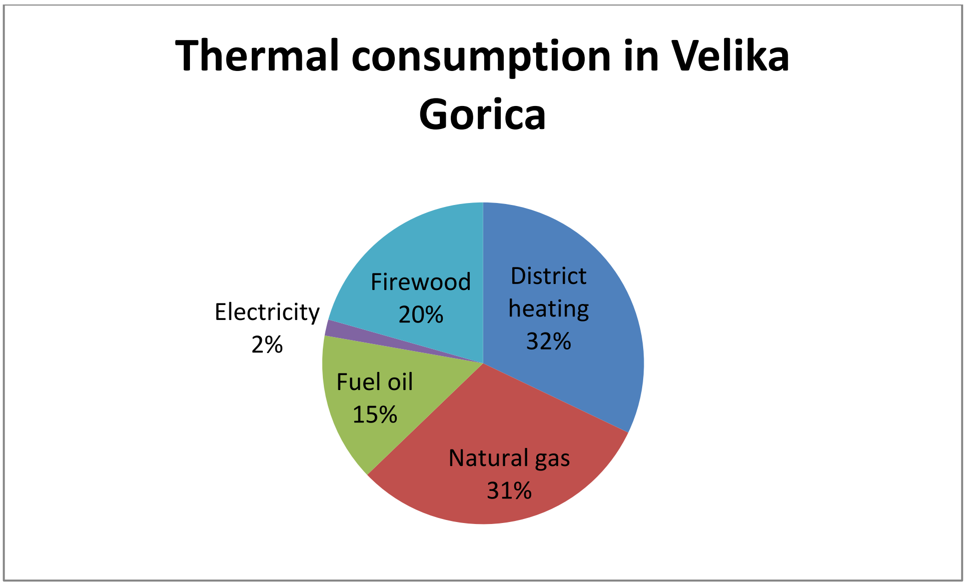


Figure 1 Structure off energy source for heating in the building sector

2.2 Current situation in the district heating system

Most of 1970's and 1980's architecture in the central part of the town is with collective housing buildings. 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 [5], [14]. Only one of the fourteen installed plants is gas operated bearing 60.76% of the total installed capacity, while the rest use fuel oil resulting in a high level of CO_2 emissions.

In the district heating system, the heat is produced in a heating plant and then it is transported to the connected buildings by a primary pipe network. In the connected buildings heat is exchanged in a heat exchanger to secondary pipe network where the heat is finally used by the consumers.

The address name, the installed capacity and the percentage over the global installed capacity of the fourteen heating plants are shown in Table 2. The heating plant number 2, placed in Vidriceva 1, is the largest one because it has been connected with the plant number 1, M.Magdalenica 3. The rest of the heating networks remain not interconnected. The location of the plants is shown in Figure 2 which shows the district heating network of the City.

Number	Address	P installed (MW)	%
1	M.Magdalenica 3	0	0.00%
2	Vidriceva 1	35.61	60.76%
3	J.Dobrile 40a	3.52	6.01%
3	Domjaniceva 3	2.16	3.69%
4	J. Dobrile 8	1.89	3.22%
5	Zagrebacka 126	1.15	1.96%
7	Zagrebacka 71	0.45	0.77%
8	Zagrebacka 19	0.26	0.44%
9	Zagrebcka 12	0.11	0.19%
10	CV naselje 10	2.76	4.71%
11	Zvonimirova 9	6.93	11.82%
12	Trg k.tomislava 34	1.28	2.18%
13	E. laszowskos 35	0.49	0.84%
14	Sibenska	2	3.41%

Table 2 Heating plants of Velika Gorica and installed capacity [14]

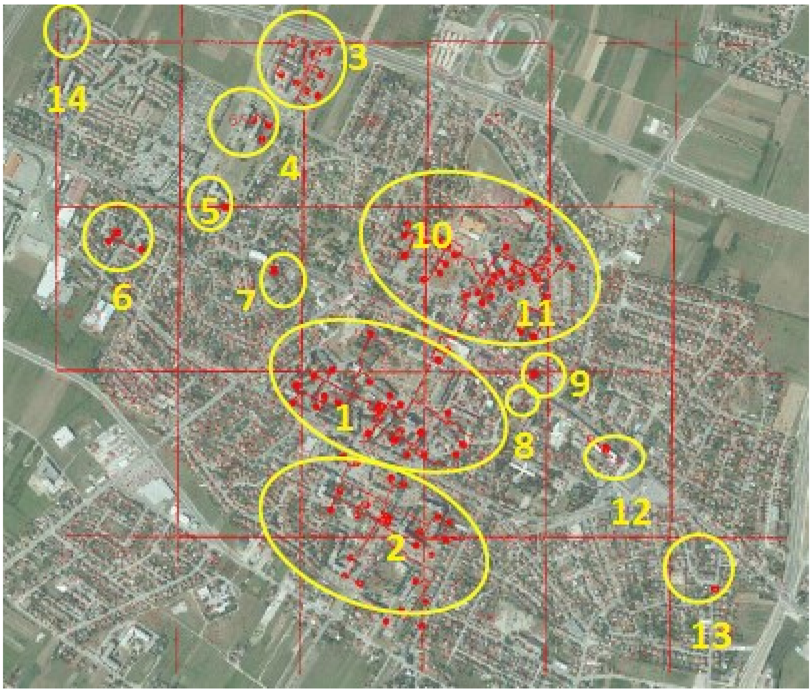


Figure 2 District heating networks of Velika Gorica [14]

The utility company provided as well the water working temperatures in the boiler rooms. The return water temperature from the district heating network to the boiler is 70 °C and the delivered water temperature from the boiler to the district heating network is 105 °C. Thus the district heating network belongs to a high temperature district heating system. Furthermore all but one of the district heating plants are fuel oil operated, resulting in a high level of CO_2 emissions and expensive heat cost.

2.3 Actions in the sustainable energy Action Plan SEAP

The European Union 2020 targets were set to promote a focus on a sustainable future. By 2020 the European Union has committed to reduce emissions of greenhouse gases by 20%, to reduce the energy consumption by 20% through energy efficiency, and to cover 20% of the EU energy needs from renewable sources.

Sustainable Energy Action Plan (SEAP) accepted by the City Council in 2011 – worked out in cooperation with the Regional Energy Agency of Northwest Croatia (REGEA)- is aligned with the aforesaid EU 2020 targets. Proposed actions in SEAP related with solar energy are shown in Table 3 [2], each action has its estimated cost and its expected energy saving per year.

Sustainable Energy Action Plan of Velika Gorica

Sector	Action	Estimated cost [€]	Expected energy saving [MWh]	
Municipal buildings, equipment/facilities	Solar flat plate thermal collectors for educational, cultural, administrative and sports municipal institution	152000 €	735.33	Heat
	Construction of small photovoltaic systems (30 kW) on the roof of municipal buildings	54000 €	210	Electricity
Tertiary (non municipal) buildings, equipment/facilities	Installation of solar systems on tertiary buildings	5641220 €	1214	Heat
	Construction of small photovoltaic systems (30 kW) on the roof of tertiary buildings	95000 €	420	Electricity
Residential buildings	Installation of solar systems in 600 households	454054 €	2423	Heat
	Construction of small photovoltaic systems (30 kW) on the roof of residential buildings	95000 €	420	Electricity
	Total	6491274 €	5422.33	

Table 3 Actions to develop by the City [2].

More actions are needed in residential buildings because it is the most energy consuming sector in the City, thus this project is focused on the introduction of the solar energy in residential buildings to produce Domestic Hot Water (DHW), furthermore of the introduction of solar energy into the district heating system to produce DHW and Space Heating in the buildings of the City.

3 Energy consumption in the City

Reports of energy audits have been used to collect the data of energy consumption in residential sector, public buildings and commercial buildings and service activities. Data has been collected for: 37 residential buildings, 7 kinder gardens, 4 schools, 1 university, 1 art school, 1 polytechnic, 2 museums, 1 culture house, 1 sport center, 3 administration buildings and 1 firehouse.

The energy audits have been made by the next companies: TUV Croatia d.o.o [15], A B A C O d.o.o [16], INTERKONZALTING d.o.o [17], alfa-inzenjering [18] and INEL [19].

This energy consumption has been used to estimate: the Domestic Hot Water demand (DWH), the Space Heating demand (SH) and its distribution along the year in order to integrate the solar energy into the City and to analyze the current situation regarding to the thermal consumption.

Energy consumption in a district heating plant was studied with the data of the hourly gas consumption for three years provided by the national utility company. This data has been processed with MATLAB [6] to obtain the hourly consumption for a typical day of each month and the monthly consumption in the district heating plant.

3.1 Criterion used to estimate the energy consumption in buildings

Four cases were found in energy audit reports to analyze: 1- All the data were available, 2- Monthly heating consumption was available, 3- Yearly thermal energy consumption was available and 4- Only an estimation of yearly heating consumption was available. First and second cases were used to estimate the energy consumption. Further, an estimation of the distribution along the year of the thermal energy consumption in residential buildings was made using the measured energy consumption along the year; the DHW consumption and the specific heating consumption were also estimated.

3.1.1 All the data available. Template example building AG Matoša 5.

There were 23 buildings which contain all the data required. The building case AG Matoša 5 is shown as a template example. The next steps describe the used criteria for the analysis: 1- Gathering the data of the thermal energy consumption of the building. 2- Calculation of the energy required for DHW. 3- Subtracting the energy of the DHW, demand from the thermal energy consumption and to obtain the energy consumption for SH.

Gathering the data of the thermal energy consumption of the building. Thermal energy consumption in energy audit report “IZVJEŠĆE O PROVEDENOM ENERGETSKOM PREGLEDU” for the group of buildings on A.G. Matoša (5, 7, 9) for different years is shown in Table 4. Thermal energy consumption consists of DHW and SH. In order to calculate the energy of one building, an average for the three years was made and divided by the number of buildings, see Table 5.

Year	2010		2011		2012	
Month	[MWh]	[kn]	[MWh]	[kn]	[MWh]	[kn]
January	187	60188	149	50839	167	55267
February	162	54038	150	51085	185	59695
March	144	49610	113	41983	104	40416
April	102	39278	73	32143	79	34166
May	43	24764	40	24025	26	20916
June	24	20090	22	19597	18	18916
July	22	19598	20	19105	16	18416
August	21	19352	19	18859	13	17666
September	38	23534	22	19597	18	18916
October	94	37310	84	34849	54	27916
November	110	41246	142	49117	98	38916
December	156	52562	158	53053	189	75598
Total	1103	441567	992	414252	967	426804

Table 4 Monthly thermal consumption for 3 buildings [15]

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Average thermal energy consumption MWh in 3 buildings	167.67	165.67	120.33	84.67	36.33	21.33	19.33	17.67	26.00	77.33	116.67	167.67
Thermal energy consumption MWh in 1 building	55.89	55.22	40.11	28.22	12.11	7.11	6.44	5.89	8.67	25.78	38.89	55.89

Table 5 Monthly thermal consumption for one building

During summer months (June, July and August) all the thermal energy consumption was considered for DHW as SH during summer months is not used. The DHW consumption for the rest of the months is estimated to be constant.

The number of liters per person per day of DHW was estimated with the next equation:

$$Q_{DHW} = Liters \cdot P \cdot Days \cdot (60 - T_m) \cdot C_p / 3600 \quad (1)$$

P=60 people, Days= number of days in the month. T_m=Mains water temperature (13.5) [20], Cp=4184 J/kg K. The DHW temperature was estimated as 60 °C.

70 liters per person per day were used for DHW demand in this case, a very high value that shows the high thermal consumption in Velika Gorica.

The Space Heating consumption, results subtracting the DHW demand from the thermal energy consumption see Table 6.

	January	February	March	April	May	June	July	August	September	October	November	December	year
Thermal consumption kWh	55889	55222	40111	28222	12111	7111	6444	5889	8667	25778	38889	55889	340222
DHW demand kWh	7111	7111	7111	7111	7111	7111	6444	5889	7111	7111	7111	7111	85332
SH consumption kWh	48778	48111	33000	21111	5000	-	-	-	1556	18667	31778	48778	256779

Table 6 Space Heating consumption in AG Matosa

SH consumption was used to know the specific SH consumption of the building which has an area of 1653 m^2 which represents a specific SH consumption of 157.06 kWh/m^2. This specific SH consumption is very high and shows again the need to implement actions to increase the energy efficiency in the City. These actions have already been proposed in the SEAP [4].

3.1.2 Available monthly SH consumption. Template example building kralja Stjepana Tomaševića 1.

In this case 15 buildings were found. Data were obtained from energy audits reports. The building kralja Stjepana Tomaševića 1 was used as a template example.

SH consumption is shown in Table 7. In this case water is heated with electrical boilers. The SH consumption matches with the first case see Table 6, only May is shown as an exception, this is because the district heating is usually turned off the 10th of May.

	January	February	March	April	May	June	July	August	September	October	November	December	year
SH consumption kWh	33333	33667	20333	8333	1667	-	-	-	1000	11333	20667	31000	161333

Table 7 SH consumption in Kralja Stjepana Tomasevica

With an area of 1265 m^2 there is an annual specific consumption of 127.47 kWh/m^2. DHW demand was estimated with the average obtained from the rest of the buildings.

3.2 Results of energy consumption in buildings

Results of energy consumption in the buildings of the City are shown below. An average of the thermal consumption of the analyzed cases was made to determinate the thermal consumption distribution along the year of the residential buildings, public buildings and commercial buildings and service activities.

3.2.1 Results in residential buildings

Distribution of the thermal consumption was made with the thermal consumption percentage for each month over the year see Table 8.

January	February	March	April	May	June	July	August	September	October	November	December
16.4%	16.2%	11.8%	8.3%	3.6%	2.1%	1.9%	1.7%	2.5%	7.6%	11.4%	16.4%
18.6%	18.2%	11.9%	6.7%	3.1%	2.0%	1.7%	1.7%	2.1%	6.9%	11.2%	16.0%
16.0%	15.9%	11.2%	7.8%	4.1%	2.7%	2.4%	2.2%	3.0%	7.9%	11.6%	15.1%
16.0%	15.4%	11.3%	7.6%	4.4%	3.6%	3.3%	3.0%	3.6%	6.6%	11.2%	14.0%
16.6%	15.4%	11.0%	7.0%	3.9%	3.1%	2.7%	2.7%	3.1%	6.8%	12.5%	15.3%
17.1%	17.9%	10.8%	6.3%	3.3%	2.6%	2.2%	2.2%	2.6%	6.7%	11.9%	16.4%
17.1%	16.9%	11.2%	7.3%	3.8%	2.4%	2.3%	2.2%	2.6%	7.4%	11.2%	15.6%
16.5%	16.2%	11.0%	7.1%	3.8%	2.9%	2.5%	2.3%	2.8%	7.4%	11.8%	15.6%
16.2%	16.2%	10.7%	6.8%	3.8%	2.9%	2.5%	2.5%	3.3%	7.8%	12.1%	15.0%
16.8%	17.7%	11.8%	7.3%	3.2%	1.8%	2.1%	2.0%	2.6%	6.9%	11.8%	16.1%
16.9%	17.0%	10.6%	6.8%	3.6%	2.6%	2.3%	2.2%	2.9%	7.2%	11.2%	16.7%
16.6%	16.6%	11.2%	7.4%	3.6%	2.7%	2.3%	2.2%	2.5%	7.5%	11.4%	15.9%
16.5%	17.8%	10.2%	6.6%	3.9%	3.0%	2.6%	2.3%	2.9%	6.8%	11.8%	15.7%
16.9%	17.3%	11.2%	7.0%	3.4%	2.3%	2.1%	2.1%	2.4%	7.6%	12.2%	15.5%
16.6%	16.7%	11.3%	7.3%	3.7%	2.6%	2.3%	2.3%	2.5%	7.4%	11.5%	15.9%
16.2%	16.4%	11.3%	7.1%	3.8%	2.7%	2.5%	2.4%	3.0%	7.5%	11.7%	15.4%
17.2%	17.2%	11.5%	7.0%	3.2%	2.3%	2.4%	2.0%	2.2%	7.4%	11.7%	16.0%
16.7%	16.9%	11.1%	6.9%	3.5%	2.4%	2.3%	2.3%	2.8%	7.8%	11.3%	15.9%
18.8%	18.0%	11.4%	6.8%	2.9%	1.9%	1.6%	1.1%	2.2%	7.5%	11.8%	16.0%

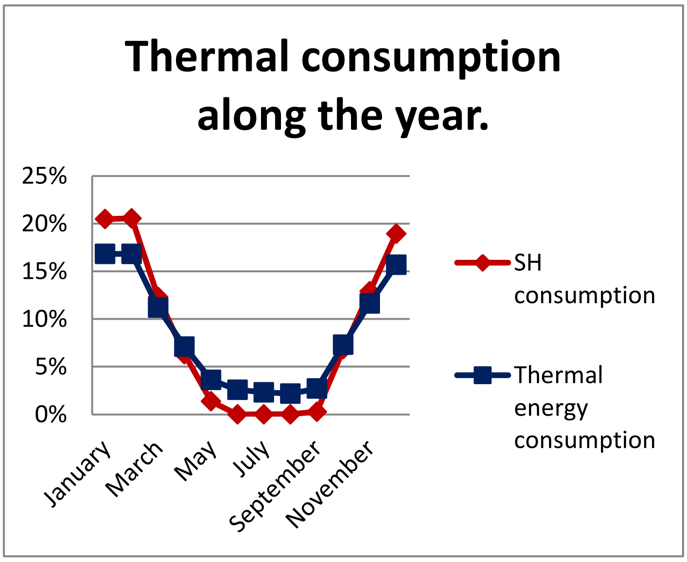
Table 8 Thermal consumption distribution along the year in residential buildings

Standard deviation shows a low variability, see Table 9, so the average was used to estimate the distribution of the thermal energy consumption along the year.

	January	February	March	April	May	June	July	August	September	October	November	December
Average	16.83%	16.83%	11.19%	7.10%	3.61%	2.57%	2.33%	2.18%	2.71%	7.30%	11.64%	15.71%
Max.	18.82%	18.15%	11.87%	8.30%	4.38%	3.57%	3.28%	3.05%	3.60%	7.91%	12.51%	16.67%
Min.	15.99%	15.37%	10.18%	6.34%	2.92%	1.82%	1.61%	1.10%	2.12%	6.65%	11.15%	14.01%
St. dev.	0.0074	0.0083	0.0041	0.0044	0.0036	0.0044	0.0037	0.0040	0.0038	0.0040	0.0036	0.0060

Table 9 Standard deviation of thermal consumption

The same method was used for estimating the SH distribution and DWH consumption. The consumption distribution along the year and the percentage used for SH and DHW in residential buildings are shown in Figure 3.



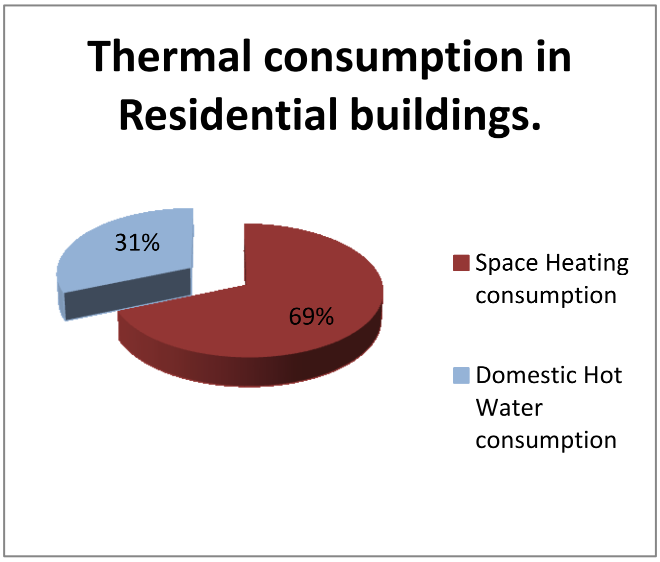


Figure 3 Consumption distribution and thermal consumption in residential buildings

The average DHW consumption is 62 liters per person per day and the specific annual thermal consumption is 193.22 kWh/m^2 on average. The annual electricity consumption is 61.86 kWh/m^2 on average. Only annual data of electricity consumption was found thus no distribution along the year of electricity consumption was done. A high specific thermal consumption was found thus actions to increase the energy efficiency are required, these actions are already proposed in the SEAP.

To evaluate the use of solar energy to produce DHW a template example with the calculated averages was made.

3.2.2 Results in public buildings and commercial buildings and service activities

An average of the analyzed cases was made to determine the thermal consumption distribution in the public buildings and commercial buildings and service activities. The same method as before was used. High variability of energy consumption for each building and low DHW consumption, only 12% of the thermal energy consumption, was found. Thus a template example is not possible to be made for these buildings and a specific studio has to be made for each building to implement the solar energy. A high specific thermal energy consumption of 200.52 kWh/m^2 on average for public buildings and 180.0 kWh/m^2 on average for commercial buildings and service activities was found, thus actions to increase the energy efficiency prior to improve/change the energy supply systems are required. These actions have been proposed in the SEAP [4]. The electricity consumption is 64.48 kWh/m^2 on average in public buildings and 50 kWh/m^2 on average in commercial buildings and service activities.

3.3 Energy consumption in a district heating plant

The district heating plant of Vidriceva 1 was analyzed. Vidriceva is a gas operated plant bearing 60.76% of the total installed capacity. In this studio hourly gas consumption for three years (2012, 2013 and 2014) was provided by the national utility company. These data were processed with MATLAB [6]. Gas consumption was used to calculate the monthly gas consumption in the district heating plant in order to use a validated simple model which requires a low calculation effort, to calculate a central solar heating plant with seasonal storage.

The energy supplied by the district heating plant was estimated to be the 60.76% of the total energy supplied by the district heating network in the City. Thus 38470 MWh were supplied by the district heating plant in Vidriceva. To estimate the distribution losses a comparison between the estimated energy supplied and the gas consumption was made.

The gas consumption of the plant was 5385897 m^3 in 2014. 1 m^3 of gas gives 9.2607 kWh of thermal energy [5], thus 49877 MWh of thermal energy were consumed in one year. As the estimated energy supplied were 38470 MWh the thermal distribution losses were estimated to be a 22.87% of the energy supplied. As the utility company did not provide the required information this estimations could not be validated.

A comparison between the gas supplied and the estimated consumption is shown in Figure 4. As well a comparison between the distribution percentages of the energy supplied by the heating plant and the thermal consumption in residential buildings is shown in Figure 4. Both trends are similar only a small difference is shown in January and February.

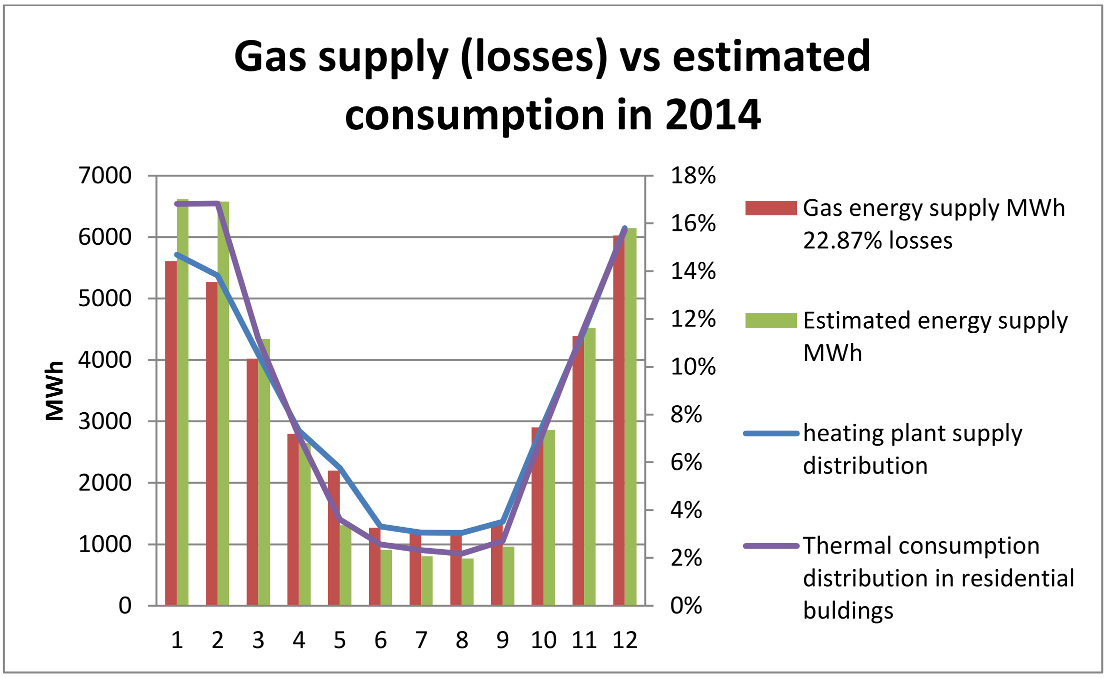


Figure 4 Comparison between gas supplied and thermal consumption in residential buildings in 2014

Distribution thermal losses are found to be high in comparison with the low temperature district heating systems, where distribution losses are between 10-15% [21], [22], due to the District heating network in the City belongs to a high temperature district heating system, the return water temperature from the district heating network to the boiler is 70 °C and the delivered water temperature from the boiler to the district heating network is 105 °C. A low temperature district heating system is recommended to obtain lower distribution losses. Because the lower the temperature is, the lower the thermal gradient is the lower the losses are.

One of the targets of the project Beyond Energy Action Strategies (BEAST) [3] is to reduce the greenhouse gas emissions and increase renewable energy sources supply, thus this project has been focused on the introduction of the solar energy into the district heating system proving a feasible and profitable scenario. Two scenarios have been analyzed: (i) hot water preheating in a district heating plant; and (ii) thermal energy storage in a solar heat plant. The system has been modeled as a low-temperature district heating system with 50 °C as delivered water temperature and 30 °C as return water temperature.

4 Climatic data and solar resources

Climatic data of Velika Gorica were taken from the software Meteonorm V7 [7]. Considered data were those corresponding to the weather station situated on the north of the City in Zagreb-Pleso Airport. The City situation and weather station position were shown in Figure 5. The geographic coordinates are: latitude: 45.73; longitude: 16.06; and altitude: 106 m.

Figure 5 Geographical location of Velika Gorica

Average ambient temperature, average daily radiations: for a horizontal surface, for 34° tilted surface and for a tracked surface with 1 and 2 axes are shown in Table 10.

	Ambient temperature	Global irradiation on horizontal surface	Irradiation on 34° tilted surface	Irradiation for tracked, 1 axis N-S	Irradiation for tracked, 2 axes
Month	Ta [°C]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]
Jan	-0.1	32	55	40	71
Feb	2.5	56	80	69	99
Mar	6.9	91	114	114	143
Apr	11.9	121	133	147	169
May	17	171	171	218	243
Jun	20.4	175	168	213	230
Jul	21.7	182	178	226	247
Aug	21.3	156	167	200	229
Sep	16	98	114	121	143
Oct	11.7	68	93	85	114
Nov	6.7	33	50	40	62
Dec	1.5	24	38	29	48
Year	11.5	1207	1361	1502	1798

Table 10 Monthly meteorological data considered for Velika Gorica [7]

Hourly irradiance for a representative day on a tilted surface is shown in Table 11 and Hourly ambient temperature for a representative day is shown in Table 12.

Irradiance on 34 ° tilted surface [W/m^2]												
Hour	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	3.4	7.6	3.8	0.1	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	9.7	43.8	54.3	46.9	19.9	1.4	0.0	0.0	0.0
7	0.0	0.0	19.5	90.2	171.8	161.0	154.4	127.9	66.5	10.5	0.0	0.0
8	0.6	26.4	143.8	221.4	323.5	296.5	318.9	297.3	184.6	119.3	25.8	0.5
9	107.9	144.2	292.0	355.6	457.5	436.2	475.2	469.4	316.3	237.1	105.3	62.8
10	188.7	277.2	390.6	462.1	586.7	567.6	610.0	610.3	413.5	330.8	158.6	138.4
11	256.9	386.3	464.2	563.5	682.5	661.9	733.4	715.7	471.2	400.4	214.5	174.0
12	294.5	413.1	505.6	606.2	655.2	689.1	651.3	679.2	511.2	442.7	259.0	201.8
13	262.0	392.8	520.8	556.3	679.7	694.0	682.9	645.0	514.0	430.8	263.5	186.8
14	293.5	456.3	505.0	521.3	601.8	626.2	627.3	584.8	488.7	433.3	300.4	226.0
15	239.2	398.0	394.6	446.5	509.5	531.4	557.5	494.3	407.9	345.3	235.4	168.5
16	129.6	255.3	273.4	324.3	393.8	406.2	415.6	383.6	261.7	194.7	115.5	78.1
17	2.5	113.8	154.3	204.6	254.2	272.5	284.7	239.0	142.5	61.1	0.8	0.0
18	0.0	1.4	28.3	80.7	119.2	142.2	143.2	106.3	34.5	0.5	0.0	0.0
19	0.0	0.0	0.1	6.7	29.0	50.0	46.3	17.0	0.5	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.9	6.5	3.3	0.3	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 11 Hourly irradiance for a typical day considered for Velika Gorica [7]

Average Temperature [°C]												
Hour	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	-1.28	0.48	4.17	8.51	12.80	16.11	17.50	17.43	12.72	9.33	5.05	0.46
2	-1.74	-0.09	3.51	7.73	11.95	15.35	16.67	16.64	11.93	8.65	4.52	0.03
3	-2.18	-0.68	2.95	7.33	11.50	14.90	16.21	16.22	11.54	8.05	3.96	-0.35
4	-2.41	-0.96	2.58	6.94	11.19	14.63	15.87	15.83	11.11	7.74	3.67	-0.54
5	-2.64	-1.25	2.20	6.69	11.22	14.76	15.89	15.66	10.82	7.41	3.40	-0.77
6	-2.80	-1.45	2.09	6.91	12.39	15.92	17.03	16.22	10.90	7.18	3.21	-0.88
7	-2.98	-1.59	2.55	8.20	14.11	17.29	18.57	17.79	12.05	7.52	3.11	-1.03
8	-2.90	-1.04	4.25	9.77	15.75	18.69	20.23	19.53	13.62	9.19	3.79	-0.96
9	-1.59	0.57	6.13	11.38	17.37	20.17	21.90	21.37	15.35	10.91	5.35	0.11
10	-0.16	2.34	7.83	12.87	18.90	21.58	23.44	23.09	16.92	12.61	6.72	1.42
11	1.26	4.00	9.28	14.28	20.28	22.84	24.94	24.62	18.30	14.13	8.06	2.53
12	2.38	5.26	10.47	15.46	21.25	23.86	25.77	25.61	19.39	15.35	9.18	3.42
13	3.00	6.11	11.38	16.17	22.01	24.63	26.51	26.26	20.21	16.16	9.90	3.94
14	3.57	6.92	12.02	16.62	22.47	25.09	26.93	26.59	20.75	16.75	10.51	4.46
15	3.64	7.25	12.17	16.78	22.56	25.22	27.15	26.55	20.96	16.79	10.46	4.39
16	3.04	6.88	11.78	16.46	22.42	25.11	27.02	26.31	20.54	16.15	9.69	3.68
17	1.96	5.88	10.94	15.88	21.84	24.64	26.50	25.70	19.75	14.97	8.53	2.80
18	1.53	4.69	9.71	14.89	20.92	23.84	25.62	24.71	18.54	13.91	8.12	2.53
19	1.13	4.13	8.73	13.72	19.74	22.84	24.48	23.50	17.45	13.24	7.66	2.24
20	0.70	3.54	7.95	12.77	18.60	21.63	23.32	22.47	16.58	12.51	7.22	1.95
21	0.34	2.93	7.21	11.81	17.45	20.46	22.03	21.36	15.68	11.88	6.80	1.65
22	-0.06	2.33	6.44	10.87	16.29	19.21	20.86	20.31	14.78	11.20	6.32	1.28
23	-0.47	1.74	5.67	9.88	15.15	18.06	19.59	19.25	13.86	10.54	5.90	1.02
24	-0.83	1.13	4.91	8.93	14.01	16.87	18.40	18.18	12.92	9.85	5.47	0.72

Table 12 Hourly temperature for a typical day considered for Velika Gorica [7]

5 Study of Technologies

The technical feasibility of the current technologies was studied. The considered technologies found in the literature to be implemented in the City were: concentrating solar power (CSP), flat plate thermal collectors, photovoltaic panel (PV), photovoltaic-thermal collector (PVT), heat pumps (HP), biomass and thermal seasonal storage.

A summary of these technologies with their advantages and disadvantages is presented in this chapter. Seasonal thermal energy storage and photovoltaic-thermal collectors PVT are explained in greater detail in Appendix B, to promote understanding of both technologies, because they are new technologies and not as widely known as the rest of technologies presented in the chapter.

5.1 Concentrating solar power (CSP)

The Concentrating Solar Power (CSP) technologies use mirrors to concentrate the direct solar irradiation and turn it into heat to create water steam to drive a turbine that generates electrical power (see Figure 6). CSP can also be paired with existing or new traditional power plants. Some types of CSP allow the heat to be stored for many hours so that electricity can be produced at night (PCC, Parabolic cylindrical collector, Central Tower) [23]. Water-cooled CSP plants could be used like a Cogeneration system using the waste heat for steam condensation. CSP plants require abundant direct solar radiation in order to generate electricity, given that only strong direct sunlight can be concentrated to the temperatures required for electricity generation. This limits CSP to hot, dry regions. To be economic at present a CSP plant requires direct normal irradiance levels (DNI) of 2000 kWh/m^2/year or more [24], so for the location of Velika Gorica is unsuitable, although there is no technical reason why CSP plants cannot run at lower levels of DNI.

Figure 6 Concentrating solar power

Advantages: Some CSP can store heat to produce electricity at night. Could be used as a cogeneration system if is Water-cooled CSP plant.

Disadvantages: It is required more land than with PV. There are high differences of temperature in short periods of time. Initial investment is higher than for other technologies. Thermal production in experimental designs has been lower than flat plate thermal collectors [25]. CSP plants require abundant direct solar radiation thus they are only suitable for a number of regions with an excellent solar resource.

5.2 Flat plate thermal collectors

Flat plate thermal collectors consist of a dark flat-plate absorber, a transparent cover that reduces heat losses, a heat-transport fluid to remove heat from the absorber and a heat insulating backing, see Figure 7. Flat plate thermal collectors usually use water or air as fluid, the fluid circulates through tubes to transfer heat from the absorber to: an exchanger, a water tank or the space to heat (air as fluid).

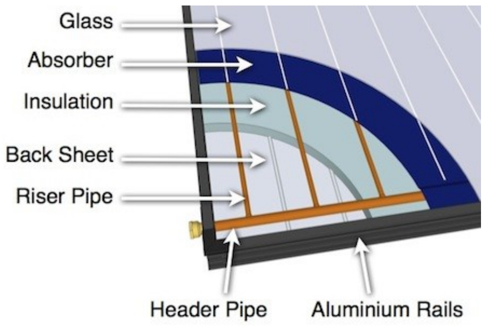


Figure 7 Basic construction of a flat plate thermal collector [80]

Flat plate thermal collectors can heat hot water for domestic, commercial use, or heat spaces such as houses or offices. Flat plate thermal collectors can also provide heat for industrial processes or can be used for space cooling, using absorption for cooling needs [26]. Technologies as heat pumps can be used combined with flat plate thermal collectors with a high efficiency [27]. For large scale use there is a specific design with large size collectors manufactured by Arcon-Sunmark [28] that can reach 13 m^2. Though in small scale use, small size collectors, that usually reach around 2 m^2, are used. There is another modality, evacuated tube collectors, but have not been considered in this project.

Small size flat plate thermal collectors were evaluated in this project in two scenarios: (i) to produce Domestic Hot Water (DHW) in a residential-scale use; and (ii) to preheat water in a district heating plant. Moreover large size flat plate thermal collectors were evaluated in this project in two scenarios: (i) to preheat water in a district heating plant; and (ii) to produce hot water in a solar heating plant with seasonal thermal energy storage.

Advantages: flat plate thermal collectors are a developed and widely used technology with low maintenance. Collectors can be mounted on buildings and save space.

Disadvantages: Large use of Land.

5.3 Photovoltaic panel (PV)

A photovoltaic panel turns solar energy into direct current electricity using semiconducting materials (usually silicon). The cost of photovoltaic has declined steadily since the first solar cells were manufactured [29] and the electricity cost from PV is starting to be competitive with conventional electricity sources.

Figure 8 Roof-mounted PV installation

These installations can be mounted on buildings (see Figure 8). Rooftop PV does not require an electricity transmission or distribution network and it does not require new land area. It can also be ground-mounted installations.

The production of heat with PV requires the combination with heat pumps which beyond the scope of the project. PV was evaluated combined with a flat plate thermal collector in a hybrid technology explained below. Because of aforesaid reasons PV were not evaluated to be implemented alone.

Advantages: There is a lower use of land than concentrating solar power, the space is saved in case of roof-mounted installations, the cost of PV is becoming competitive and its requires low maintenance.

Disadvantages: The PV only produces electricity, the production of heat with PV requires the combination with heat pumps, the PV efficiency decreases when is heated by the sun and the electricity is more difficult and costly to be stored.

5.4 Photovoltaic-thermal collector (PVT)

Photovoltaic-thermal collector (PVT) is a hybrid technology which integrates photovoltaic and solar thermal systems for the co-generation of electrical and thermal power from solar energy. Photovoltaic panel works as the absorber of the flat plate thermal collector and the flat plate thermal collector works cooling the PV cells increasing the PV efficiency, thus electricity and thermal energy are produced.

The energy outputs can be used in different ways. Electrical energy of the PVT can either be used directly or be supplied to the grid while the thermal output depends strongly on the thermal system design and the amount of heat that is extracted by the user.

The PVT cogeneration technology offers a solution for space limitations when both technologies are competitive. As the available space in Velika Gorica is low this technology was taken into account to know if it was profitable and it was also compared with a flat plate thermal collector.

PVT collectors were evaluated in this project in two scenarios: (i) to produce Domestic Hot Water (DHW) in a residential-scale use; and (ii) to preheat water in a district heating plant.

Advantages: All the combined advantages of PV and flat plate thermal collectors.

Disadvantages: PVT collector has lower thermal performance than flat plate thermal collector but higher performance than PV collector.

As this is a new technology a market survey was made for PVT, the evaluated collectors are shown in Table 13.

Company	Collector	Fluid type	State	Cost [€]	Area [m^2]	Evaluated
Absolicon [30]	Absolicon X10 PVT	Liquid (concentrating)	Developing stage	No provided	--	No
AnafSolar [31]	H-NRG	Liquid	Available	No provided	1.65	No
DualSun [32]	DualSun	Liquid	Available	No provided	1.64	No
Ecomesh [33]	Ecomesh	Liquid	Available	800	1.65	Yes
HYSOLAR [34]	HYSOLAR	Liquid	No answer	No provided	--	No
institute Fraunhofer für Solare Energiesysteme [35]		Liquid	Developing stage	No provided	--	No
MILLENNIUM ELECTRIC LTD. [36]	MSS MIL-PVT 250W-MO2	Liquid	Available	No provided	1.63	No
Power panel [37]	Power panel	Liquid	No answer	No provided	--	No
Power-spar	Power-spar	Liquid (concentrating)	No longer available	No provided	--	No
Sekisui Chemical Co [38]		Liquid	No longer available	No provided	--	No
SELA SOLAR [39]	M-240 PVT	Liquid	Available	1800	2.26	Yes
Solar wall [40]	Solar wall	Air	Available	No provided	--	No
Solartwin [41]	Solartwin	Liquid	No answer	No provided	--	No
Solarus [42]	Solarus_CPC-PVT	Liquid (concentrating)	Available	600	2.44	Yes
Solimpeks [43]	powervolt	Liquid	Available	310	1.37	No
Solimpeks [43]	Powetherm	Liquid	Available	340	1.43	Yes
TES SOLAR WATER [44]	TES ZEUS	Liquid	Available	No provided	-	No
Twin solar [45]	Twin solar	Air	Available	No provided	--	No

Table 13 market survey in PVT collectors

5.5 Biomass boiler

Biomass boiler is an already project that has been studied by the utility company and the City, so this project is not focused on it and only proposes it as auxiliary heat source. The biomass exploitation takes advantage of the agricultural, forest, manure residues in extent and urban and industrial wastes among others, which with limited environmental impacts can generate heat and electricity [46]. Biomass can be used as an auxiliary system to central solar heating plant with seasonal storage in a district heating system reaching a 100% renewable fraction. Biomass can be stored during long periods (since the collecting period in April-May till it is used in winter) with low storage cost and no (or negligible) efficiency losses.

5.6 Heat pumps (HP)

Heat pumps are devices that transfer heat from a colder to a warmer reservoir using external energy for it. Heat pump technology reduces the fuel oil and gas consumption because it has a high coefficient of performance (COP) so it consumes less energy than other technologies [47] e.g. electrical resistance heaters; boilers… thus decreases also air pollution [48]. The most used heat pumps technologies in the district heating systems are gas engine heat pump (GEHP) and electrical heat pump.

The utility company is already studying the implementation of heat pumps in the district heating system. Thus only small explanation of a possible use of heat pumps with solar energy was made in this project in order to be considered for the utility company in the future.

Integrating heat pump to solar district heating system with seasonal thermal energy storage would help to optimize the inlet and outlet temperature of the solar energy system, to reduce the heat loss from the storage and to increase the solar heat production. The aim is to run the heat pump when the electricity prices are low to cool the storage (cold sink), providing heat to the DH system (hot sink) and increasing the long term storage capacity [49]. Even the use of Heat pumps for Domestic Hot Water production would increase the solar heat production.

Advantages: Helps to optimize the temperatures in the solar energy system with seasonal energy storage, helps increasing efficiency of flat plate thermal collector, increased solar heat production in a renewable energy systems, reduction of storage size and it can utilize “surplus” electricity from hybrid collectors.

Disadvantages: Electricity input needed in the case of compressor driven heat pump, using absorption heat pump can be challenging due to limited experience in these applications and it has complex controls.

5.7 Thermal seasonal storage

Solar energy is a time-dependent energy resource. Energy needs for a very wide variety of applications are also time dependent but in a different way than the solar energy supply. Consequently, the storage of energy is necessary if solar energy is intended to meet substantial portions of these energy needs. The ideal storage system for many thermal systems is the use of water as material storage, among all technologies of thermal storage, only water as material storage has been taken into account in this project [8].

Thermal storage can be classified into short-term storage and long-term storage according to different storage durations [50]. Using excess heat produced in the summer to compensate the heat supply insufficiency during the wintertime is the concept of Seasonal Thermal Energy Storage Systems (STES), also called long-term heat storage.

For thermal solar energy, STES becomes important to meet the thermal needs during winter with the overproduction during summer making a higher solar fraction. Thus STES is helpful for balancing between the supply and the demand of energy. There are four storage concepts using water as material storage: Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES).

The seasonal thermal energy storage in a solar heating plant was proposed in this project using the pit thermal energy storage PTES.

Advantages: Thermal energy storage offers the option to improve output control for some energy technologies, it is able to reduce the mismatch between supply and demand, some storage materials like the water or ground have universal availability and low cost.

Disadvantages: The energy stored decreases with the time due to the heat losses, some storage technologies are still in developing stage, some technologies are expensive, and for seasonal storage e.g. are needed very big volumes.

6 Residential-scale use of solar energy

After analyzing the sustainable energy action plan, SEAP, accepted by the City Council was found that more actions were needed in residential buildings, because is the most energy-consuming sector in the City.

The production of Domestic Hot Water (DHW) has been the proposed scenario in the introduction of solar energy in the residential-scale use. This proposed scenario was designed for the residential buildings which are not included in the district heating system.

To design this scenario the DHW consumption of a building template example saw in the section 3.2.1 Results in residential buildings was used. The evaluated technologies to produce DHW were the flat plate thermal collectors and the photovoltaic-thermal collector, PVT that have already seen in sections 5.2 Flat plate thermal collectors and 5.4 Photovoltaic-thermal collector (PVT). Both technologies have been compared and an economical assessment has been made.

In residential-scale applications, performance predictions can be done with ‘’short-cut’’ methods [8]. The *f* -chart method of Klein and Beckman [51] is made with correlations of the results of a large number of detailed simulations in terms of easily calculated dimensionless variables.

The *f*-chart method is accepted in different countries for the initial estimation of solar thermal systems and it accuracy has been validated in different TRNSYS simulations and measured data [51], [52], [53], [54]. Nowadays a significant number of studies use the *f*-chart method to assess the accuracy of newly developed methods [55].

The electrical output of the hybrid collector was calculated as well. The electrical output has been compared with Photovoltaic Geographical Information System (PVGIS) [56], that is a tool for Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology and gets a quick overview of the grid-connected PV potential.

6.1 The f-chart method

The *f*-chart method provides means for estimating the fraction of a total heating load that will be supplied by solar thermal energy for a given solar heating system. The primary design variable is collector area; secondary variables are collector type, storage capacity, fluid flow rates, and load and collector heat exchanger sizes. The method is a correlation of the results of many hundreds of thermal performance simulations of solar heating systems. The conditions of the simulations were varied over appropriate ranges of parameters of practical system designs. The resulting correlations give *f,* the fraction of the monthly heating load (for Space Heating and Domestic Hot Water) supplied by solar energy as a function of two dimensionless parameters. One is related to the ratio of collector losses to heating loads, X, and the other is related to the ratio of absorbed solar radiation to heating loads, Y.

The two dimensionless groups are:

$$X = F_R U_L \frac{F'_R}{F_R}(Tref - Ta)\frac{A_{total}}{L} \quad (2)$$

$$Y = F_R(\tau\alpha)_n \frac{F'_R}{F_R}\frac{(\tau\alpha)}{(\tau\alpha)_n} HDays \frac{A_{total}}{L} \quad (3)$$

Where:

$$\frac{F'_R}{F_R} = \left[1 + \left(\frac{A_c F_R U_L}{(mC_p)_c}\right)\left(\frac{(mC_p)_c}{\varepsilon(mC_p)_{min}} - 1\right)\right]^{-1} \quad (4)$$

A_{total}=Total collector area, m^2
F_R=Collector heat removal factor, %
U_L= Collector overall energy loss coefficient, W/m^2°C
(τα)/(τα)n = 0.94
τ = Cover transfer coefficient
α = Absorption coefficient of the absorber
T_a= Monthly average ambient temperature, °C
Tref=100 °C
H=Monthly average daily radiation on the surface of the collector, Wh/m^2
L= Monthly loads for space heating and hot water, Wh
Days=Number of days in the month
$(mC_p)_c$=fluid capacitance rate in collector side
$(mC_p)_{min}$=Minimum fluid capacitance rate, It is the same for both sides of the exchanger
ε= Heat exchanger efficiency, %
$F_R U_L$ and $F_R(\tau\alpha)_n$ are obtained from collector test results.

The ratio *F'R/FR* corrects for various temperature drops between the collector and the storage tank.

The fraction *f* of the monthly total load supplied by the water heating is given as a function of X and Y:

$$f[m]=1.029Y-0.065X-0.245Y^2-0.0018X^2+0.0215Y^3 \quad (5)$$

The annual factor covered with solar energy is:

$$F_{annual} = \frac{f[m]L}{L * 12} \quad (6)$$

6.1.1 Corrections

Storage capacity

The *f* -chart was developed for a standard storage capacity of 75 liters of stored water per square meter of collector area. The performance of systems with storage capacities in the range of 37.5 to 300 liters/m^2 can be determined by multiplying the dimensionless group *X* by a storage size correction factor *Xc/X:*

$$Xc/X = \left(\frac{actual\ storage\ capacity}{standard\ storage\ capacity}\right)^{-0.25} \quad (7)$$

In the analyzed case in this project a volume of 80 liters per collector square meter has been selected.

Domestic Hot Water heating systems

The *f* -chart was developed for Space Heating and Domestic Hot Water heating systems. Performance of only use DHW heating systems can be determined by multiplying the dimensionless group *X* by a DHW heating correction factor *Xc/X:*

$$Xc/X = \frac{11.6 + 1.18Tw + 3.86Tm - 2.32Ta}{100 - Ta} \quad (8)$$

Tw= Domestic Hot Water temperature (60°C)
Tm= Mains water temperature
Ta= Ambient temperature

6.1.2 Data elaboration

Data from collectors

Two collectors with good efficiency have been considered to be used with the *f*-chart method, Eborx Eco Classic 2.0 [57], a flat plate thermal collector, and Ecomesh, a hybrid photovoltaic-thermal collector.

The data from collectors was given with a second-order equation meant to the average temperature of the collector. In the *f*-char method the parameters of F_RU_L and $F_R(\tau\alpha)_n$ are needed. To obtain these values a thermal test data conversion is needed.

First a linear equation is desired and a second-order collector equation is known so a numerical conversion was done to obtain a linear equation. It is necessary to choose two values of Δt/G where the collector works and the two curves intersect. The maximum difference temperature between the ambient temperature and the collector during summer was chosen to be Δt=52.5 °C and the minimum difference temperature during winter was chosen to be Δt=10 °C (in winter the mains water temperature is 13 °C and the average ambient temperature is 0°C). The incident radiation was chosen to be G =800 W/m^2. The chosen points for Δt/G are 0.0125 and 0.065625. There are two equations with two unknowns:

$$F'(\tau\alpha)\eta - F'U_L \cdot \frac{\Delta t}{G} = \eta_0 - a_1 \cdot \frac{\Delta t}{G} - a_2 \cdot \frac{\Delta t}{G^2} \cdot 800 \quad (9)$$

Which leads to $F'(\tau\alpha)_n$ and $F'U_L$ for the lineal equation. These values are meant with the average temperature collector and ambient temperature, Δt =Tc –Ta, but values meant with the inlet water temperature and ambient temperature, Δt=Ti-Ta, are needed, to obtain the $F_R(\tau\alpha)n$ and the F_RU_L desired. The equations 10 and 11 show the relation:

$$F_R(\tau\alpha)n = F'(\tau\alpha)n * (1 + \frac{A_c F' U_L}{2mC_p})^{-1} \quad (10)$$

$$F_R U_L = F'U_L * (1 + \frac{A_c F'U_L}{2mC_p})^{-1} \quad (11)$$

m= 0.014167 Kg/sm^2 has been selected for 50 l/hm^2 with a fluid density 1.02 Kg/liter (propylene glycol 50%).

C_p = 3680 J/KgK (propylene glycol 50%).

A frost-resistant mixture of water and glycol of 50% was used to prevent the heat-transfer fluid from freezing in the solar circuit because of the historical minimum temperature in the City was -33 °C.

Technical features for the hybrid and flat plate thermal collector are shown in **Table 14**.

	$F_R(\tau\alpha)_n$	F_RU_L (W/m^{2}K)	n_0	a_1 (W/m^{2}k)	a_2 (W/m^{2}k^2)	FR'/FR	Ac	P_c(W)
Ecomesh	0.69	5.87	0.69	2.59	0.06	0.97	1.63	230
Eborx Eco Classic 2.0	0.78	4.05	0.80	3.80	0.01	0.98	1.82	0

Table 14 Technical data of the considered solar collectors

Meteorological data

The monthly average ambient temperature, the monthly average daily radiation on the surface of the collector and the mains water temperature are shown in the **Table 15**, these data have been collected using Meteonorm software [7] and supplied by the utility company, zagrebački holding [20].

Month	Ta [° C]	Irradiance on tilted 34° surface, daily mean [kWh/m^2]	days/month	Irradiance on tilted 34° surface, monthly mean [kWh/m^2]	Mains water temperature (Tm) [° C]
Jan	-0.1	1.774	31	55	13.2
Feb	2.5	2.857	28	80	12.7
Mar	6.9	3.677	31	114	12.4
Apr	11.9	4.433	30	133	13.5
May	17	5.516	31	171	13.5
Jun	20.4	5.600	30	168	13.5
Jul	21.7	5.742	31	178	14.1
Aug	21.3	5.387	31	167	14.5
Sep	16	3.800	30	114	15.0
Oct	11.7	3.000	31	93	14.6
Nov	6.7	1.667	30	50	14.5
Dec	1.5	1.226	31	38	13.8

Table 15 Meteorological data in Velika Gorica

Energy demand

The energy demand has already been analysed in the section 3.2.1 Results in residential buildings. The average Domestic Hot Water (DHW) demand per person and month is 106 kWh it means an average of 62 liters per person per day.

The building of J. Dobrile 18-24 has been used as a template example for the f-chart method because it has the average DHW consumption required of 62 liters per person per day, 36667 kWh per month for 346 people.

Energy prices

To make an economic analysis of the project, the prices of the energy consumed at present and its future estimation were needed.

EUROSTAT data base has been used [58] to know the electricity and gas price and its future price estimation. The annual energy report “Energy in Croatia” [59] has been used to know the fuel oil price and its future estimation. Based on this sources, the electricity price in 2016 is estimated to be 0.1467 €/kWh, the residential gas price is estimated to be 0.0498 €/kWh and the fuel oil price in 2016 is estimated to be 0.101 €/kWh, see Figure 9.

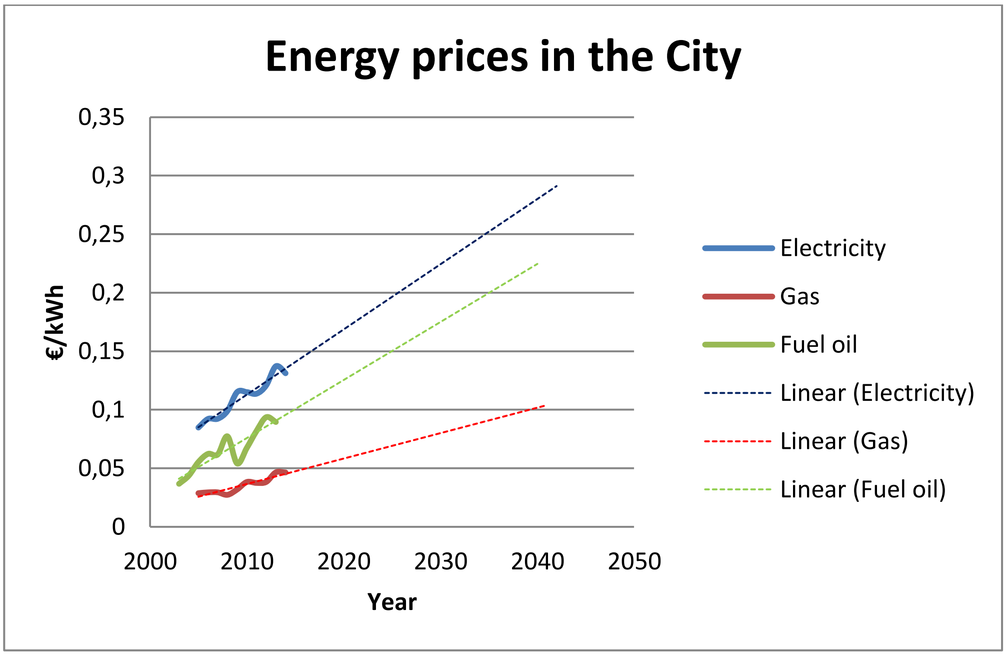


Figure 9 Energy prices in the City

6.2 Electricity output of hybrid collector

The photovoltaic-thermal collector, PVT, and the flat plate thermal collector were used to produce DHW. The *f*-chart method gives the thermal outputs of the collectors thus the electrical output in the PVT has to be calculated with another method to get a quick overview of the PV potential.

The electrical system has been considered with 20% losses, and the equation for the energy produced by the system each month is:

$$P_{e,month}[m] = \frac{P_{nom}}{1000 * A_c} H_G[m] A_{total} Losses \qquad (kWh) \qquad (12)$$

[m]=Month.

P_{nom}= Nominal collector power, 230 W

H_G=Monthly average daily radiation on the surface of the collector, KWh/m2

A_{total}=Total collector area, m^2

Losses= System losses, 20 %

The electricity outputs,153.6 kWh/m^2, with this method have been compared with the tool PVGIS [56], for estimation of performances of Grid-connected PV, 170.9 kWh/m^2. The electrical outputs of 153.6 kWh/m^2 were chosen because a lower electrical performance, 10 % lower, is expected due to the higher collector temperature producing DHW [60].

6.3 Results and economic assessment

The physical and economical results were analysed, the main goal is the 100% coverage of the building needs for DHW in July and August. Three annual solar fractions have been analysed, 50%, 60% and 70%.

Only the 70% annual solar fraction is able to cover the DHW demand during the most irradiated months in the year. The hybrid collector physical results are shown in **Table 16.** 456 m^2 of hybrid collectors are needed for a 70% annual solar fraction however 400 m^2 of flat plate thermal collector are needed for the same annual solar fraction. Thus the flat plate thermal collector has a 14% higher thermal efficiency than the hybrid collector.

Hybrid 465 m². Annual solar fraction 70%

Month	Demand [kWh]	Solar energy produced [kWh]	Solar fraction [%]
Jan	36667	14625	39.89%
Feb	36667	20285	55.32%
Mar	36667	27066	73.81%
Apr	36667	30426	82.98%
May	36667	36293	98.98%
Jun	36667	35870	97.83%
Jul	36667	36667	100.00%
Aug	36667	35727	97.44%
Sep	36667	27067	73.82%
Oct	36667	23000	62.73%
Nov	36667	13423	36.61%
Dec	36667	10431	28.45%

Table 16 70 % solar fraction with hybrid collector

Solar energy produced vs. demand is shown in Figure 10 for 70% solar fraction considering the hybrid PVT solar collectors. The flat plate thermal collector has similar trends but with a lower amount of collectors.

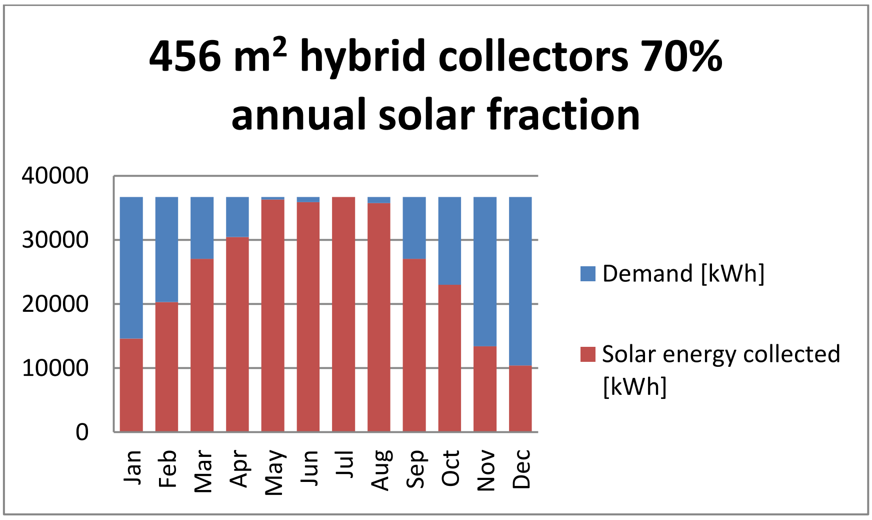


Figure 10 Solar energy produced vs. demand for 456 m² of hybrid collectors

Economic assessment has been performed with data given by the installers companies and economic evaluations from other projects:

Inv_{elsys}=150 €/m^2 is the investment for an electric system including all the components (batteries, connections, inverters…) except the collector [61].

Inv_{thsys}=215 €/m^2 is the investment for a thermal system including all the components (installation cost, insurances, engineering…) except the collector [62].

The investment cost for the hybrid system is the sum of the electric system, the thermal system and the collector price $P_{c,m2}$ per square meter:

$$H_{inv} = P_{cm2} + Inv_{elsys} + Inv_{thsys} \tag{13}$$

The investment cost for the flat plate thermal collector system is the sum of the thermal system and the collector price $P_{c,m2}$ per square meter:

$$TH_{inv} = P_{cm2} + Inv_{thsys} \tag{14}$$

The annual operation and maintenance costs are estimated in 1.5 % (f_{ope}=0.015 $year^{-1}$) of the investment cost. The amortization factor is calculated considering an annual interest rate, i in $year^{-1}$, of 3%. The estimated lifetime is 25 years, ny=25. The number of collectors is N. Therefore the annual costs Z_{hybrid}, $Z_{thermal}$ €/year are calculated with the next equations:

$$A = \frac{i \cdot (1+i)^{ny}}{(1+i)^{ny} - 1} \tag{15}$$

$$Z_{hybrid} = N \cdot H_{inv} * \left(A + f_{ope}\right) \tag{16}$$

$$Z_{thermal} = N \cdot TH_{inv} * \left(A + f_{ope}\right) \tag{17}$$

The solar heat unit cost, c_{solar}, is the annual costs divided by the energy production by the solar system. In the scenario for hybrid collector, all the annual electrical output is used instead of buying electricity from the grid. Thus the electricity is saved with an estimated price for 2016 [58] :

$$C_{solar} = \frac{Z_{hybrid} - P_e \cdot P_{el}}{Q_{col}} \tag{18}$$

The payback period is expressed as the initial investment divided by the energy sold with the estimated energy price in the year 2016 [58]:

$$PB_{thermal} = \frac{Th_{inv}}{Q_{col} \cdot P_g} \tag{19}$$

$$PB_{hybrid} = \frac{H_{inv}}{Q_{col} \cdot P_g + P_e \cdot P_{el}} \tag{20}$$

The project present value for 25 years is calculated considering the summation of the project yearly profit with the estimated energy prices in the future:

$$PV_{Thermal} = TH_{inv} - \sum_{y=1}^{25} \frac{Q_{col} \cdot P_g[y]}{(1+i)^y} \tag{21}$$

$$PV_{hybrid} = H_{inv} - \sum_{y=1}^{25} \frac{Q_{col} \cdot P_g[y] + P_e \cdot P_{el}[y]}{(1+i)^y} \tag{22}$$

The collector efficiency is expressed as the energy produced divided by the irradiation received. The energy produced can be expressed as well per square meter. kWh_e/m^2 is the electricity generated per square meter and kWh_t/m^2 is the thermal energy generated per square meter. The investment per person is the investment divided by the number of people living in the building. The results for different amount of hybrid collector without grant and with a 40% investment grant are shown in Table **17** and Table 19. The results for different amount of flat plate thermal collector without grant and with a 40% investment grant are shown in Table **18** and Table **20**.

Surface	**SF**	**Payback**	**PV [25]**	**n_coll**	**Q_col**	**P_e**	**Investment**	**Investment / person**	**Solar cost**
[m²]	[%]	[years]	[€]	[%]	[kWht/m²]	[kWhe/m²]	[€]	[€/p]	[€/kWh]
296.66	50.34%	15.78	167661	66.15%	746.6	153.6	268441	776	0.05759
374.9	60.88%	16.84	197046	63.79%	714.5	153.6	339239	980	0.06018
456.4	70.65%	18.8	221131	61.34%	681.1	153.6	412986	1194	0.06313

Table 17 Results for hybrid collector without grants

Surface	**SF**	**Payback**	**PV [25]**	**n_coll**	**Q_col**	**Investment**	**Investment/person**	**Solar cost**
[m²]	[%]	[years]	[€]	[%]	[kWht/m²]	[€]	[€/p]	[€/kWh]
263.61	50.98%	11.57	146721	62.52%	850.9	129229	373	0.0419
327.24	60.75%	12.05	168414	60.02%	816.8	160422	464	0.04365
399.96	70.71%	12.65	186693	57.16%	777.9	196071	567	0.04583

Table 18 Results for flat plate thermal collector without grants

Surface	SF	Payback	PV [25]	Investment/person
[m^2]	[%]	[years]	[€]	[€/p]
296.66	50.34%	9.47	274800	466
374.9	60.88%	10.10	332442	588
456.4	70.65%	11.28	385960	716

Table 19 Results for hybrid collector with 40% grant for the investment

Surface	SF	Payback	PV [25]	Investment/person
[m^2]	[%]	[years]	[€]	[€/p]
263.61	50.98%	6.94	198413	224
327.24	60.75%	7.23	232583	278
399.96	70.71%	7.59	265122	340

Table 20 Results for flat plate thermal collector with 40% grant for the investment

The collector performance is shown to be better in the hybrid collector in spite of the fact that thermal energy produced with the flat plate thermal collector is higher.

Only replacement of gas by solar energy is shown in this project because is the most extended energy source used, if fuel oil or electricity are replaced by solar energy the results are even better. With a solar fraction of 70% the flat plate thermal collector has a Payback period of 2.5 years when electricity is replaced and 3.78 years when fuel oil is replaced. The hybrid collector has a Payback period of 4.3 years when electricity is replaced and 5.9 years when fuel oil is replaced. These results are similar to results obtained by Kolaković et al. [63] where gas, fuel oil and electricity were replaced by solar collector to produce DHW.

The present value shows better results for the hybrid collector because the electricity price is estimated to rise more than the gas price.

With the current prices the payback period is better for the flat plate thermal collectors and its solar heat cost is lower than the current gas price (0.046 €/kWh in 2014).

The CO_2 emissions per year in the building sector in the City are 56.99 t CO_2/TJ for natural gas, 71.83 t CO_2/TJ for fuel oil and 323 g CO_2/kWh for electricity [4]. Therefore the CO_2 emissions savings for the building with a 70% solar fraction, replacing natural gas as energy source, are 5266 kg per year using the flat plate thermal collector and 7136 kg per year using the hybrid collector.

6.4 Conclusions

Domestic Hot Water produced by solar energy is shown to be profitable in all the studied scenarios in the expected life of the solar installation.

The best option to install a collector to produce Domestic Hot Water will depend on the energy prices, in this studio a future estimation for price trends has been done in order to clarify which option was better. In Velika Gorica is expected that electricity price will raise more than the gas price thus the hybrid collector should be considered as an option for the production of Domestic Hot Water as the present value is expected to be better. Although the solar heat cost with the flat plate thermal collector is cheaper than the current energy prices.

If the thermal consumption in residential buildings in the City no connected to the district heating system is 59.72 GWh and the Domestic Hot Water consumption of the thermal energy is 31%, then the expected energy to be saved with solar energy in the production of Domestic Hot Water is 12.96 GWh per year considering a solar fraction of 70%.

For a representative building, the CO_2 emissions savings with a 70% solar fraction are 5266 kg per year using the flat plate thermal collector and 7136 kg per year using the hybrid collector.

In this studio an estimation of the solar heat cost has been done. If the company or the City decide to implement the solar energy to produce Domestic Hot Water a deeper, detailed and individual for each building should be done with dynamic simulations in order to know the best design parameters.

7 District-scale use of solar energy: Preheating scenario

One of the targets of the project Beyond Energy Action Strategies (BEAST) [3] is to reduce the greenhouse gas emissions and increase renewable energy sources supply, thus this project is focused on the introduction of the solar energy into the district heating system proving a feasible and profitable scenario.

The use of solar energy to preheat the water in a district heating plant was one of the two proposed scenarios for the use of solar energy at a district-scale.

The evaluated technologies to preheat the water were the flat plate thermal collectors (conventional size and large size)and the photovoltaic-thermal collector, PVT that have already seen in sections 5.2 Flat plate thermal collectors and 5.4 Photovoltaic-thermal collector (PVT). All the aforesaid technologies have been compared and an economical assessment has been made.

Energy storage has not been considered for the preheating scenario, all the energy produced by the collectors is used by the district heating system without any energy overproduction.

7.1 Model description

The preheating scenario model has been done estimating the solar production with a representative day for each month of the year, this model is inspired in the work developed by Guadalfajara et al. [10] but without seasonal thermal energy storage. The collected meteorological data are made for a representative day for each month [7]: Ambient temperature T_a (°C) and irradiance Q_r (Wh/m^2). The return temperature from the district heating system has been estimated to be 30 °C.

The collector data have been obtained from the datasheet issued by the companies. Only PVT collectors which their cost was provided by the companies have been evaluated (see Table 13 in the section 5.4 Photovoltaic-thermal collector (PVT)). The evaluated PVT collectors were: Ecomesh; Powetherm, Sela Solar and Solarus PVT. The evaluated flat plate thermal collectors were: For a small size (conventional) flat plate thermal collector a random collector with a good efficiency has been evaluated: Eborx Eco Classic 2.0 [57]. Arcon Solar HEATstore 35/10 [28] was the large size flat plate thermal collector chosen manufactured by Arcon-Sunmark.

The thermal solar production, Q_{col}[h;m], is calculated hourly using the datasheet efficiency curve, the solar irradiance Q_r[h;m] and the temperature difference among the solar collector T_c and the ambient temperature T_a. Only the positives values for efficiency are considered for the solar production. The solar collector temperature T_c is the average between collector fluid inlet, T_i, and outlet,T_o, temperature. The collector outlet temperature depends on the inlet temperature, the flow rate m_s=55 l/(hm^2) (was recommended by the manufacturers[2]), the specific heat capacity of the fluid C_p=3680 J/(KgK) and its density ρ =1.02 Kg/l (50% propylene glycol). Considering that the mass heat capacity (m_sC_p) of the fluids circulating through the primary circuit (solar collector) and through the secondary circuit (return from district heating) is the same. The inlet temperature depends on the outlet temperature, the heat exchanger efficiency E_{ff} = 0.9 and the return temperature, T_r=30 ºC:

$$Q_{col}[h;m] = Max(A_c \cdot (\eta_0 \cdot Q_r[h;m] - a_1 \cdot \Delta T[h;m] - a_2 \Delta T[h;m]^2); 0) \quad (23)$$

$$\Delta T[h;m] = T_c[h;m] - T_a[h;m] \quad (24)$$

$$T_c[h;m] = \frac{T_i[h;m] + T_o[h;m]}{2} \quad (25)$$

$$T_o[h;m] = T_i[h;m] + \frac{Q_{col}[h;m]}{m_{hc}} \quad (26)$$

$$T_i[h;m] = T_o[h;m] - E_{ff}(T_o[h;m] - T_r) \quad (27)$$

Fluid heat capacity m_{hc} ,W/K, is:

$$m_{hc} = m_s \cdot C_p \cdot \rho \frac{A_c}{3600} \quad (28)$$

η_0, a_1, a_2 are the values for the efficiency curve of the collector and A_c is the surface of the collector.

The above shown equations are solved using Engineering Equation Solver EES [9] to obtain the hourly solar collector production. The monthly production of the solar field $Qcol_{month}$, kWh, is the sum of the hourly production multiplied by the number of collectors N and the number of the days of the month:

$$Qcol_{month}[m] = N \cdot Days[m] \cdot 10^{-3} \sum_{h=1}^{24} Q_{col}[h;m] \quad (29)$$

The annual energy produced per square meter is $Qcol_{year}$, kWh/m^2. The thermal performance, $\eta_{thermal}$, is calculated in annual basis and monthly basis:

$$\eta_{thermal} = \frac{Qcol}{Q_r} \quad (30)$$

To know the electrical power produced by the hybrid collectors, the temperature of the solar collector was estimated to be the same as the temperature of the photovoltaic cells.

The performance of the hybrid collector η_e [h; m], %, depends on the nominal performance η_{ne}, %, the temperature of the cell T_c [h; m], °C, and the temperature coefficient of the electrical performance μ, %/°C. The power output depends on the performance of the

[2] The recommended flow rate by the manufacturers for the hybrid collectors and small size flat plate thermal collector was m_s=55 l/(hm^2), the same mass flow rate was used for the large size flat plate thermal collector because is in the working flow rate range and is a preheating scenario, although large size flat plate thermal collector usually works with flow rates of 20 l/(hm^2) for seasonal thermal energy storage applications [11].

hybrid collector, the surface of the collector A_c, the solar irradiance Q_r [h; m] and the performance factor for PV technology PR (85 %):

$$\eta_{ne} = \frac{P_{nom}}{A_c \cdot I_{est}} \tag{31}$$

$$\eta_e[\mathrm{h;m}] = \eta_{ne} - \mu \cdot (T_c[\mathrm{h;m}] - 25) \tag{32}$$

$$P_e[\mathrm{h;m}] = \eta_e[\mathrm{h;m}] \cdot A_c \cdot Q_r[h;m] \cdot PR \tag{33}$$

The electrical monthly production $P_{e,month}$, kWh,is the sum of the hourly production multiplied by the number of collectors N and the number of the days of the month:

$$P_{e,month}[m] = N \cdot Days[m] \cdot 10^{-3} \sum_{h=1}^{24} P_e[h;m] \tag{34}$$

I_{est}= Irradiance in standard conditions, 1000W/m^2

P_{nom}= Collector nominal power, W

The annual electrical power produced per square meter $P_{e,year}$, kWh/m^2. The electrical performance, η_e , is calculated in annual basis and monthly basis:

$$\eta_{electrical} = \frac{P_e}{Q_r} \tag{35}$$

The collector performance, η_{coll}, is the sum of the electrical performance and thermal performance:

$$\eta_{coll} = \eta_{electrical} + \eta_{thermal} \tag{36}$$

7.2 Results and economic assessment

Grants or financial subsides for renewable energies have not been considered in this studio.

The year irradiation on a 34° tilted surface in the City is 1364 kWh/m^2. The obtained results for each evaluated collector, energy outputs and collector performance are shown in Table 21.

		Thermal features					Electrical features				Collector efficiency
	S absorber	η_0	a_1	a_2	Qcol year	$\eta_{thermal}$	η_{ne}	μ	$P_{e\ year}$	$\eta_{electrical}$	$\eta_{collector}$
Collector	m^2	%	W/(m^{2}K)	W/(m^{2}K^2)	kWh/m^2	%	%	%/ºC	kWh/m^2	%	%
Ecomesh	1.63	0.690	2.590	0.058	694	50.94%	14.11%	0.0038	128.0	9.39%	60.33%
Powetherm	1.42	0.486	4.028	0.067	389	28.49%	10.92%	0.0043	93.0	6.81%	35.30%
M-240 PVT	2.00	0.715	3.176	0.023	835	61.21%	12.00%	0.0043	95.0	6.96%	68.17%
SOLARUS	2.20	0.670	4.800	0.012	553	40.50%	10.45%	0.0043	75.9	5.56%	46.07%
Eborx eco classic 2,0	1.82	0.802	3.800	0.007	722	52.92%	-	-	-	-	52.92%
Arcon solar HEATstore	12.60	0.827	1.118	0.032	929	68.10%	-	-	-	-	68.10%

Table 21 Technical electrical and thermal features of compared collectors

Economic assessment is done as in the previous section 6.3 Results and economic assessment, but in this case the industrial gas price is considered instead of the residential gas price. The industrial gas price is estimated to be 0.0286 €/kWh in 2016 [58]. It has not been possible to know the fuel oil price in the district heating system.

The economical results for the collectors are shown in Table 22.

	Z	Csolar	PV 25 years
Collector	€/m^2 year	€/kWh	€/m^2
Ecomesh	61.41	0.06135	310.1
Powetherm	43.51	0.07688	29.05
M-240 PVT	91.48	0.09288	-333
SOLARUS	44.1	0.05967	206.6
Eborx eco classic 2,0	30.09	0.04168	211
Arcon solar HEATstore	25.3	0.02724	486.6

Table 22 Economic results in a preheating scenario

The M-240 PVT collector has the best collector efficiency of the evaluated collectors but its price is too expensive to be profitable in a real application so a negative present value was obtained. The large size thermal collector, Arcon Solar has the second best collector efficiency and is the most profitable collector even having a lower solar heat cost than the current gas price. The Ecomesh hybrid collector has the third best collector efficiency and is the second most profitable collector depending on the energy prices. The small size collector, Eborx eco classic 2.0, has the fourth best collector efficiency and is the third most profitable collector depending on the energy prices.

7.3 Comparison between the hybrid collector and the flat plate thermal collector

To know which collector is better depending on the energy prices a comparison between the Ecomesh hybrid collector and flat plate thermal collector (Eborx eco classic 2.0 and Arcon solar HEATstore) has been made because are the best evaluated collectors in the previous section. Estimations of future energy prices have been considered to compare the thermal and PVT collector. The profit per square meter that the hybrid collector has over the flat plate thermal collector depending on the energy prices is used for the comparison.

The profit consists in the € per square meter that the hybrid collector has over the flat plate thermal collector. It depends on the annual electrical output per square meter $P_{e,year}$, the electricity price P_{el}, the annual thermal energy harvested per square meter by the flat plate thermal collector $Qcol_{year,thermal}$ and hybrid collector $Qcol_{year,PVT}$, the gas price P_g, the investment in the thermal system TH_{inv}, the investment in the hybrid system H_{inv} and the amortization factor considering an annual interest rate, i in year^{-1}, of 3%.

$$Profit\ \left[\frac{€}{m^2}\right] = P_{e,year} \cdot P_{el} - \left(\left(Qcol_{year,thermal} - Qcol_{year,PVT}\right) \cdot P_g + \left(H_{inv} - Th_{inv}\right) \cdot \left(A_{amc}\right)\right) \qquad (37)$$

Two scenarios were evaluated: (i) a small scale solar field (small scale applications) where the Ecomesh hybrid collector was compared with the small size flat plate thermal collector Eborx eco classic 2.0; and (ii) a large scale solar field (large scale applications e.g. solar plant with seasonal storage) where the Ecomesh hybrid collector was compared with the large size flat plate thermal collector Arcon Solar HEATstore.

It was considered in this studio that all the electricity produced was sold.

7.3.1 Small scale solar field

The Ecomesh collector and Eborx eco classic 2.0 thermal collector were compared to evaluate a small solar field. The profit of the Ecomesh collector over the Eborx collector versus gas price and electricity price is shown in **¡Error! No se encuentra el origen de la referencia.**Figure 11. Green values represent that the profit of the Ecomesh collector is positive over the Eborx collector.

A strong dependence on the electricity price is shown, the higher the electricity price is the higher the profit of the hybrid collector is. The profit of the hybrid collector over the flat plate thermal collector is positive with an electricity price of 0.192 €/kWh, whatever the gas price is. The thermal energy generated by both collectors is similar so the dependence on the gas price is weak and has no influence.

The hybrid collector is shown to be profitable over the thermal collector only for high electricity prices.

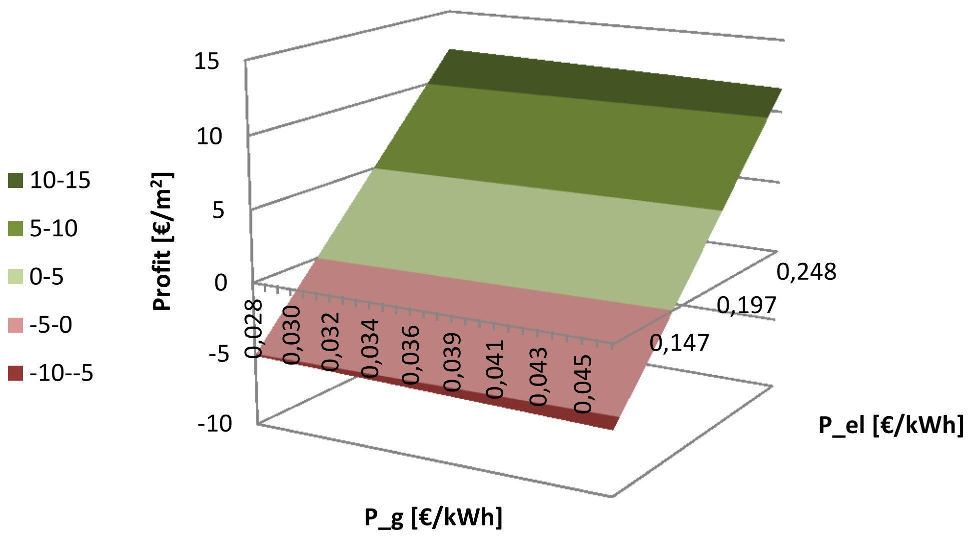


Figure 11 Profit of the Ecomesh collector over the Eborx collector

7.3.2 Large scale solar field

The Ecomesh collector and Arcon Solar collector were compared to evaluate a large solar field. The profit of the Ecomesh collector over the Arcon Solar collector versus gas price and electricity price is shown in Figure 12. Green values represent that the profit of the Ecomesh collector is positive over the Arcon Solar collector.

A strong dependence on the gas price and electricity price are shown. The higher the gas price is the less profitable the hybrid collector is and the lower the electricity price is the less profitable the hybrid collector is. The hybrid collector is a better option than the thermal collector only for very high electricity prices and very low gas prices.

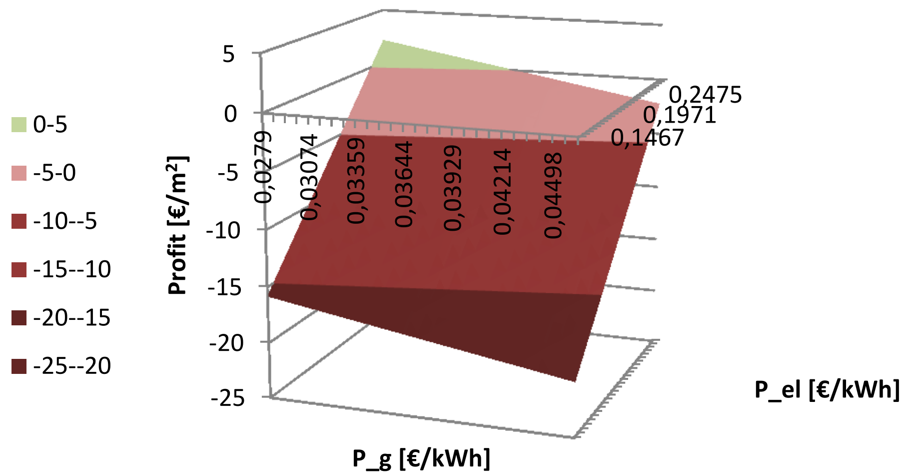


Figure 12 Profit of Ecomesh collector over Arcon Solar collector

7.4 Conclusions

The economical results using the solar energy for preheating the water of a district heating plant have shown in Table 22. The solar heat cost for the large size collectors has been shown to be cheaper than the current energy used for heating (natural gas and fuel oil). Thus a solar field to preheat the water of a district heating plant is a feasible, cheaper than the current system and reliable option to consider.

For large scale solar fields, the large size solar collector as the one from Arcon Solar is the most suitable option because of the higher performance and the lower cost per square meter. The hybrid technology of the photovoltaic-thermal collector PVT should be developed to decrease the collector prices to be a real option for large scale solar fields.

For small scale solar fields, the PVT collector efficiency is higher than the flat plate thermal collector efficiency. PVT collectors are a real option to be considered, though the most suitable option depends on the electricity price (as both collectors have a similar thermal performance, energy price replaced for heating is less important). In the current situation in Velika Gorica, the PVT collector of the brand Ecomesh was more suitable than a flat plate thermal collector of the brand Eborx eco classic 2.0 because of the future price estimation in electricity and gas.

In this studio environmental profit, grants or subsidies for renewables have not been considered. To consider any kind of environmental profit, grants or subsidies for renewables would have shown even better results for the implementation of the solar energy in the City.

These results are an estimation of the solar heat cost for a solar field preheating water in a district heating plant; if the company decides to build a solar heat plant a deeper and detailed studio with dynamic simulations to know the best design parameters should be done.

8 District-scale use of solar energy: Seasonal storage scenario

As part of the aforesaid project Beyond Energy Action Strategies (BEAST) [3], the second proposed scenario for the use of solar energy at a district-scale was a central solar heating plant with seasonal storage.

There are several examples of solar plants using seasonal storage around the world [50]. 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.

To calculate a Central Solar Heating Plant with Seasonal Storage (CSHPSS) there are several options, create a dynamic model with TRNSYS [64] with a high calculation effort and high investment of time or to use a simple calculation method, providing reasonable accurate results for a feasibility study.

There are several simple calculation methods to calculate central solar heating plants with seasonal storage, these methods use simple climatic and demand data and require low calculation effort. Some simple calculation methods are: Lunde method [65]; BKM method [66]; DS method [67]; GLS method [11], [10] and Feasibility evaluation tool [49].

Among the previous referred methods the selected method has been the GLS method (Simple Method), which is a validated method providing good results [68] and allowing the optimization of the CSHPSS. Moreover, the available data in this project are similar to the required input data to this method.

Furthermore the use of the GLS method to estimate the operation of a real CSHPSS plant located in Canada, The Drake Landing Solar Community [69], which uses boreholes as thermal storages, got good results changing appropriately the heat transfer coefficient [70]. Thus this method can be adapted to estimate the behavior of CSHPSS with different seasonal storage technologies. These great results have motivated the use of the Method GLS with a pit thermal storage (PTES) as storage system.

8.1 Model

The Central Solar Heating Plant with Seasonal Storage (CSHPSS) model has been done using the Method GLS (Simple Method) proposed by Guadalfajara et al. [11], [10], [12]. 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.

The system scheme is shown in Figure 13 and identifies the main energy flows that appear in the simple model. 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 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 tank temperature. In a seasonal storage tank, the premise of considering constant the water tank 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.

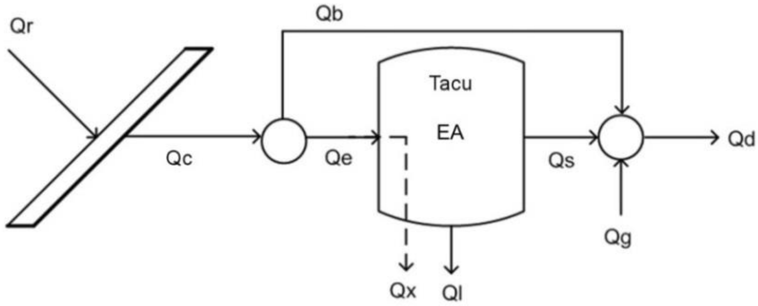


Figure 13 Energy flow chart of the simple model of central solar heating plant with seasonal storage [10]

The monthly operation of the seasonal storage tank has two different operation modes during the year: i) charge and ii) 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 tank 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 thermal accumulated energy in the storage tank is denoted by the variable EA (Figure 13).

As shown in Figure 14 the simple method consists of four sequential modules for the calculation of the annual and monthly performance of a CSHPSS. In base of public data that can be easily obtained the Module 1 elaborates the hourly and monthly climatic and demand data required to calculate the system performance (hourly radiation on tilted surface, hourly ambient temperature, monthly demand…). The Module 2 calculates the monthly production of the solar field based on the hourly radiation and hourly ambient temperature of a typical day for each month, and on the tank temperature at the beginning of the considered month. The calculation of the solar collector is based on the performance equation of the solar collector field. The efficiency equation of the heat exchanger between the primary and the secondary circuits (between the solar field and the seasonal storage tank) is also considered. Each month an energy balance, considering production, demand and losses, calculates the energy charged/discharged/accumulated in the seasonal storage and if required the auxiliary energy, as well as the final temperature of the water in the tank and the heat rejected, in case the storage tank would be fully charged (Module 3). The Module 4 calculates and presents the technical results: annual energy balance, global efficiency of the system and of the considered components, solar fraction, among others, as well as an estimation of the investment, operation and maintenance costs of the system and the solar heat cost.

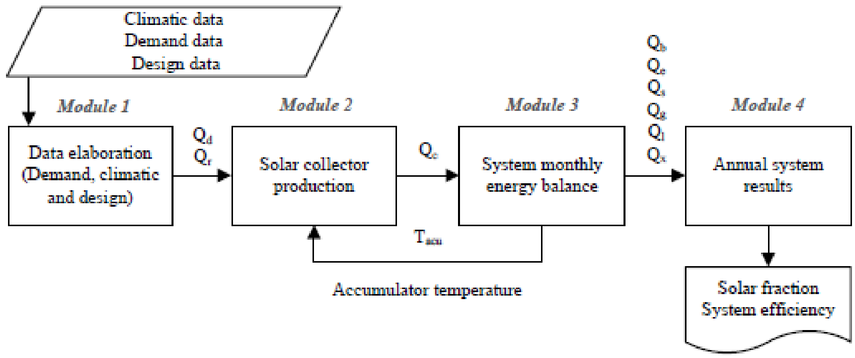


Figure 14 Information flow chart and scheme of the simple method calculation modules [10]

In the case study of Velika Gorica the real demand data of a district heating plant provided by the utility company is used [5] and a representative meteorological day for each month of the year is calculated using Meteonorm software [7]. For the energy balance in the module 3 thermal losses are calculated for pit thermal energy storage instead of tank thermal energy storage. For the economical assessment in the module 4 an own studio is made to estimate the solar investment and solar heat cost because in this studio a pit thermal energy storage is evaluated due to its lower investment cost. As well roof mounted collectors are evaluated in this module 4.

8.2 Design parameters

Available data in Velika Gorica are used, annual and monthly demand for Domestic Hot Water and Space Heating provided by the company [5] (see 3.3 Energy consumption in a district heating plant), the meteorological data has been collected with the Meteonorm software, a representative day for each month of the year is made considering irradiance over horizontal surface and temperatures see chapter 4 Climatic data and solar resources.

The studio is considered in Velika Gorica, to supply part of the thermal demand of a district heating plant which supplies 49.88 GWh per year.

The design variables considered are the next: 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/year); 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), the large size flat plate thermal collectors have been used due to its specific design for CSHPSS, as it has already been explained in the section 5.2 Flat plate thermal collectors; 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_{SH}; temperature of the water returning from the district heating network, T_{ret}; maximum temperature in the seasonal storage (accumulator), T_{max}. see **Table 23**. The rest of the parameters are explained bellow.

	Parameter	Value		Parameter	Value
Solar collector field	RAD: Ratio collector area / demand	m^2/(MWh/year)	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)		T_{max}: Maximum storage temperature	90 °C
	a_2: Heat loss coefficient	0.032 W/(m^2·K^2)		RHB: Ratio lid length and depth	0.16 m/m
	Β: Tilt	34°		$U_{acu,lid}$: Heat transfer coefficient Lid	0.19 W/(m^2·K)
	Θ: Orientation	0°		$U_{acu,walls}$: Heat transfer coefficient walls and bottom	0.276 W/(m^2·K)
	m_s: Mass flow rate	20 l/(h·m^2)		EA_{max}: Max energy accumulated	MWh
	Material used	50 % propylene glycol		Material used	Water
	E_{ff}: Heat exchanger efficacy	0.9	District heating	T_{sup}: Supply temperature	50 °C
Heating demand	Q_d: Annual demand	49877 MWh/year		T_{ret}: Return temperature	30 °C

Table 23 Design parameters

The seasonal storage is assumed as an underground pit thermal storage which is different to the thermal storage tank used by the Simple Method. Pit thermal storage has been used for large size storage systems instead of thermal storage tank because of its lower construction cost, although it has a lower thermodynamic performance than a thermal storage tank. Calculation of heat losses in pit thermal storage is shown below.

8.3 Calculation of heat losses in pit thermal energy storage

The calculation of the heat loss coefficient of a pit thermal storage is a new issue to use the Simple Method. The storage heat losses in a pit thermal storage without an integrated heat pump are between 20-30 % of the delivered solar energy, depending on the storage size [49].

There are two options to the use of the Simple Method for pit thermal storage: i) using the shape proposed by Guadalfajara et al. with a thermal loss coefficient to get a thermal storage performance between 70-80%; ii) using the shape of a pit thermal storage and its thermal losses but with the same equations proposed in the Simple Method.

The calculation has been done considering the pit storage in a steady state where the transitional heat losses are negligible or nil, after 2 to 4 years since built [49], [71], [25].

i) Using shape of cylindrical tank

The Simple method is calculated considering a cylindrical tank with specific dimensions to calculate central solar heating plants with seasonal storage. The use of this method with pit thermal storage requires higher heat losses than the heat losses obtained with a tank in the Simple Method. A new global heat transfer coefficient has been calculated to get thermal losses between 20-30%, depending on the size of the seasonal storage, the new value is U_{tank}=0.62 W/m^2K. The new heat transfer coefficient provides 20-30% losses with a solar fraction of 38-85% of the heat demand, in a design of do not reject heat and use the maximum installed capacity, for this value RAD varies from 0.5 to 1.4 and RVA varies from 1.2 to 4.2.

ii) Using shape of a truncated pyramid

The volume has been calculated as a truncated pyramid using Marstal Sunstore 4 [72] and Marstal Sunstore 2 [25] designs as examples. In Sunstore 4 the pit is slightly rectangular and measures 88 meters by 113 meters at the top, the water depth is 16 meters. The slope of the sides is 1:2 (2 horizontal meters by 1 vertical meter) which means an angle of 26.6° with respect to the horizontal level [73].

The top of the truncated pyramid calculated for the model is square instead of rectangular; the ratio between dimensions is the same as in Marstal designs. The volume of the pit is:

$$V = \frac{h}{3}\left(B_1 + B_2 + \sqrt{B_1 B_2}\right) \tag{38}$$

$$B_1 = B^2 \tag{39}$$

$$B_2 = b^2 \tag{40}$$

$$b = B - 2(2 * B * RhB) \tag{41}$$

B=lid length

b=Bottom length. The slope of the sides is 1:2 (2 horizontal meters by 1 vertical meter) Thus b=B-2*(2*B*RHB)

h=Depth

The ratio between the lid length and the depth is RHB=0.16.

$$RHB = \frac{h}{B} \tag{42}$$

The heat loss coefficient of the lid in a pit thermal storage is $U_{acu,lid}$=0.19 W/m^{2}K [74]. The insulation on the sides and bottom are calculated using the measured temperatures of the surrounding zone of a PTES in Marstal [74], [25]. The temperature of the sensors placed near the pit is shown in the Figure 15.The thermal losses are produced between the water in the pit and the surrounding soil with part of the soil working as insolation.

The temperature at 6.5 meters is stable for sensor “B”, see Figure 15, there is an angle of 63.43° between the lid and the line sensors thus it has been considered that there are 5.8 meters of soil working as thermal insulation from the pit. The thermal conductivity of the soil is 1.6 W/mK [74], thus the heat transfer coefficient of 5.8 meters of soil working as insulation is 0.276 W/ m^{2}K for bottom and walls.

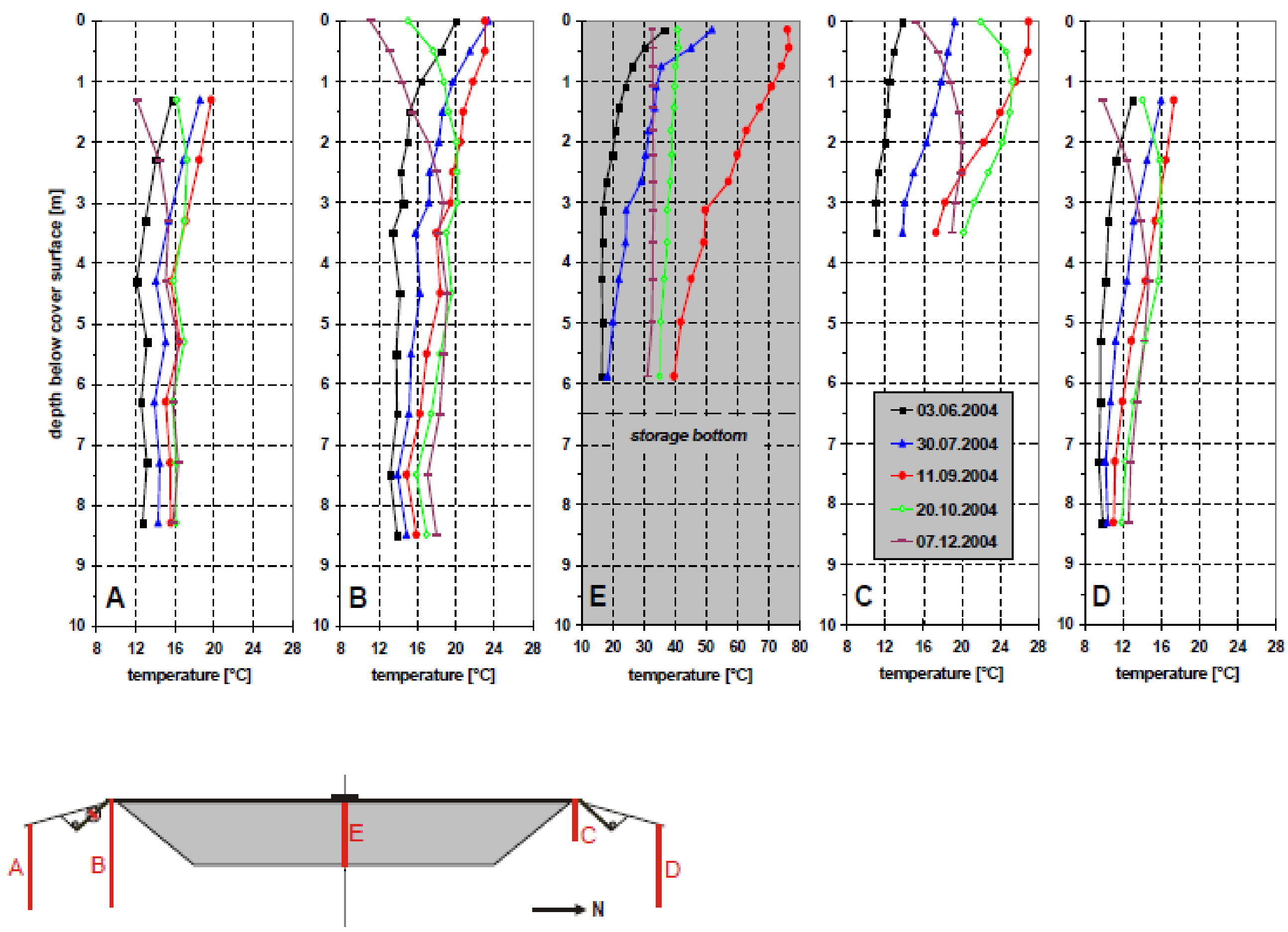


Figure 15 Temperature development in and around the pit heat store [25]

Thus the equation for thermal losses is:

$$Q_l[m] = (U_{acu,lid} \cdot B_1 \cdot (T_{acu}[m-1] - T_a[m]) + U_{acu,walls} \cdot A_{walls} \cdot (T_{acu}[m-1] - T_{grnd}[m])) \cdot 24 \cdot Days[m] \cdot 10^{-6} \quad (43)$$

Where:

T_a = Ambient mean temperature for each month

A_{walls} = The area of bottom and walls of a truncated pyramid

T_{grnd} = The ground mean temperature for each month, [20]

The seasonal storage performance is the extracted energy from the accumulator divided by the inlet energy to the seasonal storage:

$$\eta_{acu,2} = \frac{Q_s}{Q_e} \quad (44)$$

To calculate the thermal losses of the seasonal storage the Simple method has been used in a design of do not reject heat, Q_x=0, and use the maximum installed capacity. The thermal performance of pit thermal energy storage, with the shape of a truncated pyramid, is between 71.3% and 79.7%, depending on the dimensions, for solar fractions between 37.8% and 84.9%, see Table 24. A_total means the area of the solar field, A_top is the area of the accumulator cover and A_walls is the area of the walls and bottom of the accumulator. As the results are the desired results, thermal losses between 20-30%, the second option has been chosen to estimate the thermal losses of a PTES.

RAD	RVA	V	A_total	A_top	A_walls	n_acu_2	SF_y
[m^2/MWh]	[m^3/m^2]	[m^3]	[m^2]	[m^2]	[m^2]	[%]	[%]
0.5	1.3	32420	24939	5502	6067	0.713	0.379
0.6	1.7	50875	29926	7429	8193	0.7474	0.431
0.7	2.3	80302	34914	10072	11106	0.765	0.4889
0.8	2.7	107734	39902	12252	13510	0.7754	0.5439
0.9	3.1	139157	44889	14531	16024	0.7841	0.5995
1	3.4	169582	49877	16578	18282	0.7852	0.6464
1.1	3.6	197513	54865	18352	20237	0.7892	0.6949
1.2	3.9	233424	59852	20514	22622	0.7937	0.7509
1.3	4	259360	64840	22007	24268	0.7978	0.8002
1.4	4.2	293277	69828	23886	26340	0.7977	0.8459

Table 24 Seasonal storage performance depending on size

8.4 Economic assessment

An specific studio to do an economic assessment of solar heating plant with seasonal storage has been done to estimate the solar investment and the solar heat cost. Pit thermal energy storage, ground mounted collectors and roof mounted collectors are evaluated.

The total costs of the solar district heating system encompass:

- Cost of land
- Collectors
- Collectors field installation including piping in the field
- Anti-freeze fluid
- Transmission piping (collector field to heat exchanger unit)
- Heat exchanger unit
- Connection to existing district heating system
- Storage
- Control system
- Design & optimization
- Miscellaneous (e.g. building, ground shaping, fence, assurances, engineering)
- Operation costs.
- Maintenance costs

It has not been considerate the renovation of the actual district heating system (it is a task already proposed by the company).

Cost of land

The cost of land has not been considered as the collector fields should be placed in a public land or in the roof of the buildings without an overrun for the project.

Cost of solar collectors, collectors field installation including piping in the solar field, anti-freeze fluid and Heat exchanger unit

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 Figure 16 and Figure 17 [75]. Prices will typically be between the upper and lower line. The green line is considered as the optimistic prediction of cost and the red line is considered as the pessimistic cost prediction.

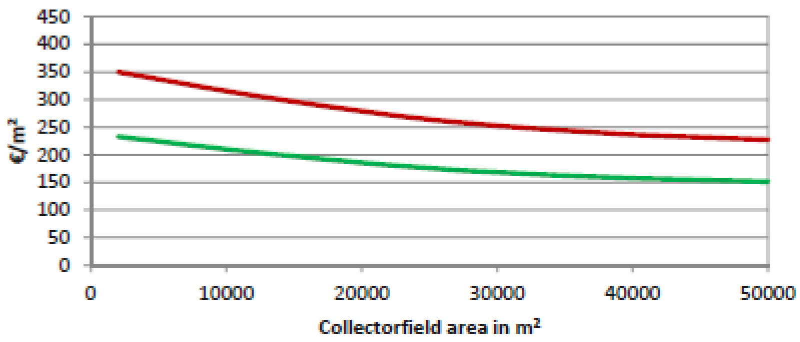


Figure 16 Cost of ground mounted collectors [75]

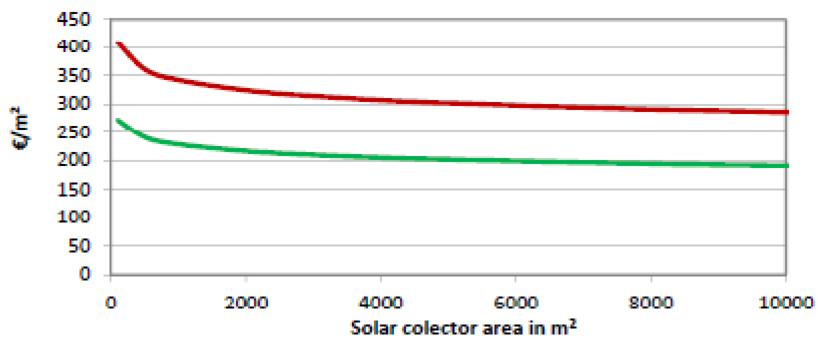


Figure 17 Cost of roof mounted collectors [75]

Cost of transmission piping (collector field to heat exchanger unit) and connection to existing district heating system

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.

If location is known it is recommended to calculate the cost as suggested by Nielsen et al. [75]. An overrun of 10% may cover to install a plant with a distance of 2 km from the connection point.

Storage costs

The cost data of the built pilot and demonstration storages and some studies are shown in Figure 18 [76]. There is a strong cost decrease with an increasing storage volume. Generally TTES are the most expensive ones. On the other hand they have some thermodynamic advantages and they can be built everywhere. The lowest cost can be reached with ATES and BTES but they have higher requirements on the local ground conditions, e.g. additional costs for site exploration and if necessary additional maintenance costs for water treatment in aquifer storages. The investment costs for PTES vary between 40 and 250 €/m^3.

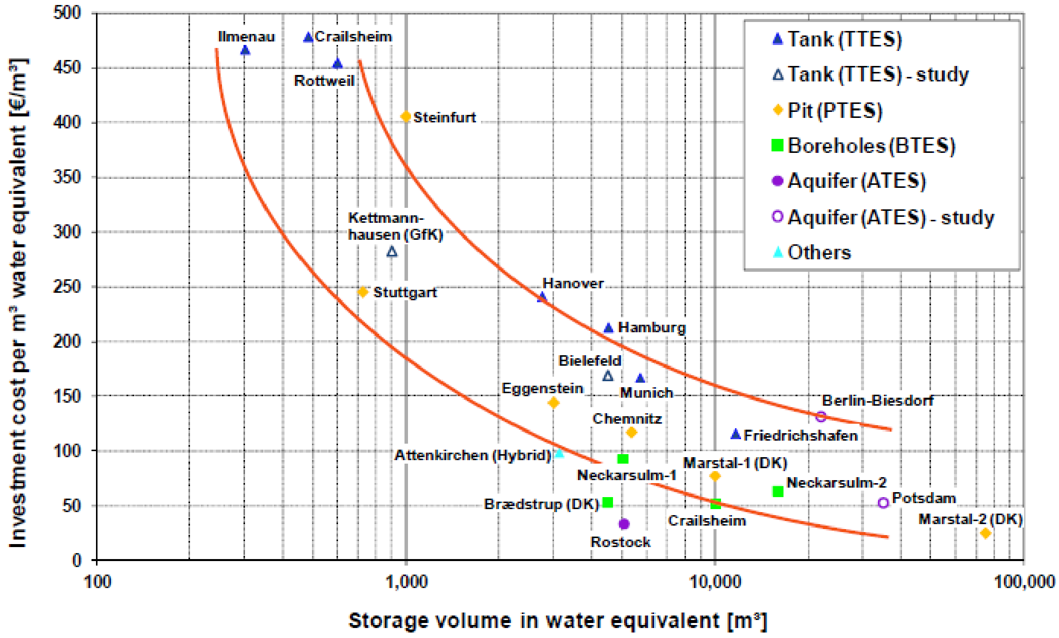


Figure 18 Specific investment cost for STES (without VAT) [76]

Based on the previous figure, a graph for PTES has been made to estimate the cost of the storage volume per m^3. Cost dependence on storage volume for PTES is shown in Figure 19.

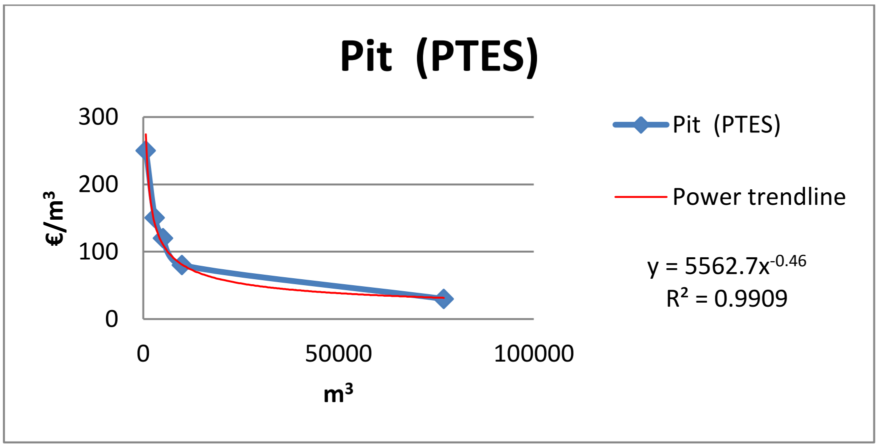


Figure 19 Specific investment cost for PTES

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 even 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 [77].

Control system, design & optimization and Miscellaneous.

The cost of the planning, designing & optimization is approximately 2-5 % of the total investments [75]. The cost of control system and miscellaneous can increase the cost to 12%. So the indirect cost of the project is estimated as an overrun of 12%.

Example of cost distribution in Toring, Denmark, without seasonal storage is shown in Figure 20 [75].

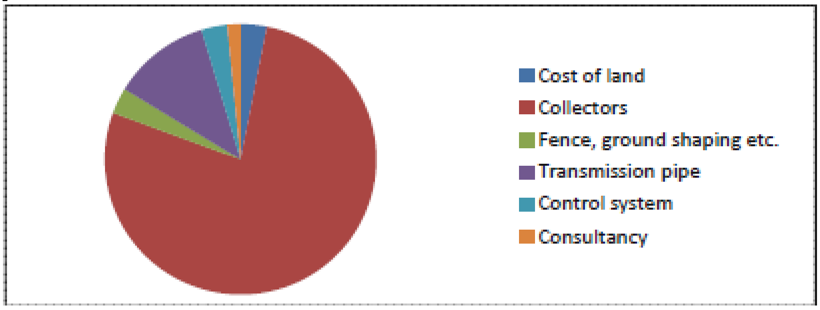


Figure 20 Cost distribution in Toring DK [75]

Operation and maintenance costs

Operation costs and maintenance represents 1.5% of the total investment [78].

8.5 Results and economical assessment

The physical and economical results are analysed in this section. There are 2 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: i) do not reject any heat produced, Q_x=0; ii) reach the maximum usage of the accumulation installed capacity in order do not oversize the storage.

8.5.1 First criterion

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 Figure 21. If RVA is lower than 2.7, the accumulator needs to reject energy Q_x; the accumulator efficiency rises up linearly until a 2.7 m^3/m^2 RVA value, then the efficiency becomes stagnant and for high values of volume (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 a fixed value of RAD=0.8 changing the storage size are shown in Table 25, for an interest rate of 3%. The expectance life time is set up to a technical lifetime of 25 years [77]. C_gr_op means the solar heat cost for an optimistic prediction in ground mounted collectors, C_gr_pess means the solar heat cost for an pessimistic prediction in ground mounted collectors, C_roof_op means the solar heat cost for an optimistic prediction in roof mounted collectors and C_roof_pess means the solar heat cost for an pessimistic prediction in roof mounted collectors, see section 8.4 Economic assessment.

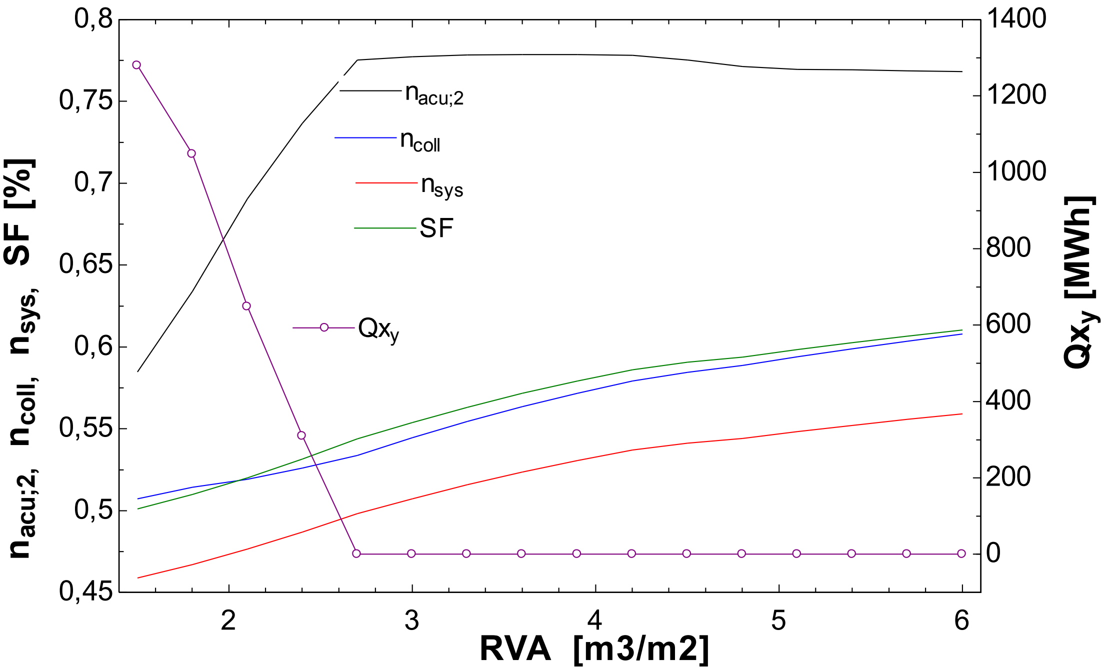


Figure 21 System trends for different RVA values with a fixed collector area

RVA	V	Qx	SF	n_sys	n_coll	n_acu_2	C_gr_op	C_gr_pess	C_roof_op	C_roof_pess
[m^3/m^2]	[m^3]	[MWh]	[%]	[%]	[%]	[%]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]
1,5	59852	1280	0.501	0.4589	0.5073	0.5848	30.6	41.04	33.4	45.43
1,8	71823	1048	0.5098	0.467	0.5142	0.6339	30.94	41.2	33.7	45.52
2,1	83793	649	0.52	0.4764	0.5192	0.6906	31.12	41.18	33.82	45.41
2,4	95764	310.1	0.5315	0.4869	0.526	0.7367	31.17	41.01	33.81	45.15
2,7	107734	0	0.5439	0.4982	0.5338	0.7754	31.13	40.75	33.72	44.79
3	119705	0	0.5538	0.5073	0.5445	0.7773	31.2	40.65	33.74	44.62
3,3	131675	0	0.5631	0.5159	0.5545	0.7783	31.27	40.56	33.76	44.46
3,6	143646	0	0.5716	0.5236	0.5635	0.7786	31.36	40.51	33.81	44.35
3,9	155616	0	0.5792	0.5306	0.5717	0.7785	31.47	40.5	33.89	44.29
4,2	167587	0	0.5861	0.5369	0.5791	0.7781	31.6	40.52	34	44.27
4,5	179557	0	0.5907	0.5411	0.5845	0.7753	31.84	40.69	34.21	44.41
4,8	191528	0	0.5938	0.544	0.5888	0.7713	32.13	40.94	34.5	44.64
5,1	203498	0	0.5984	0.5482	0.594	0.7696	32.33	41.08	34.68	44.75
5,4	215469	0	0.6026	0.552	0.5989	0.7692	32.54	41.22	34.87	44.87
5,7	227439	0	0.6066	0.5557	0.6035	0.7687	32.74	41.37	35.06	44.99
6	239410	0	0.6104	0.5592	0.6079	0.7682	32.95	41.52	35.25	45.12

Table 25 Results of system behavior for a fixed RAD=0.8

The economical criterion in the optimistic prediction for the collector cost is that the best storage size is the lowest possible. But if the volume, RAV, is increased a relative minimum for the solar cost is found when the RVA is 2.7 m^3/m^2 see Figure 22 (left), 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 [10].

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 Figure 22 (right); 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 for RVA=3.9 m^3/m^2 and it is reached in August.

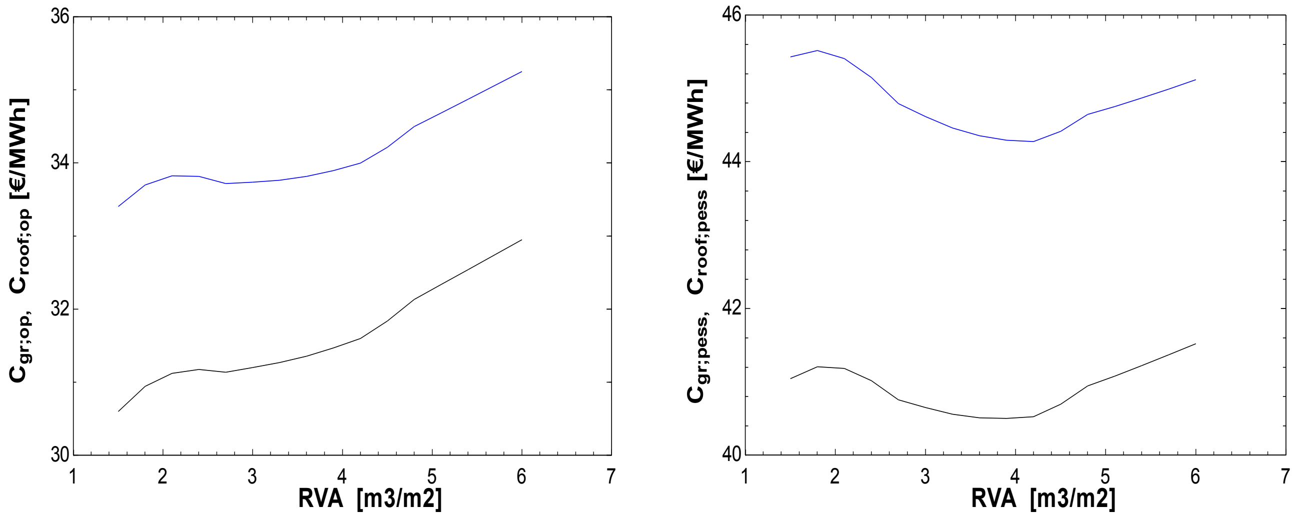


Figure 22 Solar heat cost for a positive (left) and pessimistic (right) prediction

8.5.2 Second criterion

The second criterion is based on the critical volume which follows the next premises: i) do not reject any heat produced, Q_x=0; ii) reach the maximum usage of the accumulation installed capacity in order do not oversize the seasonal storage that could be inefficient.

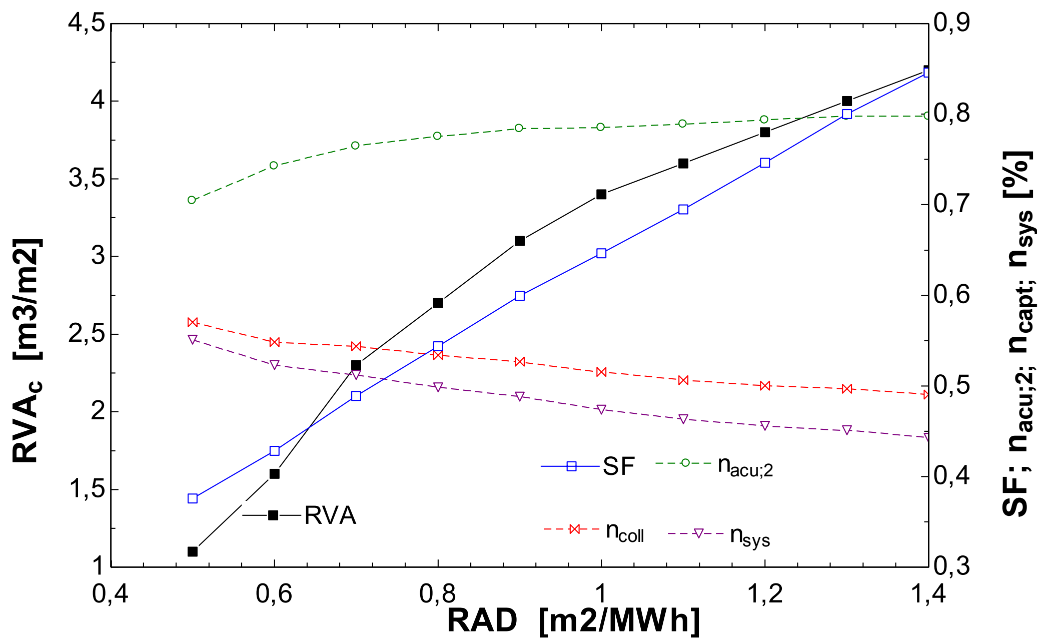


Figure 23 System trends for different solar collector area with critical volume criterion

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 Figure 23. 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 is 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. The results for the system behavior are shown in Table 26.

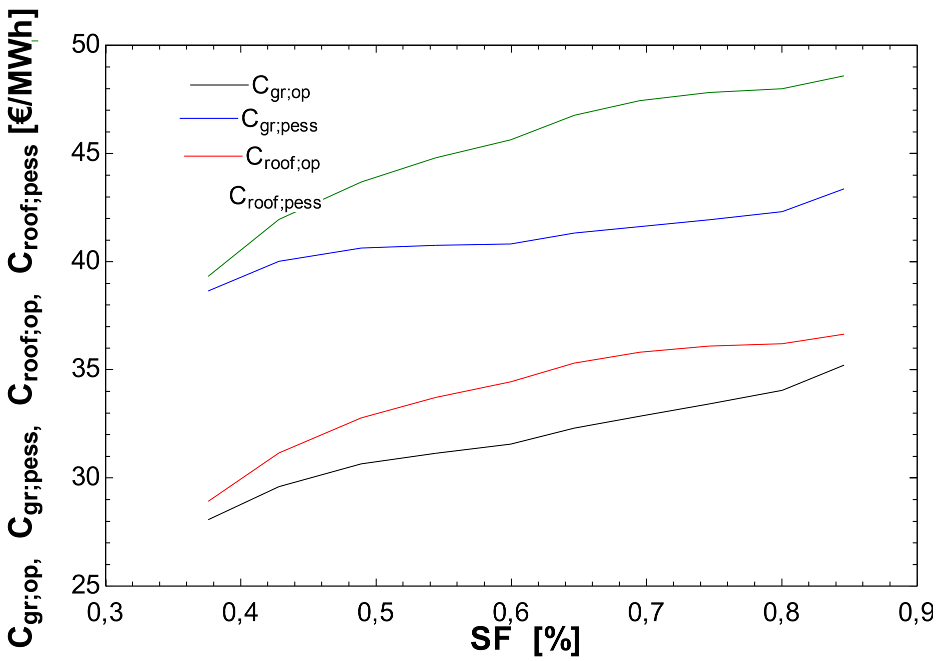


Figure 24 Effect of Solar Fraction in solar heat cost

Economical results for different solar fractions are shown in Figure 24 and Table **26**, for an interest rate of 3% and with the expectance life time set up to a technical lifetime of 25 years [77]. 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 €/MWh for optimistic prediction of the cost of the collectors (C_gr_op) to 38.64 €/MWh for the pessimistic prediction (C_gr_pess); and for a solar fraction of 84.6% varies from 33.42 €/MWh for optimistic prediction to 41.92 €/MWh for pessimistic prediction. For roof mounted collectors, the solar heat cost for a solar fraction of 37.6% varies from 28.92 €/MWh for optimistic prediction of the cost of the collectors (C_roof_op) to 39.32 €/MWh for pessimistic prediction (C_roof_pess); and for a solar fraction of 84.6% varies from 36.45

€/MWh for optimistic prediction to 48.58 €/MWh for pessimistic prediction. These economical results are in concordance with solar heat cost of solar plants installed in Denmark [79].

RAD	RVA	SF	n_acu_2	n_coll	n_sys	C_gr_op	C_gr_pess	C_roof_op	C_roof_pess
[m^2/MWh]	[m^3/m^2]	[%]	[%]	[%]	[%]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]
0.5	1.1	0.3759	0.7046	0.5702	0.5508	28.07	38.64	28.92	39.32
0.6	1.6	0.4282	0.7431	0.5484	0.5229	29.6	40.01	31.15	41.95
0.7	2.3	0.4889	0.765	0.5439	0.5119	30.65	40.62	32.78	43.67
0.8	2.7	0.5439	0.7754	0.5338	0.4982	31.13	40.75	33.72	44.79
0.9	3.1	0.5995	0.7841	0.5269	0.4882	31.56	40.81	34.43	45.63
1	3.4	0.6464	0.7852	0.5153	0.4738	32.3	41.31	35.31	46.76
1.1	3.6	0.6949	0.7892	0.5063	0.463	32.85	41.61	35.81	47.43
1.2	3.8	0.7462	0.7935	0.5004	0.4558	33.42	41.92	36.09	47.82
1.3	4	0.8002	0.7978	0.4969	0.4512	34.04	42.31	36.2	47.98
1.4	4.2	0.8459	0.7977	0.4903	0.4429	35.21	43.36	36.65	48.58

Table 26 Results of the system behavior for different solar collector area with critical volume criterion

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 Table 27. It is shown that the higher the solar fraction is the higher the investment is.

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 €

Table 27 Estimated investment depending on the solar fraction and the solar field predictions

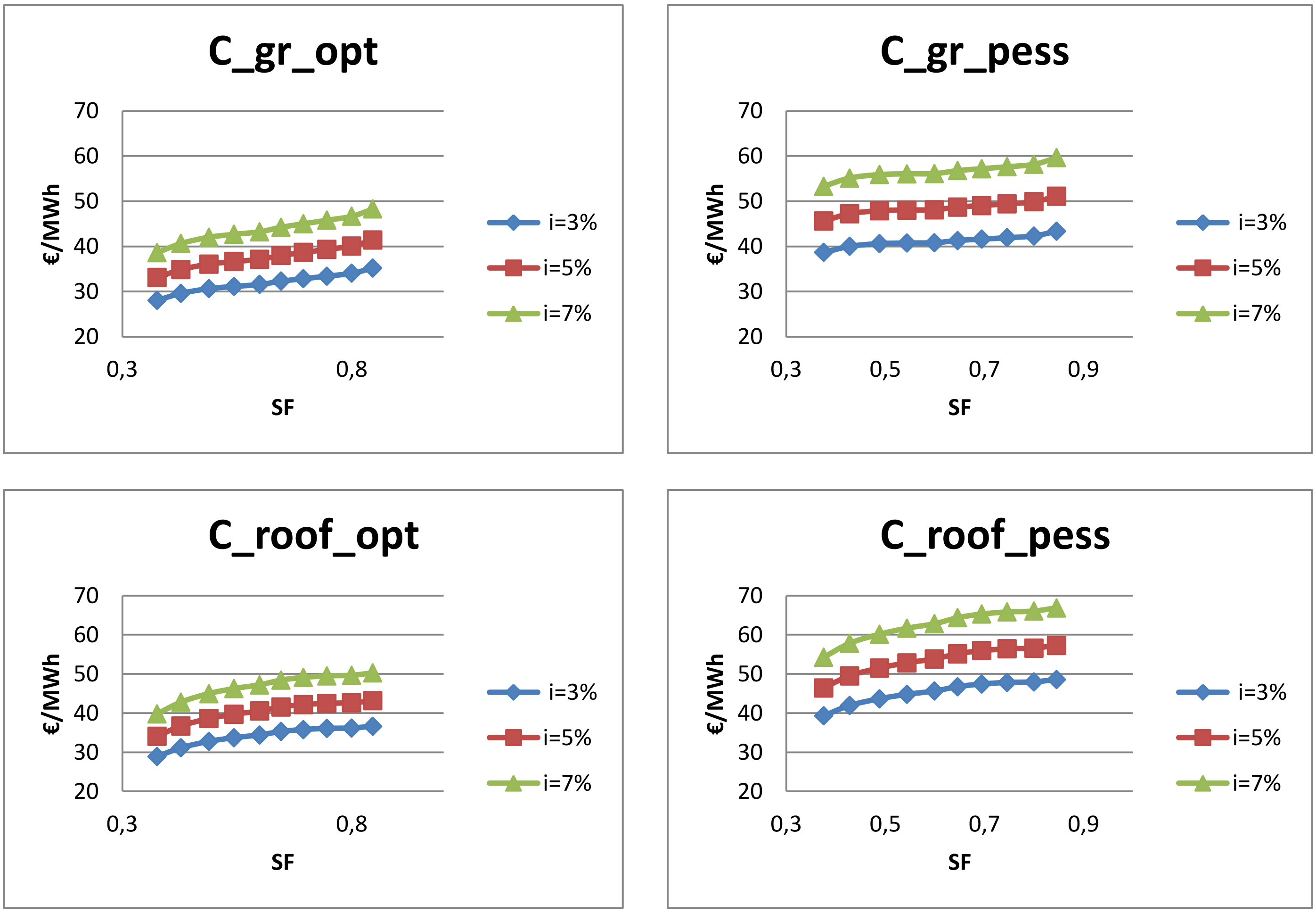


Figure 25 Sensitivity analysis for different interest rates

A sensitivity analysis has been made for different interest rates; results are shown in Figure 25. For an interest rate of 7% solar heat cost with the cost optimist prediction of ground mounted collectors is under 50 €/MWh whatever the solar fraction is and with the pessimistic prediction is under 60 €/MWh. With the same interest rate solar heat cost with the cost optimistic prediction of roof mounted collectors is under 50 €/MWh whatever the solar fraction is and with the pessimistic prediction is under 70 €/MWh.

The prices in Velika Gorica for heating (in the District heating network) in 2011 were 0.42425 Kunas/kWh which means 55.8 €/kWh. It is expected that the prices of energy will increase in the future,see Figure 9, in this studio the solar heat cost has been calculated to be the same during the 25 years of the solar heat plant expecting life time. Thus the solar heat cost of a solar heat plant with seasonal storage is shown to be cheaper than the current prices, even better in the future when the energy prices will continue increasing. Thus a solar district heating plant is a feasible, cheaper than the current system and reliable option to consider.

8.6 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.

The economical results with a critical volume criterion have been shown in **Table 26** (These economical results are in concordance with solar heat cost in Denmark [79]). For all the considered options, ground mounted collectors, roof mounted collectors, pessimistic prediction and positive prediction, the solar heat cost (see Figure 25) is lower than the current energy price in the district heating system, 55.8 €/MWh. Only in the sensitive analysis studio for roof mounted collectors, pessimistic prediction and an interest rate of 7 %, the solar heat cost is more expensive than the current price. Furthermore it is expected that the prices of energy will increase in the future, thus a central solar district heating plant with seasonal storage is feasible, competitive with the current system and a reliable option to consider.

The auxiliary system to provide the required heat to fulfill the demand should be the biomass boiler that the utility company and the City have been studied.

For a reasonable solar fraction of 60% the CO_2 emissions savings replacing the natural gas are 6140.15 tons per year.

In this studio environmental profit, grants or helps for renewables has not been considered. To consider any kind of environmental profit, grants or helps 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 studio with dynamic simulations to know the best design parameters should be done.

9 General conclusions

In this chapter the general conclusions of this project are explained.

The specific thermal consumption in the city was very high (see **Table 1**) thus actions to increase the energy efficiency prior to improve/change the energy supply systems are required, this actions have been proposed in the SEAP [4].

The most energy-consuming sector in the city was the residential buildings sector. For the residential buildings no connected to the district heating system, the proposed scenario has been the production of Domestic Hot Water with solar energy. Domestic Hot Water produced by solar energy has been obtained to be profitable in all the studied scenarios, using flat plate thermal collectors and most of the evaluated hybrid collectors, in the expected life of the solar installation. For a representative building, the CO_2 emissions savings with a 70% solar fraction were 5266 kg per year using the flat plate thermal collector and 7136 kg per year using the hybrid collector. The solar heat cost for the flat plate thermal collector was 0.0458 €/kWh, a lower cost than the cost for heating with the current energies (natural gas, fuel oil and electricity). The potential energy savings producing Domestic Hot Water with solar energy for a 70% solar fraction were 12.96 GWh in the entire City.

The district heating system contains 14 district heating plants which are not connected to each other working with 105 °C as delivered water temperature and 70 °C return water temperature. Thus the district heating network belongs to a high-temperature district heating system that causes high distribution thermal losses in the distribution system, therefore a low-temperature district heating system with 50 °C as delivered water temperature and 30 °C as return water temperature is recommended. Furthermore all but one of the district heating plants are fuel oil operated, resulting in a high level of CO_2 emissions and expensive heat costs, therefore to replace the mentioned energy source is critical and pressing.

When the bigger is the heat demand to be supplied by a solar heating plant with seasonal storage, the lower the solar heat cost is. Thus the integration of the district heating networks into the same network is recommended, as far as possible.

In the district heating networks where its connection in the same district heating network was not possible, see Figure 2, or the seasonal thermal energy storage was unworthy, because it is too small, the water preheating with solar energy of the district heating plant which supplies the mentioned network is recommended. This scenario has been shown to be profitable and feasible, with large size flat plate thermal collectors and 3 % interest rate, the solar heat cost was 0.027 €/kWh, lower than the current industrial gas price.

The implementation of a central solar heating plant with seasonal thermal storage has been studied with the heating consumption of the district heating plant placed in Vidriceva 1. This heating plant is gas operated and represents the 60.76% of the total installed capacity, being the only heating plant which is connected with other neighboring plant.

The central solar heating plant with seasonal storage optimization following an economical criterion was not found to be unique; it depends on the prediction of the solar field 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, thus the best heat solar cost was found when the accumulator efficiency was the highest.

For all the considered options, with a criterion of do not reject energy and reach the maximum usage of the accumulation installed capacity, ground mounted collectors, roof mounted collectors, pessimistic prediction and positive prediction of the solar field cost, the solar heat cost (see Figure 25) was lower than the current energy price in the district heating system, 55.8 €/MWh. Only in the sensitive analysis studio for roof mounted collectors, pessimistic prediction of the solar field cost and an interest rate of 7 %, the solar heat cost was more expensive than the current price.

For a reasonable solar fraction of 60% the CO_2 emissions savings were 6140.15 tons per year, replacing the heating plant operated with natural gas located in Vidriceva 1.

The auxiliary system to provide the required heat to fulfill the demand is recommended to be the biomass boiler that the utility company and the City have been studied and therefore obtain a 100% renewable fraction.

In all the scenarios the hybrid collectors have been evaluated and have been shown profitable. Its use in relation to the flat plate thermal collectors should be considered depending on the energy price estimation, the higher the electricity price was the more recommended was the use of the hybrid collectors. Although for large-scale applications as central solar heating plant, the use of big size thermal collectors was better because of its lower cost per square meter and its better thermal performance.

In all the studied scenarios, the solar heat cost has been shown to be cheaper than the current system. As the conventional energy prices were expected to be increased in the future, the use of the solar energy in the City is a reliable option to consider because the solar heat cost is constant for the expectance life time of the solar installations. Therefore the use of the solar energy in the City is feasible, profitable and cheaper than the current system. Thus the introduction of the solar energy into the City is a proposal from this project to the City and the Utility Company.

In this studio environmental profit, grants or helps for renewables has not been considered. To consider any kind of environmental profit, grants or helps for renewables would have shown even better results for the implementation of the solar energy in the City.

These results are estimations of the solar heat cost, if the utility company or the City decide to implement the solar energy in the City in any of the proposed scenarios, a deeper studio with dynamic simulations to know the best design parameters should be done.

10 Nomenclature

τ = Cover transfer coefficient
α = Absorption coefficient of the absorber
μ = Coefficient of electrical performance, %/°C
a_1 =First coefficient of thermal collector losses, W/(m^{2}K)
a_2 = Second coefficient of thermal collector losses, W/(m^{2}K)
A_c=Collector area, m^2
A_{top} = Area of the lid of the accumulator, m^2
A_{total}=Total collector area, m^2
A_{walls}= Area of bottom and walls of the accumulator, m^2
B = Tilt, °
b= Bottom length, m
B= Lid length, m
$C_{gr,op}$= Solar heat cost with ground mounted collectors and optimistic prediction, €/MWh
$C_{gr,pess}$= Solar heat cost with ground mounted collectors and pessimistic prediction, €/MWh
C_p = Specific fluid heat capacity, J/(KgK)
$C_{roof,op}$= Solar heat cost with roof mounted collectors and optimistic prediction, €/MWh
$C_{roof,pess}$= Solar heat cost with roof mounted collectors and pessimistic prediction, €/MWh
c_{solar}= Solar heat unit cost, €/MWh
Days=Number of days in the month
ε= Heat exchanger efficiency, %
EA_{max}= Max energy accumulated, MWh
E_{ff} = Heat exchanger efficiency, %
f_{ope}= Annual maintenance cost, %/year
F_R=Collector heat removal factor, %
h= Depth of seasonal pit thermal storage, m
H=Monthly average daily radiation on the surface of the collector, Wh/m^2
H_G=Monthly average daily radiation on the surface of the collector kWh/m^2.
H_{inv}= Investment per square meter for hybrid system, collectors included, €/m^2
i= Interest rate, %
I_{est}= Irradiance in standard conditions, 1000 W/m^2
Inv_{elsys}= Investment per square meter for an electric system without collectors, €/m^2
Inv_{thsys} = Investment per square meter for a thermal system without collectors, €/m^2
L=Monthly Domestic Hot Water loads, kWh
Losses= System losses, %
mC_{pc}=fluid mass capacitance rate in collector side.
mC_{pmin}=Minimum mass fluid capacitance rate. It is the same for both sides of the exchanger.
m_{hc}= Fluid heat capacity, W/K
m_s = Flow rate, l/(hm^2)
n = Number of collectors
ny= Estimated lifetime, years
PB_{hybrid}= Payback period for a hybrid system, years
$PB_{thermal}$= Payback period for a thermal system, years
$P_{c,m2}$= Collector price per square meter, €/m^2
$P_{e,year}$= Electricity energy produced by the collector, kWh
P_{el}= Electricity price, €/kWh
P_g= Gas price, €/kWh
P_{nom} = Nominal collector power, W
PR= Performance factor for PV technology, %
PV_{hybrid}= Present value of the project for a hybrid system, €

$PV_{thermal}$= Present value of the project for a thermal system, €
Q_{col}[m]= Thermal energy produced by the collectors, kWh
$Qcol_{year,hybrid}$= Thermal energy produced by the hybrid collector per square meter, kWh/m^2
$Qcol_{year,thermal}$= Thermal energy produced by the thermal collector per square meter, kWh/m^2
Q_d= Annual demand, MWh/year
Q_e= Storage energy in the accumulator, MWh
Q_l= Thermal losses of the thermal heat storage, MWh
Q_r[h;m]= Solar irradiance in tilted surface, W/m^2
Q_s= Extracted energy from the accumulator, MWh
Q_x= Heat rejected from the accumulator, MWh
RAD = Ratio collector area / demand, m^2/(MWh/year)
RHB= Ratio lid length and depth, m/m
RVA= Ratio volume area, m^3/m^2
SF= Solar fraction, %
T_a[h;m]=Hourly ambient temperature, °C
T_a= Monthly average ambient temperature, °C
T_{acu}= Accumulator temperature, °C
T_c= Solar collector temperature and cell temperature, °C
T_{grnd}= Monthly ground temperature, °C
Th_{inv}= Investment per square meter for thermal system, collectors included, €/m^2
T_i= Inlet fluid temperature to the collector, °C
T_m= Mains water temperature, °C
T_{max}= Maximum storage temperature, °C
T_{min}= Minimum storage temperature, °C
T_o= Outlet fluid temperature from the collector, °C
T_r= Return temperature from the district heating, °C
Tref=100 °C.
T_{sup}= Supply temperature, °C
Tw= Domestic Hot Water temperature, 60°C
$U_{acu,lid}$ = Heat transfer coefficient Lid, W/(m^2·K)
$U_{acu,walls}$= Heat transfer coefficient walls and bottom, W/(m^2·K)
U_L= Collector overall energy loss coefficient, W/m^2°C
V= Volume of seasonal storage, m^3
Z_{hybrid} = Annual cost for the hybrid system, €
$Z_{thermal}$ = Annual cost for the thermal system, €
Δt= Difference temperature between collector and ambient, (°C)
η_0= Optical collector efficiency.
$\eta_{acu,2}$= Accumulator efficiency, %
η_{coll}= Collector efficiency, %
η_e [h; m]= Hourly performance of the hybrid panel, %
η_{ne}= Nominal performance of the hybrid panel, %
η_{sys}= System efficiency, %
ρ = Fluid density, kg/l

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Appendix A Energy current situation

In this appendix a further information about the energy consumption in buildings and the action plan for sustainable development of energy (SEAP) in Velika Gorica [1] are presented.

A.1 Energy consumption in public buildings

Data related with the energy consumption in public buildings has been collected. The public buildings in Velika Gorica are: 19 kinder gardens 4 schools, 1 University, 1 folklore area, 1 sport centre, 1 city administration building, 1 fire house and 3 city offices of company owned by the city. The different consumptions for each category of building owned by the city are shown in Table 28, Table 29, Table 30, Table 31 and Table 32.

Thermal energy consumption (kWh) in the category of education and schooling	
heating plant	1117190
natural gas	2618154
fuel oil	2094011
total	5829355

Table 28 Thermal energy consumption in the category of education and schooling

Thermal energy consumption (kWh) of fuel oil in the City Administration building	
fuel oil	285161

Table 29 Fuel oil consumption in the City Administration building

Thermal energy consumption (kWh) in buildings category and city offices of companies	
natural gas	67207
fuel oil	153000
total	220207

Table 30 Thermal energy consumption in buildings category and city offices of companies.

Thermal energy consumption (kWh) by energy source in the category of other public buildings owned by the City	
fuel oil	564761

Table 31 Thermal energy consumption by energy source in the category of other public buildings owned by the City

A.2 Energy consumption in residential buildings

The different consumption for the residential sector is shown in Table 32, there are 5 different sources for this energy, natural gas, fuel oil, heating plant, firewood and electricity. Thermal energy is used for space heating and hot water demand.

Thermal energy consumption in the residential sector of Velika Gorica				
	Heat consumption from its own boiler (kWh)	Heat consumption of the plant (kWh)	Electricity consumption for heating (kWh)	Total
natural gas	42859082			
fuel oil	15489545			
Heating plant		56274570		
firewood	37029193			
electricity			1379448	
total	95377820	56274570	1379448	153031838

Table 32 Thermal energy consumption in the residential sector of Velika Gorica.

A.3 Energy consumption commercial buildings and service activities

The different consumption for the buildings sub-sector commercial and service activities, is shown in Table 33, there are 5 different sources for this energy, natural gas, fuel oil, heating plant, firewood and electricity.

Thermal energy consumption in buildings sub-sector commercial and service activities				
	Heat consumption from its own boiler (kWh)	Heat consumption of the plant (kWh)	Electricity consumption for heating (kWh)	total
natural gas	14556940			
fuel oil	10929600			
CTS		5480660		
firewood	3643200			
electricity			1821600	
total	29129740	5480660	1821600	36432000

Table 33 Thermal energy consumption in buildings sub-sector commercial and service activities.

A.4 Energy consumption summary

A summary of the consumption is shown in Table 34.

Energy consumption buildings sector by sub-sector		
	Heat consumption (kWh)	Electricity consumption (kWh)
Total-buildings owned by the City	7878534	1757291
Residential sector of Velika Gorica	153031838	30906134
buildings sub-sector commercial and service activities	36432000	10120000
Total	197342372	42783425

Table 34 The structure of energy consumption buildings sector by sub-sector.

According to the results of the analysis of the energy in the building sector of Velika Gorica, the most energy consumption is in the residential sector, then the commercial and service sectors and sub-sector buildings owned by the City.

Sources of energy for the different consumptions and sectors are shown in the Table 35.

	Heating plant MWh	**Natural gas MWh**	**Fuel oil MWh**
Total-buildings owned by the City	1562	3219	3096
Residential sector	56274	42859	15489
Buildings sub-sector commercial and service activities	5480	14556	10929
Total consumption MWh	63317	60635	29516

Table 35 Structure of energy source in building sector.

A.5 Actions in the sustainable energy Action Plan

The EU 2020 targets were set to promote a focus on a sustainable future. Until 2020 cutting emissions of greenhouse gases by 20%, reducing energy consumption by 20% through energy efficiency, and meeting 20% of our energy needs from renewable sources has to be achieved.

Sustainable Energy Action Plan (SEAP) accepted by the City Council in 2011 – worked out in cooperation with the Regional Energy Agency of Northwest Croatia (REGEA) is in concordance with the aforesaid EU 2020 targets. Actions related with solar energy are shown in Table 3 [**2**], each action has it estimated cost and it Expected energy saving per year.

Sustainable Energy Action Plan of Velika Gorica				
Sector	Action	Estimated cost [€]	Expected energy saving [MWh]	
Municipal buildings, equipment/facilities	Solar thermal collectors for educational, cultural, administrative and sports municipal institution	152000.00 €	735.33	Heat
	Construction of small photovoltaic systems (30 kw) on the roof of municipal buildings	54000.00 €	210	Electricity
Tertiary (non municipal) buildings, equipment/facilities	Installation of solar systems on tertiary buildings	5641220.00 €	1214	Heat
	Construction of small photovoltaic systems (30 kw) on the roof of municipal buildings	95000.00 €	420	Electricity
Residential buildings	Installation of solar systems in 600 households	454054.00 €	2423	Heat
	Construction of small photovoltaic systems (30 kw) on the roof of municipal buildings	95000.00 €	420	Electricity
	Total	6491274.00 €	5422.33	

Table 36 Actions to develop by the city [2].

The comparison between the Sustainable Energy Action Plan of Velika Gorica and the consumption in the building sector of Velika Gorica in 2008 is shown in Table 37. Thus the aim energy save percentage with the plan is shown.

There is a higher intention of covering the energy demand with renewable sources in the buildings owned by the city, reaching a percentage of 11.95% in the electricity consumption and a percentage of 9.33% in the heat consumption.

Heat consumption means space heating consumption plus hot water consumption.

	Heat consumption (MWh)	Expected energy saving (MWh)	%	Electricity consumption (MWh)	Expected energy saving (MWh)	%
Total-buildings owned by the City	7878.53	735.33	9.33%	1757.29	210.00	11.95%
Residential sector of Velika Gorica	153031.84	2423.00	1.58%	30906.13	420.00	1.36%
Buildings sub-sector commercial and service activities	36432.00	1214.00	3.33%	10120.00	420.00	4.15%
Total	197342.37	4372.33	2.22%	42783.43	1050.00	2.45%

Table 37 The comparison between the Sustainable Energy Action Plan of Velika Gorica and the consumption in the building sector of Velika Gorica in 2008 [2]

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Appendix B, study of technologies

In this appendix a deeper study in the hybrid technology, PVT and seasonal thermal storage is presented. This deeper study has been made to explain and promote understanding of both technologies because they are new technologies and not as widely known as the rest of the technologies presented in the project.

B.1 Hybrid technology, photovoltaic thermal systems PVT

A Photovoltaic-Thermal system (PVT) integrates photovoltaic and solar thermal systems for the co-generation of electrical and thermal power from solar energy. The PVT cogeneration technology offers a solution that actually makes PV systems financially feasible in standard commercial and industrial applications. This combination opens new markets and provides an added value to current solar thermal technologies. Hence, it will further increase the market penetration of solar thermal energy and will bring the European Renewable Energy goals within easier reach [**1**].

The usage of the energy output can be used in different ways. Electrical energy of the PVT can either be used directly or be supplied to the grid while the thermal output depends strongly on the thermal system design and the amount of heat that is extracted by the user.

The usage of the thermal energy for the coverage of domestic hot water (DHW) demand and space heating (SH) demand is studied in this project. The electrical energy will be used by the own building (for lighting or cooling in summer) or sold in the grid.

As mentioned by Zondag [**2**] some advantages by combining the PVT collector will contribute to solve problems such as:

- Electrical efficiency increasing due to the cooling effect.
- Provide more architectural uniformity by aesthetical design and finally minimized the usage of space will reduce the payback period. Calculations made by ECN (Energy research Centre of the Netherlands) within the IEA project showed that by using PVT collectors instead of side by side systems it is possible to reduce the collector area by 40% with the same energy output.
- Improved the total operating efficiency.
- Higher lifetime of the photovoltaic panel because the cells are working in a lower temperature.
- Generation of electricity and thermal energy, finishing a competition that nowadays both technologies have in the roof space usage.

The cost of the system can be assumed to be lower than the cost of a thermal system plus the cost of the PV system, because they have an integrated production, saving materials, saving installation costs, and using less space.

There are different types of PVT collector, Liquid PVT collector, Air PVT collector and PVT concentrator. Among all types of PVT solar collectors, the most popular PVT collector is the Air PVT collector; nevertheless, this type of collector has less application compared to the water collectors [**1**]. The liquid PVT collector is evaluated in this project. Liquid PVT collector seems to be more useful because of the simplicity, the higher number of applications and the higher performance.

Until now, research on PVT has mainly been carried out on the level of module technology. There is also a necessity of developing non-technical issues as: financing issues, testing guidelines, training and education and installation issues. In the PVT Roadmap, an action plan is presented, describing the required actions by each market actor [**1**].

An analysis of PVT technology is shown in Table 38.

Strength	Weakness
• more efficient use of area • easier to install (single system) • easier to market (one product for all) • aesthetic advantage	• reliability not yet optimised (e.g. stagnation temperature resistance) • coupling of 2 dissimilar needs • economics not clear yet • reduced thermal module efficiency
Opportunity	**Threat**
• increase efficiency by dedicated PV • optimise system design (solar cooling, heat pump) • combined subsidy • interesting niche markets (utility, autonomous systems)	• two separate industries required • marketing channels for PV and T are different • industrial involvement is small • standards are lacking • awareness is lacking • practical experience from demonstration projects is lacking

Table 38 Analysis of PVT technology [1]

B.1.1 Liquid PVT collector

Is a PV module which works as the absorber in a flat plate collector, flat plate collector works cooling the PV cells, thus collector turns solar energy into electricity and thermal energy (for example domestic hot water) see Figure 26. This collector could be used in different applications depending of the temperature:

- Low temperature: swimming pool and heat pump applications.
- Medium temperature: domestic hot water [**3**], absorption and space-heating [**4**].

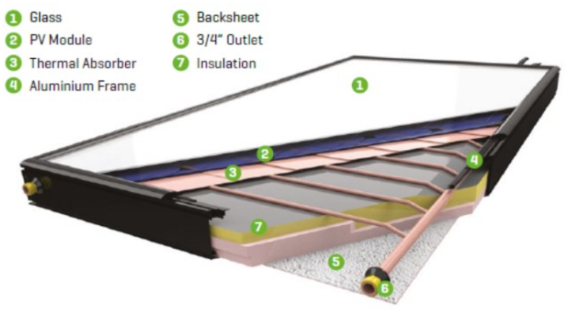

Figure 26 Liquid PVT collector

There is a big amount of different designs and studies for PVT water collector, among the different designs of PVT water collector, the tube and sheet design is the simplest and easiest to be manufactured, even though, the efficiency is 2% lower compared to other types of collectors such as, channel, free flow and two-absorber [**5**]. The PVT collector can be glazed or unglazed, if the end of the system is to use it as heating it is recommended to use a glazed technology although a lower electricity performance.

Market survey

A market survey of the different products for liquid PVT collector is presented in this section. Most of them use water as liquid. Durability of the life cell is one problem for this kind of collector. Most of the manufacturers offer a warranty of 10 years, when the payback is estimated for being between 4-10 years depending on the climatology [**6**]. These collectors are evaluated to be introduced in the district heating system of the City or to produce domestic hot water.

Anaf Solar

Anaf Solar [**7**] is an Italian company manufacturing the H-NRG, which is a combination of Photovoltaic cells combined with a very efficient aluminum thermal collector, a single device which converts solar radiation into electricity and thermal energy at the same time. There was no answer from them to know the prices in the market survey thus it has not been evaluated in this project.

DualSun

DualSun [**8**] is a French company offering a solar collector that produces simultaneously electricity (photovoltaic) and hot water (solar thermal) for homes and buildings. The patented system integrates a photovoltaic panel with a heat exchanger on the back sheet, to produce 2 – 4 times more energy than a traditional photovoltaic panel. They do not give prices directly only to installers so it has not been evaluated in this project.

Ecomesh

Ecomesh [**9**] is a Spanish company. Ecomesh panels differentiate from others for their thermal insulation transparent cover technology that improves global efficiency, recovering the heat that other hybrid panels loose through the front side. This technology has been validated, patented, tested and installed by EndeF Engineering. The company gave the collector cost thus this collector will be evaluated in this project.

Millennium Electric

Millennium Electric [**10**] is a company from Israel. The Multi Solar System (MSS) is their product. Multi Solar System uses air and water pipes to cool the PV cells in order to increase the relative efficiency of the electric system and at the same time produce hot water and hot air which can be channeled for further thermal use. According to their data sheet the total efficiency of the collector can reach 85%, 70% thermal and 15% electrical. There was no answer from them to know the prices in the market survey thus it has not been evaluated in this project.

Sela solar

Sela solar [**11**] is a company from Spain, their product is M-240 PVT., This product is made from a solar thermal collector already created by the company with an integrated photovoltaic module, the glass wool is used as insulation. The company provided the collector cost thus this collector will be evaluated in this project

Solimpeks

Solimpeks [**12**] is a company from Turkey, this company offers collector at very cheap prices. They have 2 products, Volther PowerVolt unglazed, and PowerTherm glazed. The company gave the collector costs and they can be checked online, thus these collectors will be evaluated in this project.

TES

TES [**13**] is a company manufacturing the TESZEUS PVT, and it has 4 different collectors: polycrystalline PVT hybrid collector for 240 W and 280W and monocrystalline PVT hybrid collector for 250 W and 300 W. There was no answer from them to know the prices in the market survey thus they have not been evaluated in this project.

Other companies

There are more companies which have been not possible to contact them as: Power Panel [**14**], HYSOLAR [**15**], Solartwin [**16**]. Sekisui Chemical Co [**17**] is not developing anymore their water PVT collector and the institute Fraunhofer für Solare Energiesysteme ISE [**18**] has a collector in a developing stage.

B.1.2 Air PVT collector

Similar to liquid collector but the air is used as heat transfer fluid. This type of collector has a lower performance than liquid collectors. The level of commercialization is higher than liquid PVT collectors. This product preheats ventilation air, but the main purpose of most of the products is actually to provide dehumidification of the air in cabins, garages houses. The PV cells usually supply a fan in the top of the collector with electricity.

Market survey

A market survey of the different products for air PVT collector has been done, but they are not evaluated in this project because air PVT collectors are more focused on ventilation and only liquid PVT collector is able to be introduced in the district heating system of the City or to produce domestic hot water.

Solar wall

Solar wall [**19**] is a commercial brand produced by Conserval Engineering Inc., The heat energy captured from the PVT modules is ducted into the buildings system, see Figure 27, where it is used to displace the conventional heating load, the secondary benefit is to provide PV cooling by reducing the operating temperature of the PV modules, which improves the electrical performance the total solar efficiency to over 50%.

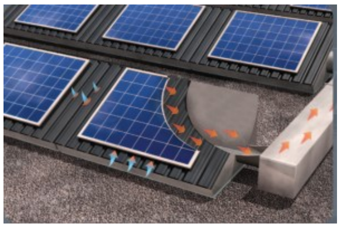

Figure 27 Solar wall PVT air collector

Twinsolar

Twinsolar is a PVT collector with PV over the whole absorber. Due to the safe and independent operation of the Twinsolar [**20**] system, it is ideal for second homes and houses not normally in use. The annual maintenance cost of the independent system at home is only the cost of changing the filter once or twice a year. Air is circulating in the panel, entering and exiting in the same (lowest) side see Figure 28. Hot air is used as ventilation air in the building. For areas between 60-90 m^2 the installation cost is around 64 €/m^2 [**21**].

Figure 28 TwinSolar PVT air collector

B.1.3 PVT Concentrating

It is a concentrating technology that combines photovoltaic (PV) cells to produce electricity, with thermal energy absorption to produce hot water at high temperature.

Market survey

The level of commercialization is the lowest of the PVT collectors. Some products are shown below.

Absolicon X10 PVT

Absolicon X10 PVT [**22**] is a parabolic solar concentrator that focuses the rays from the sun on a central receiver. The trough is covered by a hardened glass that protects reflector and receiver. The product is commercially sold in many countries since 2008. For now, they are not offering the product to clients as they are in a developing stage to adjust their product for mass-producing in a production line-concept, therefore no prices are available and they have not been evaluated in this project.

Power-spar

Power-spar is Canadian company; the modular Power-Spar design enables a choice of energy outputs – PV Electricity – Heat – Co-generated Electricity & Heat or Heat and Light, all from a common manufacturing platform. It has been not possible to contact them, seems to be not available anymore.

Solarus

Recently, Solarus [**23**] has developed a solar panel design that incorporates the photovoltaic to the original thermal system. A PVThermal (PVT) system was by definition a 'combination' system, which produced both electricity and heat from one integrated system using the same surface area see Figure 29. The company provided the collector cost thus this collector has been evaluated in this project.

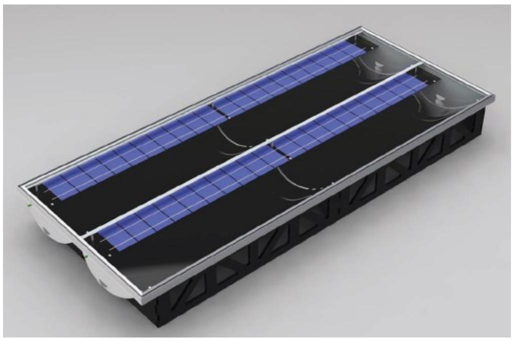

Figure 29 Solarus PVT concentrating collector

B.1.4 Conclusion

The market is similar to conventional solar thermal systems, but the characteristics of different types of solutions make them suitable for different types of customers see Table 39, [**24**].

An overview of benefits of the different PVT design options is shown in Table 40 [**24**].

PVT collectors seem to be a promising option to use in a solar system, thus there were two proposed scenarios for the use of PVT collectors in the City: (i) producing domestic hot water and (ii) preheating water in a district heating plant. In the aforesaid scenarios PVT collectors were evaluated and compared with normal flat plate collectors.

Markets (in order of size)	Type of application	Liquid modules glazed	Liquid modules unglazed	Liquid modules unglazed with heat pump	Air modules glazed	Air modules unglazed	Ventilated PV with heat recovery	PV/T concentrators
Consumers	Domestic hot water	+++						
	Domestic space heating & hot water	+		+++	+			
	Collective hot water	++						+++
	Collective space heating & hot water	++						+
	Pool heating		+++					
Tertiary	Collective hot water	++						++
	Collective space heating & hot water	+		+				+
	Office space heating	+		++	+++	+++	+++	
	Solar cooling				+	+	++	++
	Public pool heating	++	++					
Agriculture	Solar drying				+	+		
	Hot water	+	+					
Industry	Industrial process heat	+	+					+
	Industrial space heating			+		+	+	
	Solar cooling							+

Table 39 Relation between market segments and PVT systems. Future main markets are marked with +++, niche markets with ++ and +, [**24**]

	Module cost	Reliability	Market potential	Building integration	System economics	Aesthetics
Liquid modules glazed			++	+	+	
Liquid modules unglazed		+	+	+	+	+
Air modules glazed	+			+	+	
Air modules unglazed	+	++		+	+	+
Ventilated PV facades	++	++		+	+	+
PV/T concentrators	+				+	

Table 40 Overview of benefits of the different PVT design [**24**]

B.2 Seasonal thermal energy storage (STES)

Thermal energy storage systems (TES) are defined as the temporary storage of thermal energy in the form of hot or cold substances for later utilization. Energy storage can be classified into short-term storage and long-term storage according to different storage durations [25]. Using excess heat collected in the summer to compensate the heat supply insufficiency during the wintertime is the concept of Seasonal Thermal Energy Storage Systems (STES), also called long-term heat storage.

For thermal solar energy, STES becomes important to meet the thermal needs during winter with the overproduction during summer making a higher solar fraction, STES is helpful for balancing between the supply and the demand of energy.

The main types of STES are sensible and latent. Sensible STES systems store energy by changing the temperature of the storage medium, e.g., water. Latent STES systems store energy through phase change, e.g., melting paraffin waxes. Latent STES units are generally smaller than sensible storage units. More compact TES can be achieved based on storages that utilize chemical reactions [**26**], but latent techniques, thermo chemical storages and sorption storages STES systems are not yet ready for the use in seasonal thermal energy storage applications. Sensible STES systems are the most widely used for seasonal thermal energy storage.

B.2.1 Sensible STES systems

There are four storage concepts shown in Figure 30, tank thermal energy storage (TTES), pit thermal energy storage (PTES), borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES) [**27**].

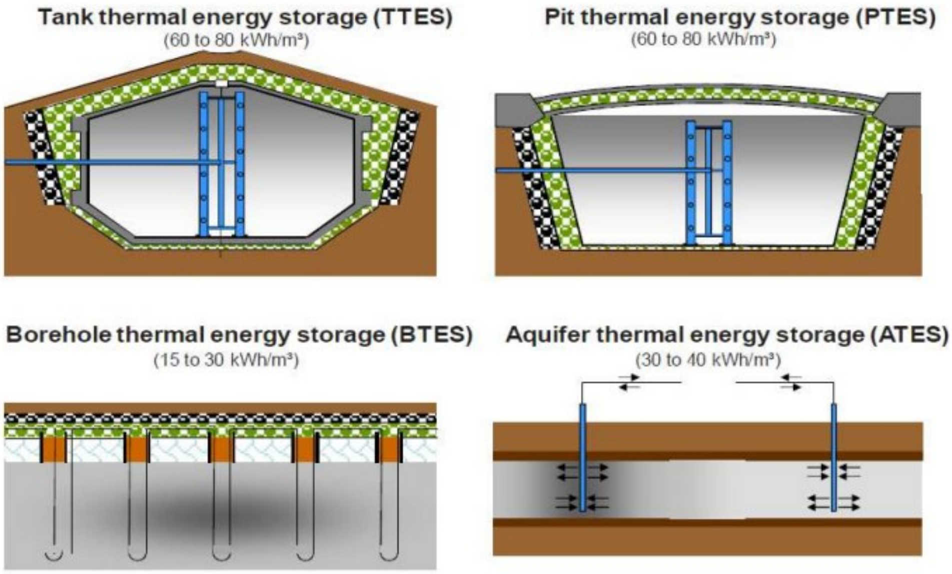

Figure 30 Four sensible thermal energy storage systems [27**]**

Tank Thermal Energy Storages (TTES)

TTES usually have a structure made of concrete, steel or glass fiber reinforced plastic. Because of the high investment cost they are in general only used as buffer tanks with volumes up to 200 m^3. Some above ground large-scale steel storage tanks are available in Austria, Denmark and Sweden [**27**]. It is usually water-filled.

Pit Thermal Energy Storage (PTES)

PTES are built without static constructions. They are entirely buried making insulation in a pit. The lid depends on the storage medium and geometry. The construction of a lid for water PTES requires major effort and is the most expensive part of the thermal energy storage and usually floats on top of the water. In the case of gravel or sand-water storage the thermal capacity is lower. In Denmark there is a big amount of water-filled PTES where Marstal is the largest one with a storage volume of 75000 m^3 [90].

Borehole Thermal Energy Storage (BTES)

In a BTES the underground is used as storage material. Only suitable geological formations as rock or water-saturated soils without natural groundwater flow are able for this kind of thermal storage. Heat is exchanged by vertical borehole heat exchangers (ducts).

Aquifer Thermal Energy Storage (ATES)

Aquifers are below-ground widely distributed and water filled permeable sand, gravel, sandstone or limestone layers with high hydraulic conductivity. They can be used for thermal energy storage if there are impervious layers above and below and no or only low natural groundwater flow. Two wells are drilled into the aquifer layer and serve for extraction or injection of groundwater.

For further information of sensible storage systems and construction details see: [25], [**27**], [28], [**29**], [30] ,[**31**].

Comparison of sensible storage concepts regarding heat capacity and geological requirements is shown in Table **41** [**32**].

Hot-water	Gravel-water	Duct	Aquifer
Storage medium			
Water	Gravel-water	Ground material (soil/rock)	Ground material (sand/gravel…-water)
Heat capacity (kW h/m³)			
60–80	30–50	15–30	30–40
Storage volume for 1 m³ water equivalent			
1 m³	1.3–2 m³	3–5 m³	2–3 m³
Geological requirements			
• Stable ground conditions	• Stable ground conditions	• Drillable ground	• Natural aquifer layer with high hydraulic conductivity (k_f> 1.10 m/s)
• Preferably no groundwater	• Preferably no groundwater	• Groundwater favourable	• Confining layers on top and below
• 5–15 m deep	• 5–15 m deep	• High heat capacity • High thermal conductivity • Low hydraulic conductivity (k_f< 1.10 m/s) • Natural ground-water flow <1 m/a • 30–100 m deep	• No or low natural ground flow • Suitable water chemistry at high temperatures • Aquifer thickness 20–50 m

Table 41 Comparison of sensible storage concepts [**32**]

Seasonal storage in lakes

Seasonal storage in natural or artificial lakes has been studied because in the city of Velika Gorica there is an artificial lake and there is an intention of using it as seasonal thermal storage.

In 1980, the Swedish designer P.Margen suggested a highly original method for medium temperature heat storage. Margen's concept was to create a watertight enclosure floating on a lake, delimiting a volume of water that is stable because it is hot and therefore lighter than the surrounding water (Figure 31) [33].

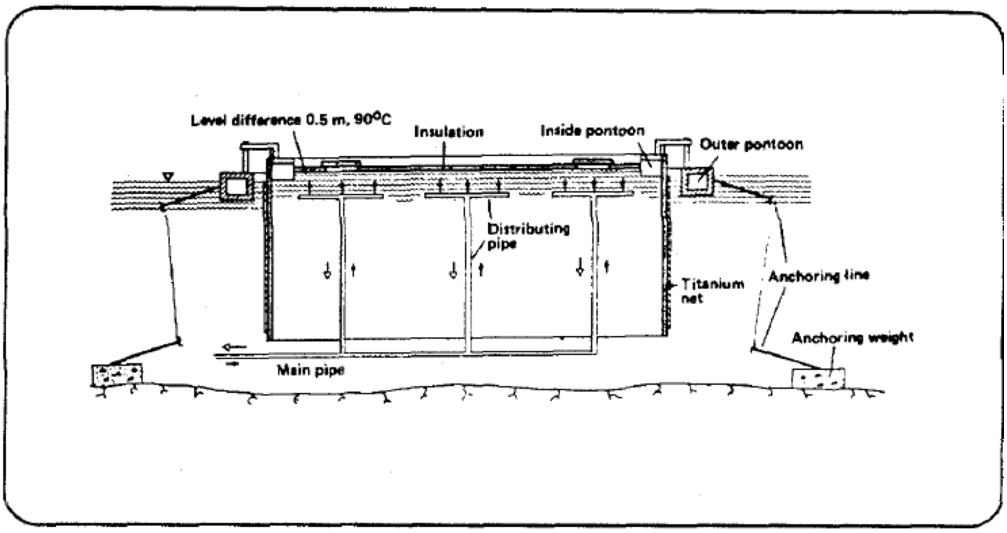

Figure 31 Arrangement for storing hot water in a natural lake [33]

The top and sides of the enclosure have to be insulated so that the temperature of the store can reach 90ºC, Selection of appropriate insulating material for the sides is complicated because the material must withstand pressure and must be submerged in water. The floating structure could be designed as PTES systems.

No projects with seasonal storage in lakes have been found and in a first analysis this technology seems to be more expensive than PTES systems so it has not been taken into account for the new proposals.

On the other hand, apart from the environmental impact problems that large-scale use may entail, natural lakes have many worthwhile possibilities as heat sources for heat pumps, as in Velika Gorica exists an artificial lake there is a great source for heat pumps.

B.2.2 Storage costs

The cost data of the built pilot and demonstration storages and some studies is shown in Figure 32 [28]. There is a strong cost decrease with an increasing storage volume, the investment costs vary between 40 and 250 €/m^3. Generally TTES are the most expensive ones. On the other hand they have some thermo-dynamical advantages and they can be built everywhere. The lowest cost can be reached with ATES and BTES but they have higher requirements on the local ground conditions, e.g. additional costs for site exploration and if necessary additional maintenance costs for water treatment in aquifer storages.

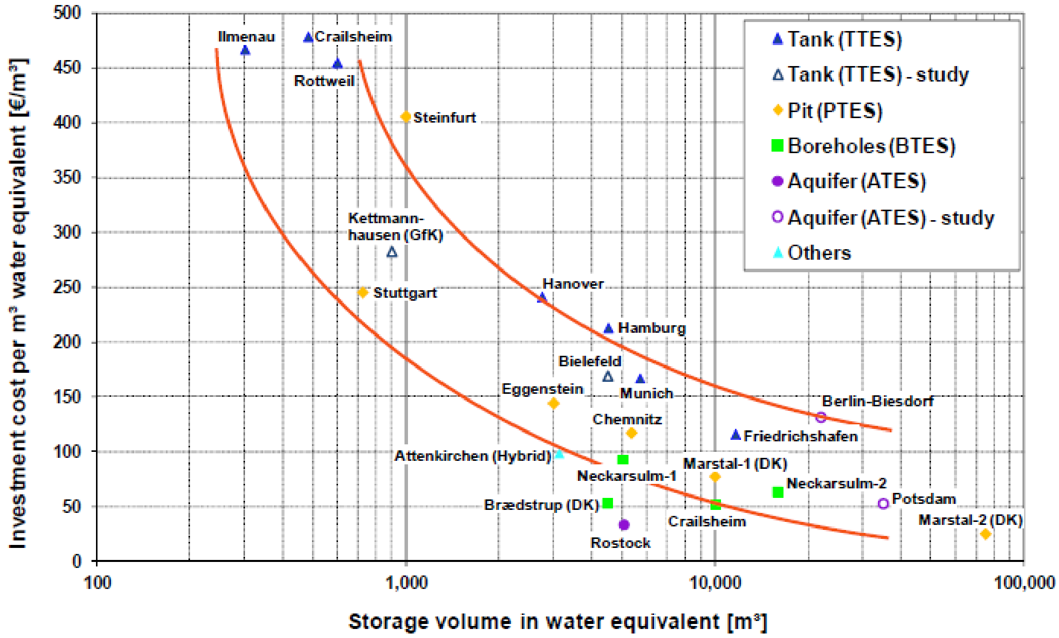

Figure 32 Specific investment cost for STES (without VAT) [28]

Graphs for TTES and PTES have been made separately to estimate the price of the storage volume per m^3. Cost dependence on storage volume for TTES is shown in Figure 33.

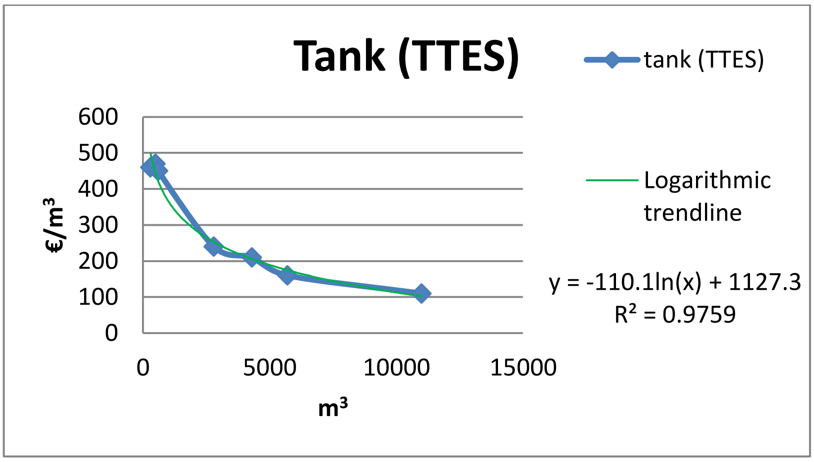

Figure 33 Specific investment cost for TTES

Cost dependence on storage volume for PTES is shown in Figure 34.

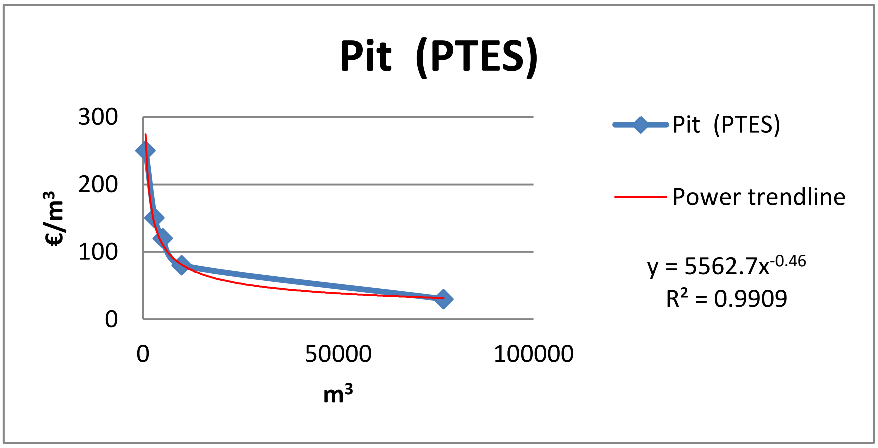

Figure 34 Specific investment cost for PTES

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 even for the heat losses the bigger the tank the better the system is.

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