

Demonstration of German Energy Transition in Zwickau (ZED) - Presentation of Concept

Dimitri Nefodov, Shengqing Xiao, Thorsten Urbaneck
 Chemnitz University of Technology, Department of Mechanical Engineering, Institute of Mechanics and Thermodynamics,
 Professorship Applied Thermodynamics
 09107 Chemnitz
 Tel.: +49 (0) 371 531-31451, Fax: +49 (0) 371 531-8-31451
 E-Mail: dimitri.nefodov@mb.tu-chemnitz.de
 Internet: <https://www.tu-chemnitz.de/mb/TechnThDyn>

Abstract—This paper discusses the general conception of a local district heating system for the implementation of a zero-emission quarter in Zwickau (living lab). The heat supply is to be provided by regenerative energy sources. For this purpose, solar thermal collectors, seasonal thermal energy stores, an electrical energy storage and heat pumps will be utilized.

Concepts of combining solar thermal systems with heat pumps exist for a long time. Therefore, this paper introduces the first two such solar thermal systems in Germany and gives an overview of other similar projects. Subsequently, an overview of the suitable thermal energy stores is provided.

Keywords—collector, district heating, heat pump, living lab, solar thermal, store, water, zero-emission quarter

I. INTRODUCTION

Almost half of the final energy consumption in Europe is required for heat supply [1]. Since the 1980s, the German government has been striving to avoid emissions of harmful gases. These emissions are mostly caused by the combustion of fossil primary energy sources. These can be avoided by using renewable energy sources and increasing energy efficiency.

The project „Demonstration of German Energy Transition in Zwickau“ (ZED) [2] was launched in November 2017 as part of the funding initiative of the BMBF and the BMWi „Solar Building/Energy-Efficient City“ [3]. The aim is to create a living lab in Zwickau (Germany) in the Marienthal district. The demographic structure here plays a special role. A high average age and a high number of single households characterize the situation. Under the given conditions, the following objectives are pursued in the area of energetical district development¹:

- massive reduction of greenhouse gas emissions (transformation into a zero-emission quarter),

- maintaining socially acceptable prices for heat supply and
- ensuring the security and the quality of supply.

II. ANALYSIS OF THE BOUNDARY CONDITIONS

The quarter Marienthal is located in the western part of Zwickau. About 15 % of the urban population live there, i.e. about 13,500 inhabitants. This future living lab for the demonstration of a local energy transition covers about 106 hectares. The buildings available for the project are renovated three- or four-storey GDR-type buildings (Fig. 1) constructed from 1957 to 1964 [2]. A comparison with statistical data (Fig. 2) on the current state of building in Germany shows that most buildings were built between 1949 and 1979. This allows a transfer of the knowledge gained in the presented project to other areas or quarter in the future.

In order to estimate the energetic effect that the project partners intend to achieve by transforming the district heating system, the current status of the heat supply system is here presented. Statistics concerning the use of different energy sources or conversion techniques in the field of heating indicate that heating with natural gas and heating oil are the most common technologies. Statistics on the use of various energy sources and conversion techniques for heat supply (Fig. 3) indicate that heating with natural gas and heating oil are the most common technologies. In Marienthal heat is currently supplied by natural gas-fed heat generators (low-temperature boilers). The space heating is supplied via small-scale local heating networks. The hot water supply is usually provided by electric instantaneous water heaters [2]. The quarter can also be regarded as representative in terms of primary energy use.

¹ This joint project comprises many tasks. Only partial tasks are presented here.



FIG. 1: QUARTER MARIENTHAL IN ZWICKAU, BUILDING TYPE Q23 AFTER RENOVATION

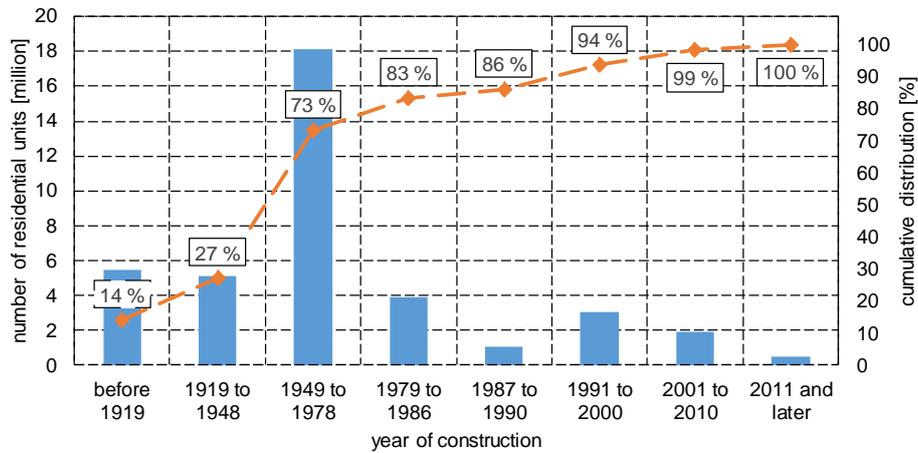


FIG. 2: BUILDING STOCK IN GERMANY BY YEAR OF CONSTRUCTION (SOURCE OF NUMERICAL VALUES [4])

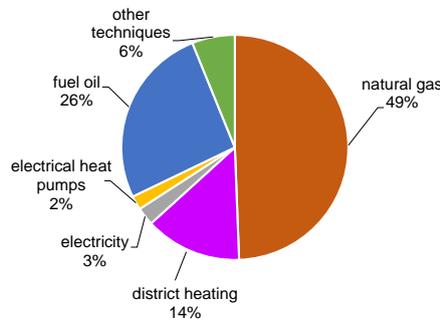


FIG. 3: ENERGY SOURCES AND TECHNOLOGIES FOR HEATING THE RESIDENTIAL PORTFOLIO IN GERMANY 2017 (SOURCE OF NUMERICAL VALUES [5])

Another important issue is the availability of environmental energy or the energy generated (e.g. waste heat) in the district. In recent years, the share of renewable electricity (Fig. 4) has increased continuously. This can be drawn from the public grid. Therefore, it is not absolutely necessary to generate all electric power in the district. With heat pumps and the auxiliary units (e.g. pumps) driven by renewable energy, it is possible to make the entire heat supply

emission-free. The solar radiation and the energy of the environment (e.g. air, soil²) are then available heat sources in the quarter. Other techniques, such as the thermal utilization of biomass, require cultivation areas, transport and conversion in the neighborhood. Furthermore, there are usually no available waste heat sources (e.g. technological waste heat from industry) in such quarters³.

² The use of boreholes requires a relatively large area. The quarter is relatively densely built-up, making

integration difficult. The use of groundwater requires a special geological situation.

³ This investigation is ongoing.

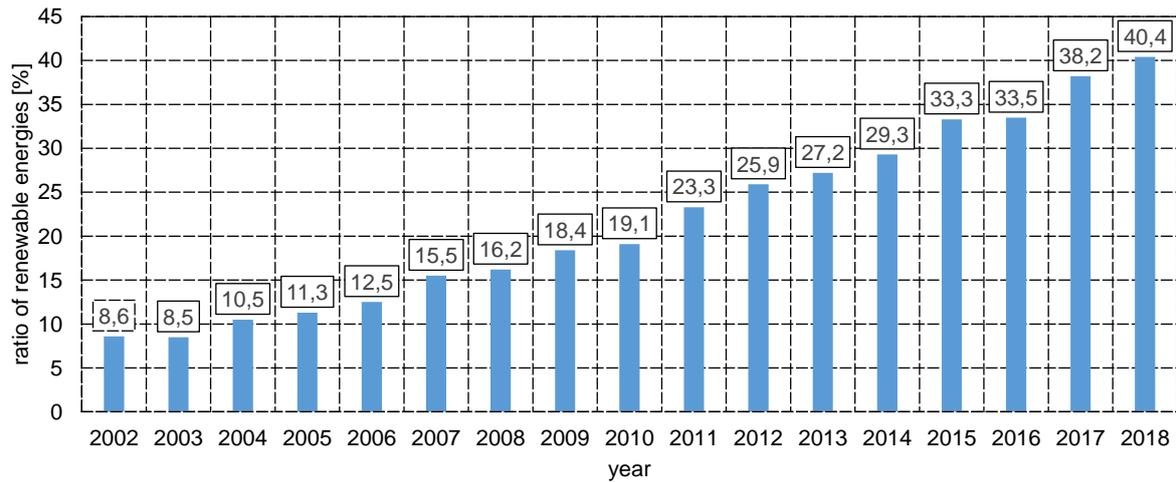


FIG. 4: SHARE OF RENEWABLE ENERGIES IN NET PUBLIC ELECTRICITY GENERATION (SOURCE OF NUMERICAL VALUES [6])

III. PROPOSALS

Three system variants with different approaches to heat supply are evaluated in the project [2]:

- conventional supply system,
- electric-thermal interconnected system with decentralised organisation,
- electric-thermal interconnected system with central organisation.

These three variants will later be compared with each other to test the effectiveness of the approaches.

The conventional system remains unchanged and serves as a reference for the evaluation of the other systems. In the decentralised interconnected system, supply is realized via decentralised components (vessels, heat pumps, collector fields and heat water stores). An intelligent heating network will also be set up. Further information can be found in Leonhardt et al. [2].

In this article, only the electrical-thermal interconnected system with central organization is considered. Fig. 5 shows the system design. The following essential points are planned:

- use of highly efficient collectors to form a large-scale and cost-effective field,
- use of water stores (5...95 °C) with low losses and very good stratification behaviour,

- use of heat pumps,
- securing the local power supply with a redox flow battery⁴.

The following operating modes are provided: With high solar radiation in summer, both water stores TES1 and TES2 can be loaded via collector fields. These function as seasonal heat water stores at a high temperature level to utilize the solar potential during the summer. Discharging in summer and autumn requires no heat pump. In winter, the heat pumps use the heat water store TES1 as a heat source and load the heat water store TES2 with high temperatures. During the winter and transition periods, the collector field operates at low temperatures, whereby the specific yield increases significantly. At low temperatures in the water store TES1, two-stage operation with HP1 and HP2 is planned. The operation of heat pumps depends on the supply of electricity from renewable energy sources. The water store TES2 decouples heat pump operation from heat net load. To drive the heat pumps and auxiliary units, renewable electricity is to be used, which is obtained via the electrical grid or local PV fields.

This concept [7] is based on several preliminary work. The next section contains a brief description of two older solar thermal systems using heat pumps. Some further systems will also be presented and analysed.

⁴ A heat recovery system is planned, which is currently under development.

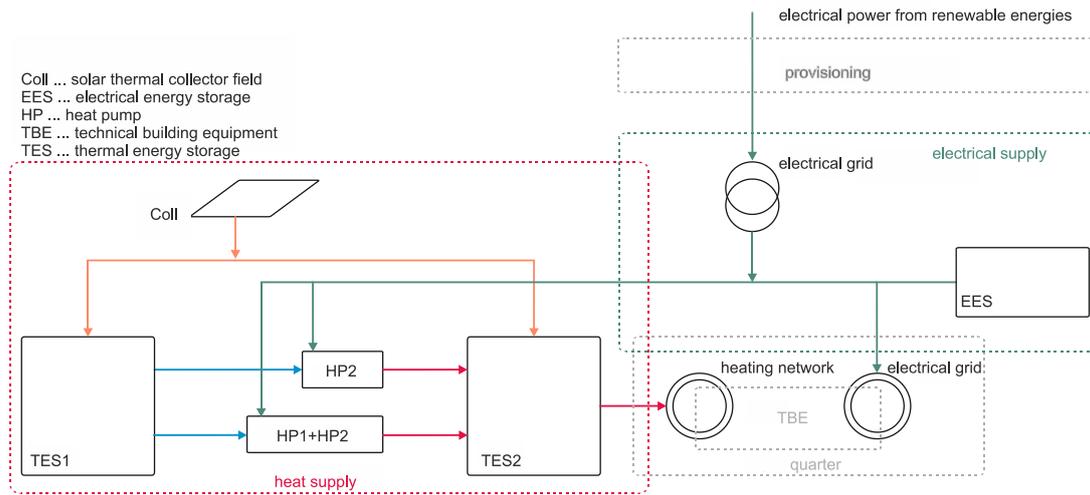


FIG. 5: SCHEME OF THE TECHNICAL CONCEPT AND ENERGY FLOW AS WELL AS BALANCE LIMITS [7]

IV. HISTORICAL HEAT SUPPLY CONCEPTS IN GERMANY

The possibility of supporting the operation of a solar thermal heat supply system with a heat pump has long been recognized. Two projects implemented in Germany are described below.

A. Swimming pool heating in Freyburg/Unstrut⁵

In May 1978, the first outdoor swimming pool heated with solar energy in the former GDR was put into operation in Freyburg/Unstrut. The collectors with an area of 187.2 m² had the task of heating the approx. 300 m² swimming pool during the bathing period. The collectors were oriented at an angle of 45° to the south (Fig. 6) [9].

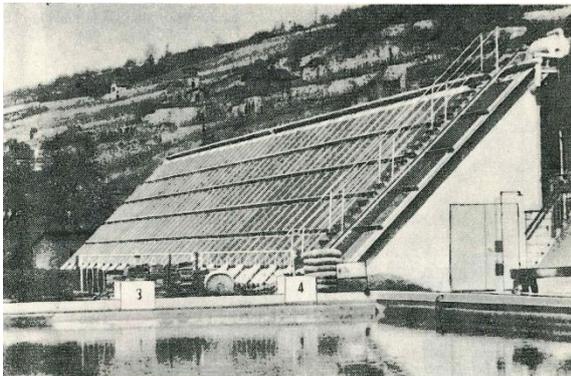


FIG. 6: SOLAR COLLECTOR SYSTEM IN FREYBURG [9]

The plant scheme is shown in Fig. 7 [9]. On sunny days, the output of the solar system was between 50 and 100 kW. The average bathing water temperature during the bathing season was around 21 °C. In Germany, long periods of bad weather often occur in summer. In order to counteract the temperature drops of the bathing water, a heat pump was installed in the system in 1979. In addition to the possibility of parallel operating of the

solar system and the heat pump, separate operation was possible as expected. The heat pump ran mostly in the night (use of off-peak electricity). The temperature of the heat source (well water) was 12 °C. The bathing water inflow temperature thus reached approx. 35 °C. The mean coefficient of performance of the heat pump was about 5.0 [9].

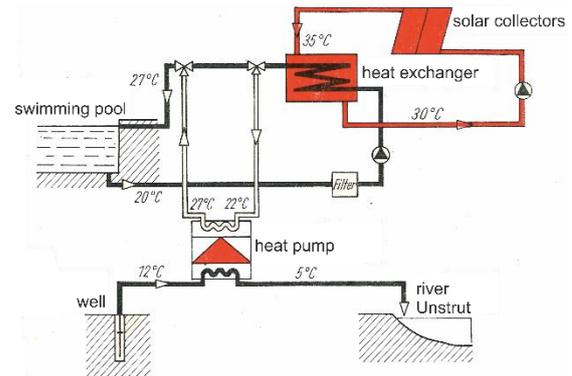


FIG. 7: SCHEME OF THE SOLAR OUTDOOR POOL IN FREYBURG/UNSTRUT [9], MODIFIED

B. Object supply in Stuttgart

The second plant described here was operated at the Institute of Thermodynamics and Thermal Engineering of the University of Stuttgart⁶ [10]. From 1986 to 1988, the system functioned as a solar heating system. The pilot plant (Fig. 8) heated a effective area (office / laboratory building) of 1375 m². From 1990 to 1992, this system served as a combined heating and cooling system. At this point the heating system is of particular interest. It consisted of unglazed collectors (metal absorbers) with a total area A_{Coll} of 211 m², the first gravel-water store with a volume V_{TES} of 1050 m³ and an electric heat pump with a thermal output of 66 kW. The heat supply was secured by local heat feeding from the cogeneration plant. In the design state, the

⁵ cf. Schabbach [8]

⁶ At present IGTE (Institute for Building Energetics, Thermotechnology and Energy Storage)

researchers/planners set a flow/return temperatures of 50/40 °C for the building heating at -14 °C outside temperature [10].

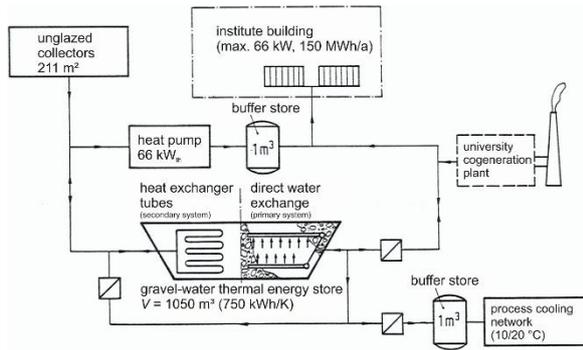


FIG. 8: SCHEME OF THE PILOT PLANT IN STUTTGART [10], MODIFIED

The heating was basically realized with the heat pump. An almost continuous monovalent heating was possible for the local system. The annual performance factor of the heat pump in the period considered was approx. 2.8 and 3.1. The collectors or the gravel-water store served as heat sources for the heat pump. The gravel-water store was loaded by the collectors when

the heat pump was out of operation. When testing the night reduction to save energy, the post-heating had to be done by the cogeneration plant. Not enough heat could be provided in the morning [10].

Most of the heat was provided by the gravel-water store (about 90 %). The mean store temperature ranged between 0.5 °C and 33 °C. The heat transfer medium in the buffer store with a volume of 1 m³ had approximately the net flow temperature. Solar fractions between 50 % and 61.2 % could be achieved [10].

V. SOLAR-ASSISTED HEATING SYSTEMS WITH HEAT PUMPS, INTERNATIONAL OVERVIEW

Over the last decades, apart from decentralized solutions (previous section), a huge number of large-scale solar systems (e.g. as solar district heating systems) have been realized. Table 1 shows an exemplary selection of systems in which solar-assisted heating systems were used in combination with heat pumps. Borehole thermal energy stores and pit stores dominate here as a design for the seasonal heat stores. These constructions have the advantage that the surrounding soil can serve as an additional heat source.

TABLE 1: OVERVIEW OF REALISED PROJECTS USING A COMBINATION OF SOLAR COLLECTORS, THERMAL ENERGY STORES AND HEAT PUMPS

location	year	energy demand (MWh/a)	collector		storage			solar fraction (%)	heat pump power (kW _{th})	references
			type	area (m²)	type	volume (m³)	volume w.e. (m³)			
Anneberg, SE	2000	1080	FC	2400	BTES	60000	15000 ^a	70	N/A	[11], [12]
Attenkirchen, DE	2002	487	FC	800	HWTES BTES	500 9850	7300	55...74	N/A	[13], [14], [15]
Crailsheim, DE	2007	4100	FC	7500	BF BF BTES	100 480 37500	10000	50	530	[13], [16], [17]
Eggenstein, DE	2008	910	FC	1600	GWTES	4500	3000	40...62	60	[12], [13], [17], [18]
Freyburg/U., DE	1978	-	FC	192-200	-	-	-	-	150	[9]
Lambohov, SE	1980-1993	833.3	FC	2700-2900	HWTES	10000	7000 ^a	37...70	N/A	[19], [20]
Rostock, DE	2000	497	FC	980-1000	ATES BF	20000 30	5000	62	110	[13], [25]
Stuttgart, DE	1985	150	uFC	211	GWTES	1050	730	59...60	66	[10], [25]
Toftlund, DK	2017	28000	N/A	25000	HWTES	80000	56000 ^a	35	N/A	[21], [22]

^a own estimation

Table 2 provides an overview of the demarcation between previous projects and the ZED project. The main differences describe the following points [7]:

- inclusion of power supply at district level (e.g. mobility),
- very high share of renewable electricity (purchased from third parties),
- use of a water store (probably flat bottom tank, two-store system) as a seasonal storage and heat source,
- integration of heat recovery of an electrical storage system,
- thereby new complex plant management.

The system is to supply an existing quarter. This means that no significant conversion measures in buildings are planned (e.g. increase in structural thermal insulation). Therefore the heat pumps have to

take over especially in the winter months and bridge relatively high temperature differences between heat source and sink.

TABLE 2: MATRIX WITH SYSTEM AND STORAGE CHARACTERISTICS FOR DIFFERENTIATION

	DHW heating	space heating	geological conditions	solar cover ratio	storage system	storage losses	complex storage management	complex system management	coupling with power supply	use of el. storage
Solarthermie2000(plus) [23], [24]	✓	✓		up to approx. 50 %	one-	moderately				
Attenkirchen [13], [14]	✓	✓	✓	up to approx. 55 %	two-	low	✓			
Drake Landing [26]		✓	✓	up to approx. 99 %	(one-)	moderately	✓			
Danish systems [21], [22]	✓	✓	✓	up to approx. 50 %	one-	high		✓	✓	
ZED (central system)	✓	✓		up to approx. 99 %	two-	low	✓	✓	✓	✓

VI. KEY FIGURE ANALYSIS OF SOLAR HEATING SYSTEMS

Key figures are suitable for the pre-dimensioning and comparison of solar thermal systems⁷. Fig. 9 shows the solar fraction as a function of the ratio of storage volume to collector area (database Table 1). Due to the design, borehole thermal energy stores (BTES) covers a very wide range of 1.3 to 9.0 m³/m², with a solar fraction of 50 to 70 %. It should be noted that the sharp increasing of the storage-collector ratio does not significantly improve the solar fraction. In the range between 1.8 and 3.0 m³/m² hot water thermal energy stores (HWTES) and gravel-water thermal energy stores (GWTES) are comparable due to similar constructions and operating regime. The solar fractions are 35 to 60 %. Due to the high geological requirements, the aquifer thermal energy store (ATES) is only used in one system. Here the key figure is 5.0 m³/m². This figure is in the same range as the borehole thermal energy store. In reality, it must be taken into account that the absolute storage volumes can be significantly higher than volumes in water equivalent.

Furthermore, key figures must be formed that take the annual heat requirement Q into account. The store volume related to the annual heat demand also covers a large area. The course of the curves is flat too. Hot water thermal energy stores and conditionally gravel-water thermal energy stores can be operated with higher storage temperatures. Compact storage constructions and better insulation solutions lead to lower heat losses. Systems with aquifer thermal energy stores (in accordance with Table 1) provide a lower solar fraction compared to borehole thermal energy stores. The heating demand in relation to the collector area (Fig. 11), however, is in a relatively narrow range between 0.9 and 3.5 m²/(MWh/a) for all systems.

Based on these considerations, an average storage volume of up to 10 m³/(MWh/a) water equivalent and a collector area (flat collectors) of 2 to 3 m²/(MWh/a) should be selected. The maximum solar fraction to be expected is then below 70 %. In order to achieve higher solar fractions economically, other concepts must be included.

⁷ Key figures hide many influences (e.g. heat losses of the storage tank, temperature level of the heating system). Therefore, the presented key figures are to be

regarded as reference values and criteria for a rough analysis.

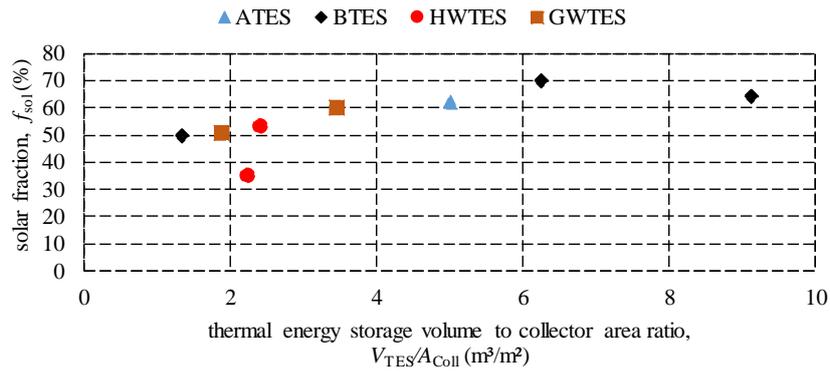


FIG. 9: SOLAR FRACTION AS A FUNCTION OF THE RATIO OF STORAGE VOLUME AND COLLECTOR AREA FOR VARIOUS LARGE-SCALE STORAGE TANK TECHNOLOGIES IN COMBINATION WITH HEAT PUMPS (DATABASE TABLE 1)

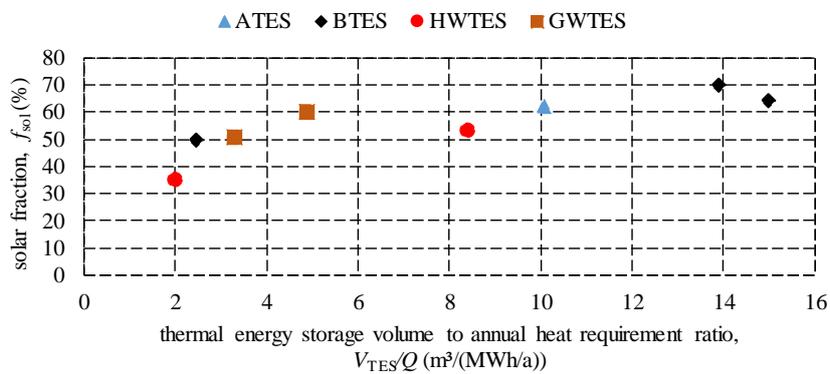


FIG. 10: SOLAR FRACTION AS A FUNCTION OF THE RATIO OF STORAGE VOLUME TO TOTAL ANNUAL HEAT REQUIREMENT FOR VARIOUS LARGE-SCALE STORAGE TANK TECHNOLOGIES IN COMBINATION WITH HEAT PUMPS (DATABASE TABLE 1)

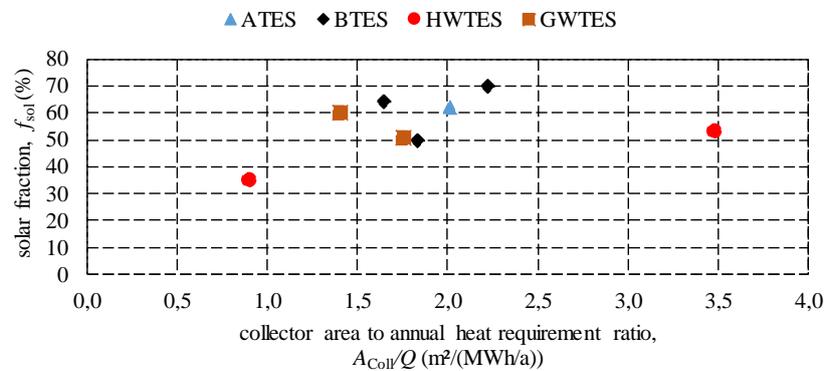


FIG. 11: SOLAR FRACTION AS A FUNCTION OF THE RATIO OF COLLECTOR AREA TO TOTAL ANNUAL HEAT REQUIREMENT FOR VARIOUS LARGE-SCALE STORAGE TANK TECHNOLOGIES IN COMBINATION WITH HEAT PUMPS (DATABASE TABLE 1)

VII. FURTHER CONSIDERATION OF STORAGE TECHNOLOGY

The geological conditions in the district were not investigated in detail. Aquifer, cavern and borehole thermal energy stores are out of the question due to the district development and the surroundings. The pit and tank design are left over for the construction of relatively large stores. Pit stores can be unobstrusively

accommodated in the environment, but require a large surface area. In this case, the installation costs are higher than for tank storage facilities.

Fig. 12 shows the different designs of tank storage. Further information can be found in [27]. In [27] the economic efficiency in connection with the storage construction and the operating temperatures is further discussed.⁸

⁸ The often found volumetric consideration of storage costs in relation to the storage volume in $\text{€}/m^3$ does not provide sufficient information.

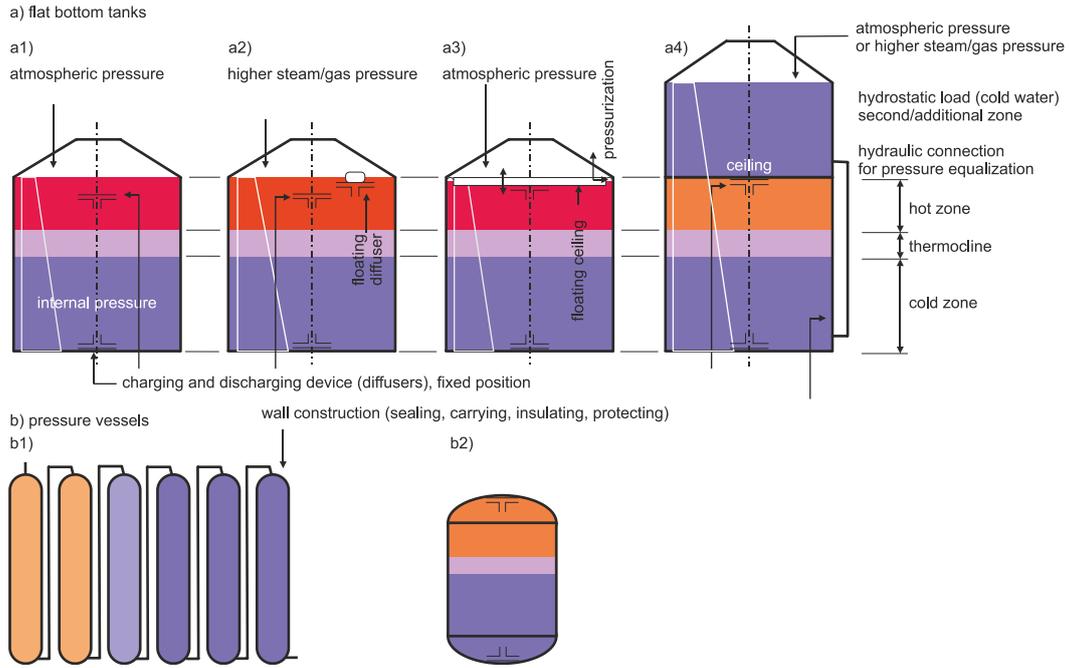


FIG. 12: OVERVIEW OF TYPICAL STORAGE CONSTRUCTIONS [27], MODIFIED

The specific installation costs for relevant storage tanks with a maximum operating temperature below 98 °C are shown in Fig. 13 (welded flat-bottomed tank, storage type a1, a2) and Fig. 14 (bolted flat-bottomed storage tank, storage type a1, a3). Fig. 15 shows the minimum specific costs of all storage types from Fig. 12. This proves that preferably bolted tanks stores have

minimum specific costs. Water is also an ideal storage medium for technical and environmental reasons. Therefore, the application of storage construction a1) or a3) will be pursued further. Maximum storage temperature of 98 °C proves to be sufficient, further increase of the supply temperature reduces collector efficiency.

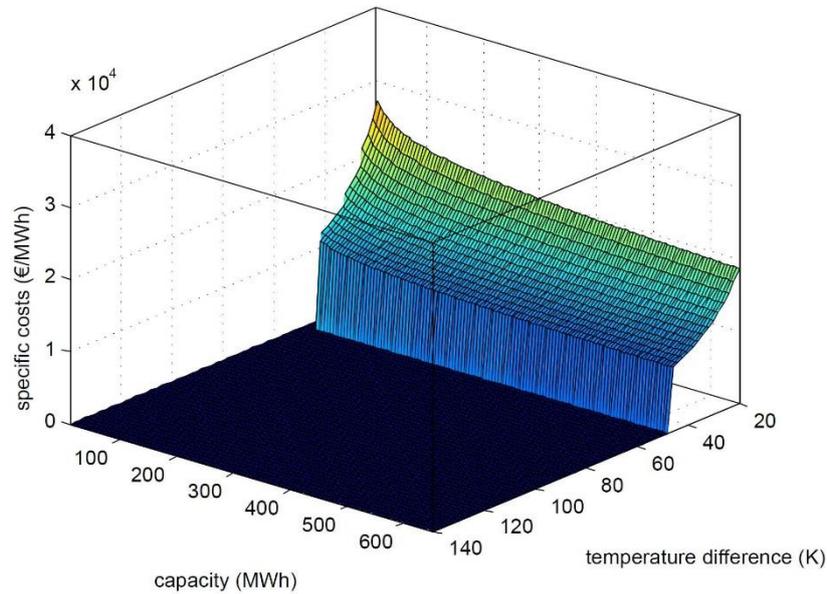


FIG. 13: SPECIFIC STORAGE CONSTRUCTION COSTS FOR STORAGE TYPES A1) AND A2) (WELDED FLAT-BOTTOM TANK) [27]

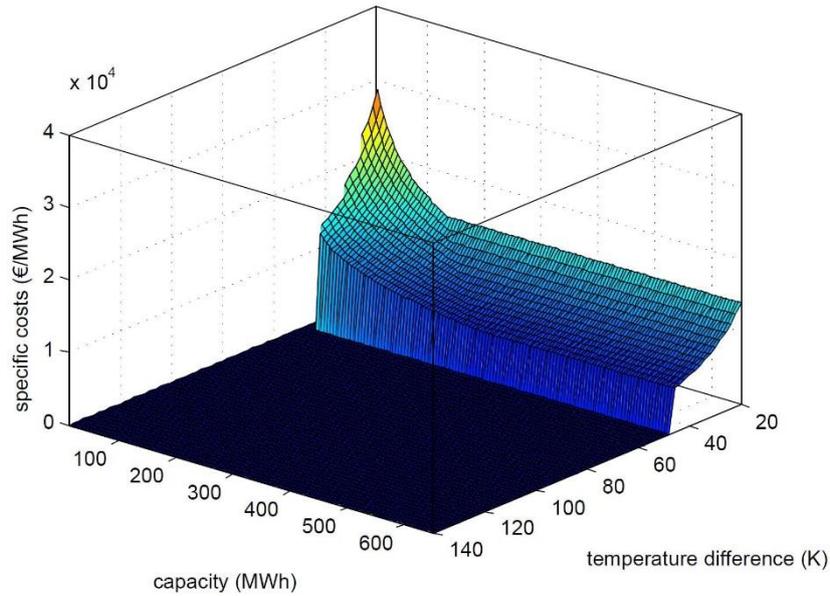


FIG. 14: SPECIFIC STORAGE INSTALLATION COSTS FOR STORAGE TYPES A1) AND A3) (SCREWED FLAT-BOTTOM TANK) [27]

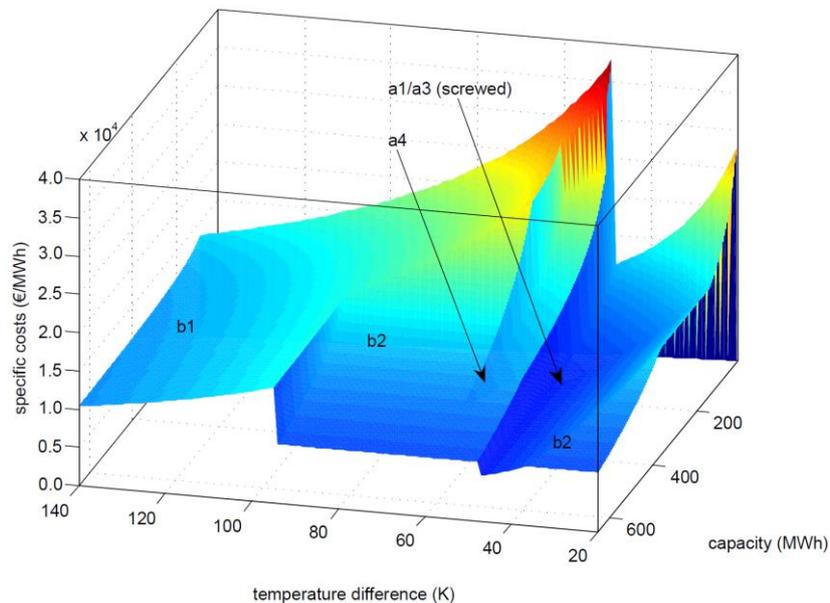


FIG. 15: SELECTION OF THE MINIMUM SPECIFIC COSTS FOR THE TANK STORAGE TANKS [27]

VIII. SUMMARY

The ZED project aims to demonstrate an emission-free and cost-effective heat supply. At the moment, the technical, energetic, ecological, economic feasibility as well as the concept development are being investigated.

Centralized supply is regarded as a comparative concept to the decentralized approach. When setting up an energy center or large subsystems, other technologies are available (e.g. large storage facilities) or other effects can be achieved (e.g. reduction of specific investment costs). Operation and management are also centralised, which also has an impact on profitability.

This article showed that a system implementation at district level is in general possible. The concept presented essentially comprises a heat pump storage

system in conjunction with solar thermal energy as well as other components and complex measures. A novelty is the use of two-tank system. The center is operated mainly with surplus electricity from renewable energy sources and a local PV system, which also corresponds to a new approach in this way. As a result, processes generating emissions are largely superseded.

ACKNOWLEDGMENT

The project on which this report is based is funded by the Federal Ministry of Economics and Energy under the number 03SBE114C on the basis of a resolution of the German Bundestag. Special thanks also go to the project management organisation Jülich for supporting the project. The responsibility for the content of this publication lies with the authors.

REFERENCES

- [1] Bundesministerium für Wirtschaft und Energie (BMWi) (Hrsg.), "Energieeffizienz in Zahlen - Entwicklungen und Trends in Deutschland 2018", Berlin, 2018.
- [2] Leonhardt, S., Höhne, E., Neumann, T., Teich, T., Bodach, M., Hoffmann, M., Kretz, D., Hempel, T., Schwind, M., Franke, S., Urbaneck, T., Gill, B., Schneider, M., "Demonstration einer energieeffizienten und sozialgerechten Quartiersentwicklung auf Basis elektrisch-thermischer Verbundsysteme in Zwickau Marienthal – Projekt ZED: Zwickauer Energiewende demonstrieren", In: Pöschk, J. (Hrsg.): Energieeffizienz in Gebäuden – Jahrbuch 2018, Berlin: VME – Verlag und Medienservice Energie, 2018, pp. 147-154, – ISBN 978-3-936062-14-4.
- [3] Projektträger Jülich, "PtJ: Solares Bauen/Energieeffiziente Stadt", 2019, URL: <https://www.ptj.de/solares-bauen-energieeffiziente-stadt> [abgerufen am: 10.02.2019].
- [4] Statistisches Bundesamt (Destatis), "Wohnungen nach Baujahr 2014", URL: <https://www.destatis.de/> [called on: 10.02.2019].
- [5] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., "Beheizungsstruktur des Wohnungsbestandes in Deutschland 2017", 2018, URL: <https://www.bdew.de> [called on: 10.02.2019].
- [6] Fraunhofer-Institut für Solare Energiesysteme ISE, "Jährlicher Anteil erneuerbarer Energien an der Stromerzeugung in Deutschland | Energy Charts", 2019, URL: <https://www.energy-charts.de> [called on: 10.02.2019]
- [7] Urbaneck, T., internal information, Chemnitz: Technische Universität Chemnitz, 2017.
- [8] Schabbach, T., "Sonnenkollektoren in der DDR. Historische Einordnung, Kollektoraufbau und Kollektorleistung. Symposium Solarthermie – Technik für die Energiewende", Staffelstein, Conexio, Pforzheim (Hrsg.), 2018, pp. 108-116.
- [9] Boschnakow, I., "Sonnenenergie - eine Alternative?", Berlin: Verlag Technik, 1982.
- [10] Hornberger, M., "Solar unterstützte Heizung und Kühlung von Gebäuden", Stuttgart, Univ., Diss.: Deutscher Kälte- und Klimatechnischer Verein, 1994.
- [11] Mahler, B., Fisch, M. N., Weiß, W., "Large scale solar heating systems for housing developments", Eurosun 2000 Conf. Proc., Copenhagen, Denmark, 2000.
- [12] Pavlov, G. K., Olesen, B. W., "Seasonal Ground Solar Thermal Energy Storage – Review of Systems and Applications", In: Proceedings of the ISES Solar World Congress 2011 ISES Solar World Congress 2011. Kassel, Germany: International Solar Energy Society (2011), pp. 1–11.
- [13] Bauer, D. et al., "German central solar heating plants with seasonal heat storage", Solar Energy 84 (2010), pp. 612–623.
- [14] Hesaraki, A. et al., "Seasonal thermal energy storage with heat pumps and low temperatures in building projects-A comparative review", Renewable and Sustainable Energy Reviews 43 (2015), pp. 1199–1213.
- [15] Reuß, M., "Solare Nahwärmeversorgung mit saisonaler Wärmespeicherung in Attenkirchen", ZAE BAYERN. URL: https://www.kreis-freising.de/fileadmin/user_upload/Aemter/Energiewende/Startseite/NEWS_Energiewende/10J_Ausstellung/Attenkirchen_Poster.pdf [called on: 12.02.2019]
- [16] Stadtwerke Crailsheim GmbH, "Technik, Ökologie und Lebensqualität im Einklang. Das Crailsheimer Solarthermie-Projekt im Überblick", URL: <https://www.stw-crailsheim.de> [called on: 12.02.2019].
- [17] Mangold, D., "www.Saisonalspeicher.de", Solites. URL: <http://www.saisonalspeicher.de/> [called on: 12.02.2019]
- [18] Mangold, D. et al., "Solare Nahwärme und Langzeit-Wärmespeicher: wissenschaftlich-technische Programmbegleitung für Solarthermie2000plus; Forschungsbericht zum BMU-Vorhaben 0329607L", Stuttgart: Solites, 2008.
- [19] Novo, A. V. et al., "Review of seasonal heat storage in large basins: Water tanks and gravel–water pits", Applied Energy 87 (2010), pp. 390–397.
- [20] Mahler, B., "Ganzheitliche Optimierung von solaren Nahwärmesystemen mit Langzeit-Wärmespeicher: Systemtechnik, Umwelteinwirkungen, Kosten", Düsseldorf: VDI Verlag GmbH, 2004.
- [21] Furbo, S. et al., "Yearly thermal performances of solar heating plants in Denmark – Measured and calculated", Solar Energy 159 (2018), pp. 186–196.
- [22] Ulbjerg, F., "Seasonal heat storage", In: 5th International Solar District Heating Conference. Graz, Austria, 2018.
- [23] Croy, R., Wirth, H. P., "Analyse und Evaluierung großer Kombianlagen zur Trinkwassererwärmung und Raumheizung. Abschlussbericht zum BMU-Vorhaben. Förderkennzeichen 0329268B", ZfS – Rationelle Energietechnik GmbH, Hilden, 2006.
- [24] Bauer, D. et al., "Solarthermie2000plus: Wissenschaftlich-technische Begleitung des Förderprogramms Solarthermie2000plus zu solar unterstützter Nahwärme und Langzeit- Wärmespeicherung", Stuttgart, 2013.
- [25] Gavalda, O., Depoorter, V., Oppelt, T., Ginderdeuren, K., "Deliverable D4.1. Report of different options for renewable energy supply in Data Centres in Europe", URL: <http://www.renewit-project.eu/documents/deliverable/> [called on: 12.02.2019].
- [26] Mesquita, L. et al., "Drake Landing Solar Community: 10 Years of Operation", In: Proceedings of SWC2017/SHC2017 ISES Solar World Conference 2017 and the IEA SHC Solar Heating and Cooling Conference for Buildings and Industry 2017. Abu Dhabi. International Solar Energy Society (2017), pp. 1–12.
- [27] Urbaneck, T., Oppelt, T., Schwöster, I., Bank, E. F., "Große Druckbehälter als thermische Energiespeicher, Teil 1: Vor- und Nachteile sowie Einsatzgrenzen", EuroHeat&Power, VWEV Energieverlag 47. Jg. (2018) vol. 11-12, pp. 18-23. – ISSN 0949-166X.

SYMBOL DIRECTORY

Symbol	Description	Unit
Latin letters		
A	area	m ²
f	solar fraction	%
Q	amount of energy	MWh/a
V	volume	m ³

Indices and abbreviations

ATES	aquifer thermal energy store ^a
BF	buffer store
BMBF	Federal Ministry of Education and Research
BMWi	Federal Ministry of Economics and Energy
BTES	borehole thermal energy store ^a
Coll	collector
EES	electrical energy storage
FC	flat plate collector
GDR	German Democratic Republic

GWTES	gravel-water thermal energy store ^a	TES	thermal energy storage
HP	heat pump	uFC	unglazed flat plate collector
HWTES	hot water thermal energy store (tank and underground storage tank) ^a	ZED	Demonstration of German Energy Transition in Zwickau
sol	solar		^a long-term heat storage
TBE	technical building equipment		