RESEARCH ARTICLE

Exergy Assessment of a Solar-Assisted District Energy System

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Abstract:

Background:

District Energy (DE) is a technology capable of using renewable energy (*e.g.*, solar thermal systems) and waste heat as energy sources efficiently. DE technology nonetheless has potential for improvement. Thermal Energy Storage (TES) can enhance DE performance significantly.

Objective:

An exergy analysis of a DE system which includes a solar thermal energy system and TES is performed, so as to improve understanding of its performance.

Method:

A case study based on the Friedrichshafen DE system in Germany is used to assess thermodynamically the role of solar energy and TES in a DE system. The system performance is separated into three modes: (1) fossil fuel is the only source of energy, (2) a discharging TES and fossil fuel provide heat for the DE system, and (3) solar energy and fossil fuels are the energy supplies. Exergy analyses are conducted for each performance mode and the overall DE system.

Results:

The results quantify the benefits of incorporating solar energy and TES on the performance of the Friedrichshafen DE system, and demonstrate that the overall exergy efficiency of the DE system increases from 23% to 27% with assistance of solar thermal collectors and TES, while the total energy efficiency increases from 83% to 87%.

Conclusion:

An increase of exergy efficiency is observed when TES is added to a DE system, due to a reduction in solar thermal energy loss by the TES, which allows more solar energy to be converted to useful energy to satisfy the DE system thermal energy demand.

Keywords: Thermal energy storage, District energy, Solar energy, Energy, Exergy, Friedrichshafen district heating system, Efficiency.

1. INTRODUCTION

Various measures for addressing environmental problems have been proposed. For instance, Robins [1] describes various practical approaches to reduce Green House Gas (GHG) emissions, while Rosen [2] describes methods to combat global warming through non-fossil fuel energy alternatives. A common approach is using energy more

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efficiently, on the basis of energy and, in particular, exergy. The thermodynamic quantity exergy is defined as the maximum work of a flow or system relative to a reference environment, or, more loosely, as the valuable part of energy [3]. Exergy analysis can help identify opportunities to increase the efficiency of a process or system. The temperature, pressure and chemical composition of a flow or system and of the reference environment both affect the exergy content of a material or energy flow [4]. Annex 49 [5] suggests using a combined energy and exergy analysis as a new method of designing energy supply systems in buildings for the use of renewable and low temperature heat sources.

District energy is a technology which can use renewable energy and waste heat as a source of energy. Using low-temperature heat from renewable energy sources, such as solar and geothermal energy, as well as industrial waste heat, in district heating has proven to be attractive [6 - 10]. Rezaie and Rosen [11] and Lake *et al* . [12] describe District Energy (DE) technology and its potential for improvement. Efficiency can be improved by using energy saving equipment [13] and recovering industrial waste heat [14], and such measures usually reduce GHG and other emissions [13]. According to the U.S. Department of Energy [15], district heating can considerably reduce GHG emissions. Lund *et al* . [16] state that DE not only decreases carbon dioxide (CO_2) emissions but also results in significant decreases in overall costs of energy systems. An example of integrating a DE system with renewable energy is the use of solar collectors consisting of vacuum tubes to generate heat for DE; this technology is popular in Europe and helps reduce GHG emissions. Other solar thermal collectors can also be used to convert solar energy to heat for DE applications. Many investigations of solar collectors and their applications have been conducted in recent years [17].

DE systems have been used in Europe since the 14th century, with one geothermal district heating system in continuous operation in France (Chaudes-Aigues thermal station) since that time [18]. The US Naval Academy constructed the first district system in USA on its Annapolis campus in 1853, and the commercial district heating system in New York was built in 1877 [19]. The first district energy system in Canada was built in Winnipeg's commercial core in 1924 [19]. Northern European countries are the main users of district energy systems. For instance, Sweden has installed a 40-TWh district heating system that supplied more than half of the heating capacity of the country in 2000 [20]. The percentage of district-heated homes is around 65% in Latvia and Lithuania. Due to use of district energy networks, the use of oil and hydroelectricity has dropped about 10% in Norway [21]. Soltani *et al* . [22] thermodynamically analyzed an integrated heat pump system for district heating applications.

Andrepont [23] states that using DE in conjunction with other energy technologies enhances overall system efficiency. Rezaie *et al* . [24] assess the positive role of Thermal Energy Storage (TES) in a DE system from the perspectives of environmental impact and fossil fuel consumption. Kharseh and Nordell [25] interpret TES as a bridge between periods of energy demand from the DE system and periods of energy supply to the DE system. TES can enhance the performance of DE systems significantly. Rad *et al* . [26] developed an integrated model for designing a solar community heating system with borehole thermal storage, while Sapińska-Śliwa *et al* . [27] critically reviewed the deep borehole heat exchangers used in underground thermal energy storage.

A common approach to address concerns regarding CO_2 and other harmful emissions is to reduce these emissions, and a common approach is to use energy resources more efficiently. Exergy analysis can facilitate this approach, as it permits investigations into the quality of energy and often suggests modifications to improve energy systems. Many applications of exergy analysis have been reported [28].

Here, a case study is used to assess thermodynamically the role of solar energy and TES in a DE system. The case study considered is the Friedrichshafen DE system in Germany. The TES stores the surplus solar energy until it is needed by thermal energy users of the DE system. Utilizing solar energy allows the DE system to use significantly less fossil fuel than would otherwise be the case. Seasonal TES, which normally requires significant thermal insulation to adequately reduce thermal losses, is used in the DE system. Originally, the Friedrichshafen DE system used only natural gas boilers. When a second residential area was added to the user base, solar thermal flat panels were added to provide energy for the entire thermal network. Energy and exergy analysis of TES in the Friedrichshafen DE system have been performed for a TES in a mixed condition [29] and in a stratified condition [30]. Here, some results from latter studies on Friedrichshafen TES are used to perform an exergy analysis on the Friedrichshafen DE, with the objective of identifying for the Friedrichshafen DE the benefits of using TES and renewable energy.

2. MODELING AND ANALYSIS

In this study, we apply energy and exergy analyses to the Friedrichshafen DE system and its various possible operation modes during a year, and determine energy and exergy efficiencies for the system during the different

operating modes.

A simplified model is developed for a DE system which utilizes solar thermal energy and TES which is representative of the Friedrichshafen DE system and which facilitates thermodynamic analysis (Fig. **1**). In this system solar collectors and a fossil fuel heater (boiler, furnace, or heater) provide energy for the DE system. During some periods, the solar collectors provide more thermal energy more than the demand and the excess energy is stored in the TES. When solar collectors cannot provide sufficient solar energy, the TES releases stored energy to the DE system. Arrows show the direction of the energy *via* heated fluid. (Fig. **1**) shows all possible modes for the Friedrichshafen DE system. Each mode is explained with energy movement direction in the following sections.
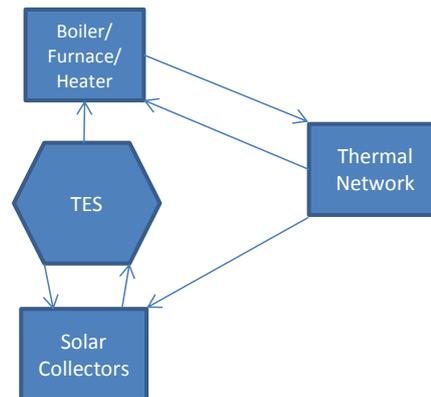
Fig. (1). Simplified illustration of a solar assisted DE system, showing flows of energy.

2.1. Energy and Exergy Analysis

Exergy analysis is used to assess efficiencies and losses for energy systems. It permits investigations into the quality of energy and often suggests modifications to improve energy systems and reduce environmental impact [31 - 34], and provides insights that complement those from conventional energy analyses. Exergy analysis is a useful tool to investigate lost exergy in DE system, as Compton and Rezaie [35] found through an application to a DE system fed by a biofuel. Also, Rezaie *et al* . [36] used exergy analysis for DE integrated with TES.

An energy balance for a general thermal system can be expressed as [37, 38]:

$$\text{Energy input - Energy output = Energy accumulation} \tag{1}$$

Where,

$$\text{Energy output = Product energy output + Waste energy output} \tag{2}$$

A corresponding general exergy balance can be written as follows:

$$\text{Exergy input - Exergy output – Exergy consumption = Exergy accumulation} \tag{3}$$

Where,

$$\text{Exergy output = Product exergy output + Waste exergy output} \tag{4}$$

Energy and exergy balances are written for the solar assisted DE system in (Fig. **1**) using these equations.

2.2. Operating Modes

The DE system, which is assisted by solar thermal energy and coupled with a TES, has three main operating modes, each of which is described separately in this section:

- Mode 1: The DE system uses fossil fuel only.
- Mode 2: The TES releases stored thermal energy to the DE system and is complemented by fossil fuel.
- Mode 3: The DE system is driven by solar energy and fossil fuel.

It should be explained that there is another mode which solar collectors generates energy more than the DE system demand. In this mode the excess heat stores into the TES system. This mode is exactly storage stage of the TES. This stage was calculated already in general [29] and in a stratified condition [30] and those results are used in the present study. In this mode, just solar collectors and the TES are involve, the thermal network is out of this performance and that is the reason this mode is not considered as Mode 4 for the Friedrichshafen DE system.

2.2.1. Operating Mode 1

In operating Mode 1 (Fig. **2**), natural gas is the only source of heating. The solar panels and the TES do not operate. Circulating media flows to the thermal network where it transfers heat to users, and returns at a lower temperature to the boilers. The temperature at the inlet to the boilers is almost the same as that of the returned circulating media from the thermal network. Energy losses for pumps, valves, splitters and pipes are small so they are neglected throughout. Mode 1 occurs when the TES is discharged and the available solar energy is either insufficient or unavailable to satisfy the DE system demand.

In the thermodynamic analysis, each component is considered within a control volume for all modes. In (Fig. **2**), F_1 is the energy supplied by the natural gas and Q_{net1} is the useful energy delivered to the consumer. Applying equations (1) and (2) to the Mode 1 operating period, Q_{net1} can be expressed as:
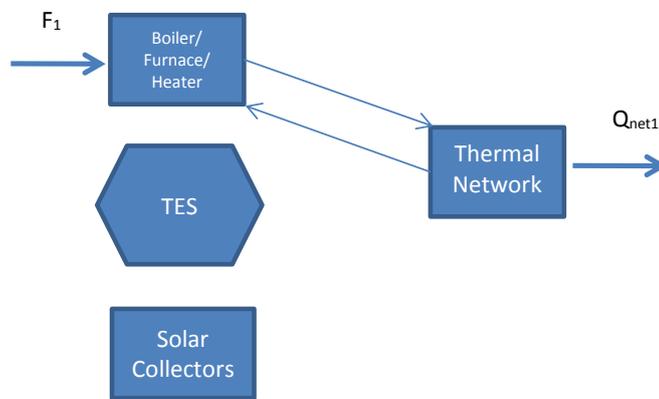
Fig. (2). Operating Mode 1 for a DE system assisted by solar thermal and TES, showing flows of energy.

$$Q_{net1} = Q_1 - Q_{loss\text{-}TN} \tag{5}$$

where $Q_{loss\text{-}TN}$ denotes the energy loss of the thermal network, and Q_1 is the energy supplied by natural gas to the DE system by a fossil fuel heater (*e.g.*, boiler, furnace, heater) having an energy efficiency η_h that can be expressed as follows:

$$\eta_h = Q_1/F_1 \tag{6}$$

The energy efficiency of the DE system for the Mode 1 can be expressed as:

$$\eta_1 = Q_{net1}/F_1 \tag{7}$$

An exergy analysis of the solar assisted DE system for operating Mode 1 is carried out, using (Figs. **2** and **3**). The latter shows the circulating media flows in the DE thermal network. The exergy of the net energy demand for Mode 1, ExQ_{net1}, can be determined as:

$$ExQ_{net1} = m_1[h_{in} - h_{out} - T_0(s_{in} - s_{out})] \tag{8}$$

Here, h_{out} and h_{in} are specific enthalpies of the circulating media outlet from and inlet to the thermal network respectively (Fig. **3**), and s_{out} and s_{in} are the corresponding specific entropies. Also, T denotes the temperature of the reference environment, and m_1 is the mass of the circulating media that passes through the thermal network during the period of operation, which can be determined as follows:
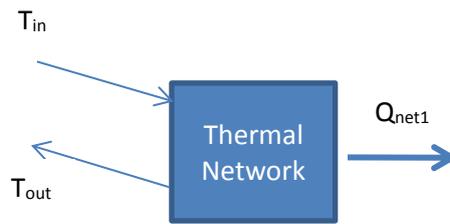
Fig. (3). Thermal network during operating Mode 1, showing flows of energy.

$$m_1 = \frac{Q_{net1}}{\Delta T\, C_p} \tag{9}$$

where, ΔT is temperature difference between the inlet from and outlet to the thermal network, and C_p denotes the specific heat at constant pressure of the flow m_1. The exergy of the flow F_1, ExF_1, can be expressed as:

$$ExF_1 = R\, F_1 \tag{10}$$

Where, R is the energy grade function for the fuel. Rosen *et al*. [32] report a value of 0.913 for the energy grade function natural gas. The exergy efficiency for the system during Mode 1, Ψ_1, can be written as:

$$\Psi_1 = \frac{ExQ_{net1}}{ExF_1} \tag{11}$$

2.2.2. Operating Mode 2

In operating Mode 2 (Fig. **4**), TES operation is added to the system described in operating Mode 1 (but solar collectors are not operating). The storage media in the TES is already heated by extra energy from the solar thermal collectors after feeding the DE system. The preheated storage media from the TES flows through the fossil fuel heater. The circulating media receives energy partially from fossil fuel and partially from the TES, which discharges its stored surplus solar energy to the DE system because there is a large energy demand for solar energy is unavailable.

In (Fig. **4**), F_2 is the fossil fuel energy input to the control volume, Q_{s2} is the thermal energy discharged from the TES and Q_{net2} is the useful energy product for Mode 2. With equations (1) and (2), we can write:
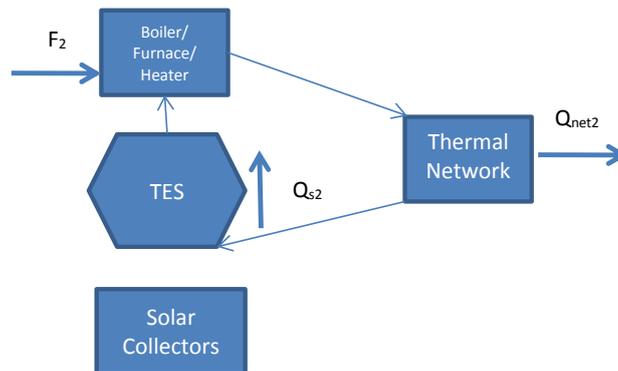
Fig. (4). Operating Mode 2 for a DE system assisted by solar thermal and TES, showing flows of energy.

$$Q_{s2} + Q_2 = Q_{net2} + Q_{loss\text{-}TN} \tag{12}$$

$$Q_{s2} = Q_{rec} \tag{13}$$

where Q_2 denotes the energy from the fossil fuel that is input to the thermal network in Mode 2, and Q_{rec} is the total energy recovered in the TES discharge stage. Details of Q_{rec} are given by Rezaie *et al* . [30], who analyse the TES charging and discharging performance for the TES in the Friedrichshafen DE system. The energy efficiency of the burner can be expressed as:

$$\eta_h = Q_2/F_2 \tag{14}$$

The energy efficiency for the DE system in Mode 2, η_2, can be written as follows:

$$\eta_2 = Q_{net2}/(F_2 + Q_{rec}) \tag{15}$$

An exergy balance for the solar assisted DE system in Mode 2 can be written using equations (3) and (4):

$$ExQ_{net2} = m_2\left[h_{out} - h_{in} - T_0\left(s_{out} - s_{in}\right)\right] \tag{16}$$

where ExQ_{net2} represent exergy of Q_{net2}, and m_2 is the mass of the circulating media passing through the thermal network during the operating period, which can be determined as follows:

$$m_2 = \frac{Q_{net2}}{\Delta T\, C_p} \tag{17}$$

Here, ΔT is defined as for Mode 1. The exergy of the fossil fuel entering the heater in Mode 2, ExF_2, and the exergy of Q_{s2}, ExQ_{s2}, can be written as:

$$ExF_2 = R\, F_2 \tag{18}$$

$$ExQ_{s2} = Ex_{rec} \tag{19}$$

where Ex_{rec} represents the exergy recovered from the TES, which has been assessed previously [30]. The exergy efficiency for the solar assisted DE system in Mode 2, Ψ_2, can be expressed as:

$$\Psi_2 = \frac{ExQ_{net2}}{ExQ_{s2} + ExF_2} \tag{20}$$

2.2.3. Operating Mode 3

In the third mode (Fig. **5**), solar collectors and fossil fuel heater equipment both provide energy for the solar-assisted DE system. In this mode the TES is not active. The solar energy is transferred directly to the fossil fuel heater for supplemental heating. Mode 3 occurs when there is a heat demand while sunlight is available. This mode can occur throughout the year, but is less common in the summer when solar collectors receive more solar energy due to the longer days.
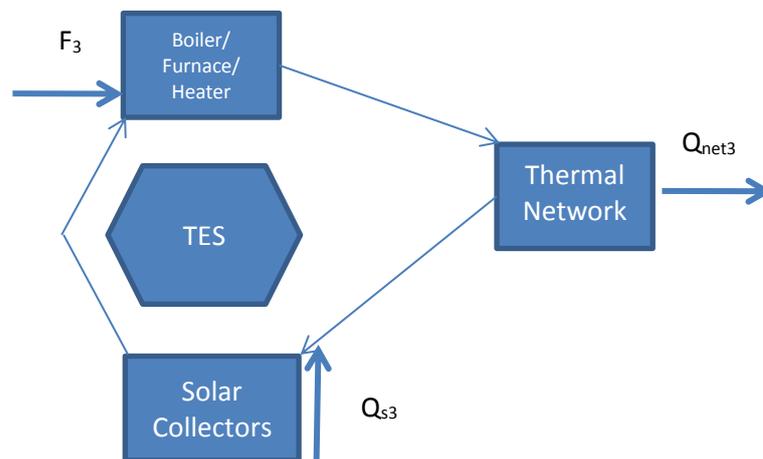
Fig. (5). Operating Mode 3 for a DE system assisted by solar thermal and TES, showing flows of energy.

In (Fig. **5**), F_3 and Q_{s3} are the energy supplied to the control volume by the fossil fuel heater and the solar collectors, respectively, and Q_{net3} is the useful energy delivered in Mode 3. Q_3 is the parameter introduced for Mode 3; from other side the annual fossil fuel consumption is known and fossil fuel energy used in Modes 2 and 3 are calculated in previous sections, thus Q_3 is difference between annual consumption and summation of Q_1 and Q_2. This can be written as follows:

$$Q_3 = Q_D - (Q_2 + Q_1) \tag{21}$$

With equations (1) and (2), the following energy balances can be written for the DE system in Mode 3:

$$Q_{net3} = Q_3 - Q_{loss\text{-}TN} \tag{22}$$

The quantity Q_{s3} can be expressed as:

$$Q_{s3} = Q_s - Q_{in\text{-}TES} \tag{23}$$

where Q_s is the total solar energy collected and $Q_{in\text{-}TES}$ is the solar energy input to the TES during the charging stage. The latter quantity has been examined in detail previously by Rezaie *et al* . [29, 30].

Also, $Q_3 = F_3 + Q_{s3}$ where F_3 is the energy the fossil fuel heater inputs to the thermal network. Then:

$$F_3 = (Q_3 - Q_{s3}) \tag{24}$$

Then energy efficiency for the Mode 3, η_3, can be written as:

$$\eta_3 = Q_{net3}/(F_3 + Q_{s3}) \tag{25}$$

An exergy balance for the Friedrichshafen thermal network in Mode 3 can be written by using equations (3) and (4) as:

$$ExQ_{net3} = m_3 \left[h_{in} - h_{out} - T_0 \left(s_{in\text{-}} s_{out} \right) \right] \tag{26}$$

Here, ExQ_{net3} of the exergy of Q_{net3}, h_{out} and h_{in}, s_{out}, s_{in}, from / to thermal network, T are already defined, and m_3 is the mass of the circulating media passing through the thermal network during the operating period, which can be determined as follows:

$$m_3 = \frac{Q_{net3}}{\Delta T \, C_p} \tag{27}$$

where, as for Modes 1 and 2, ΔT is the temperature difference between inlet and outlet circulating media for the thermal network. Also, the exergy associated with the fuel energy F_3, ExF_3, can be expressed as:

$$ExF_3 = R \, F_3 \tag{28}$$

and the exergy of Q_{s3}, ExQ_{s3}, can be written as

$$ExQ_{s3} = Q_{s3} \tag{29}$$

The exergy efficiency of the solar assisted DE system for Mode 3 Ψ_3 can be expressed as:

$$\Psi_3 = \frac{ExQ_{net3}}{ExQ_{s3} + ExF_3} \tag{30}$$

2.3. DE System Total Efficiency

To estimate the efficiency we assess the performance of the solar assisted DE system as a whole system, oprating in all modes. This approach is simplistic but, by generalizing conditions like ambient temperature over the year, loses some accuracy.

With the general approach, we consider the performance over an entire year. For simplicity, we assume that the system acts in a cyclic manner over a year, and that the system returns to its initial state after one year. A total quantity of solar energy (Q_s) is supplied to the DE system, directly (Q_{s2}) and through the TES (Q_{s3}), and the fossil fuel heater operates to provide heat to the DE system by using a total amount of fuel ($F_{gas} = F_1 + F_2 + F_3$). The total demand of the DE system is deducted by the network loss to determine the net heat demand ($Q_{net} = Q_{net1} + Q_{net2} + Q_{net3}$). (Fig. **6**) depicts the general thermal cycle, which combines various operating modes.

We consider a control volume the entire system in the thermodynamic analysis. F_{ng} and Q_s are the energy externally supplied to the control volume and Q_{net} is the annual useful energy delivered. F_{ng} denotes the fuel energy entering the

fossil fuel heater and Q_s is the total solar energy collected by the solar panels. With equations (1) and (2), we can write following equations:
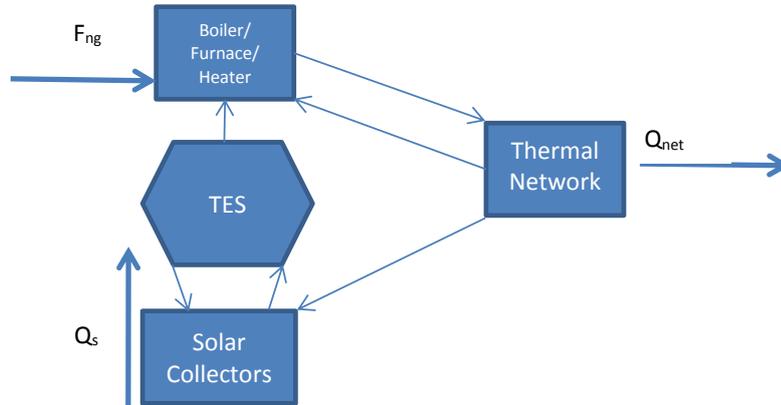
Fig. (6). Simplified representation of the general performance of the DE system assisted by solar thermal and TES, showing possible flows of energy.

$$F_{ng} + Q_s = Q_{net} + Q_{loss-TN} + Q_{loss-TES} \tag{31}$$

$$\eta = Q_{net} / (F_{ng} + Q_s) \tag{32}$$

By replacing equivalent amount for Q_{net}, F_{ng}, and Q_s from modes 1, 2, and 3 in above equation, the thermodynamic energy efficiency η of the solar assisted DE system is expressed as follows:

$$\eta = (Q_{net1} + Q_{net2} + Q_{net3})/(F_1 + F_2 + F_3 + Q_{S2} + Q_{S3}) \tag{33}$$

where the parameters are already introduced. Since $Q_{in-c} = Q_{S2}$, then values of all terms in equation (33) are known.

The exergy efficiency ψ of the solar assisted DE system can be expressed as:

$$\psi = (ExQ_{net1} + ExQ_{net2} + ExQ_{net3})/(ExF_1 + ExF_2 + ExF_3 + ExQ_{S2} + ExQ_{S3}) \tag{34}$$

Knowing $ExQ_{S2} = Ex_{in-c}$ the terms in the above equation can be calculated.

3. CASE STUDY: FRIEDRICHSHAFEN DE SYSTEM

Efforts have been made in many countries and regions to increase the application of renewable energy, such as solar and wind energy, and to reduce fossil fuel use. For example, "Solarthermie2000", the 4th programme of "Energy Research and Technology" by the Germany Federal government, has fostered significant progress in the development of second and third generation solar-assisted district heating plant in conjunction with seasonal thermal storage [39]. Seasonal thermal storage often utilizes thermal insulation with a low thermal conductivity to decrease thermal losses. Large scale, long term thermal storage is often more cost effective than small scale, short term TES [40]. A large scale TES is included in the Friedrichshafen DE system.

Nuβbicker *et al*. [41] note that the Friedrichshafen DE system has hot water thermal energy storage made of reinforced concrete with a volume of 12,000 m³. The first phase the Friedrichshafen DE system covered 280 apartments containing multi-family houses and a daycare, utilized solar collectors with an area of 2700 m², and satisfied 24% of the total heat demand of the district heating system *via* solar energy. In the second phase, established in 2004, district heating was expanded to a second set of apartments comprising 110 units, which caused the addition of 1350 m² of solar collectors to the system. Also, two gas condensing boilers, with capacities of 750 kW and 900 kW, were installed to allow the energy demand for district heating to be met if the combination of solar collectors and thermal storage was not adequate. The Friedrichshafen DE system consists of two natural gas boilers, a set of flat-panel solar thermal collectors, mostly on building roofs, a Central Solar Heating Plant with Seasonal Heat Storage (CSHPSS), several heat exchangers to allow the exchange of heat between the thermal network and the solar panels, the thermal network which distributes heat to consumers, pipes, pumps and valves. Water is the circulating thermal transport medium in the Friedrichshafen system and is also the heat storage medium. Externally supplied heat to the Friedrichshafen DE system is from boilers

and solar collectors; and thermal network is the main consumer of heat. Nuβbicker *et al*. [41] report the following data for the Friedrichshafen DE system:

- Return water temperature from network: 55.4°C.
- Measured annual heat loss of TES: 421 MWh.
- Storage efficiency: 60%.
- Annual solar yield of collectors: 1200 MWh.
- Annual solar heat input to district heating network: 803 MWh.
- Overall annual heat input into the district heating network: 3017 MWh.
- Annual heat delivery by gas bolilers: 2310 MWh.
- Solar fraction: 26%.
- Portion of heat loss of the district heating network for the 2nd residential area: 7.3%.
- Maximum temperature inside TES: 81°C (at top).
- Capacities of two gas boilers: 750 kW and 900 kW.

Also, Lottner and Mangold [40] and Fisch and Kubler [42] report the temperature of thermal network (T) to be 70°C. A typical efficiency of "gas fired condensing boilers," which is taken to be representative here, is about 90% [43, 44].

The present authors apply several simplifying assumptions including the assumption, based on a similar thermal system reported by Zhai *et al* . [45], that heat loss in pipelines can be neglected.

(Fig. **7**) depicts the history of several relevant temperatures for the Friedrishchafen DE system since it commenced operation. Although the system generally follows an annual cycle, the temperature varies from year to year. In the winter the temperature reaches a minumum and in the late summer a maximum temperature is observed.
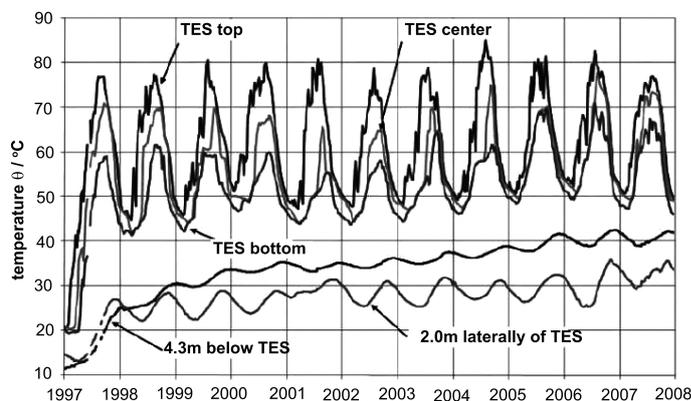
Fig. (7). History of selected temperatures for the TES and surrounding soil for the Friedrichshafen DE system.

Source: Nuβbicker *et al* . [41], Printed by permission

For the present case, we consider the year 2006. TES temperatures for each month and season of this reference year are read from (Fig. **7**), and are tabulated in (Table **1**). The ambient air temperature, which is taken to be the reference environment temperature T_o, for the 12 months of 2006 is depicted in (Table **1**) [46].

Table 1. TES and air ambient temperature during the year 2006.

Season/ Solar Generation	Month	TES Temp. (Top), °C	TES Temp. (Center), °C	TES Temp. (Bottom), °C	T_m, °C	T, °C	Soil Temp. °C	ΔT (T_{ave} − Soil Temp.), °C	$Q_{loss\text{-}TES}$, MWh
Spring / 376.07 MWh	March	60	56	52	56.0	3.4	26	30	32.6
	April	70	61	56	63.0	9.9	25	36	39.1
	May	80	69	60	70.0	13.7	25	44	47.7
Summer / 473.33 MWh	June	83	74	63	73.0	19.8	26	48	52.1
	July	82	76	67	76.0	19.7	28	48	52.1
	August	87	74	66	76.5	16.1	31	43	46.7

(Table 1) contd.....

Season/ Solar Generation	Month	TES Temp. (Top), °C	TES Temp. (Center), °C	TES Temp. (Bottom), °C	T_m, °C	T, °C	Soil Temp. °C	ΔT (T_{ave} − Soil Temp.), °C	$Q_{loss\text{-}TES}$, MWh
Fall/ 233.42 MWh	September	74	65	58	66.0	17.9	34	31	33.6
	October	60	59	50	55.0	13.0	35	24	26.0
	November	54	52	51	52.5	6.6	34	18	19.5
Winter / 116.76 MWh	December	51	50	48	49.5	2.7	32	19	20.6
	January	54	52	50	52.0	−2.6	30	22	23.9
	February	55	54	51	53.0	0.3	29	25	27.1
								Total =388	**Total = 421**

Sources: Figure 8, Rezaie *et al* . [30], and Tutiempo [46].

The total energy loss of the TES during the year 2006 was reported as 421 MWh Nuβbicker *et al* . [41]; this loss needs to be distributed into 12 months. The temperature difference between the TES and the soil at a depth of 4.3m under the TES is calculated for 12 months. The soil temperature be read from (Fig. **7**) and tabulated in (Table **1**). (Table **1**) also contains the TES monthly energy loss. The distribution of generated solar energy, estimated by Rezaie *et al* . [24], is also illustrated in (Table **1**). Besides, the total temperature differences between the average TES (T_{ave}) and the soil (Soil Temp.) over the 12 months is 388°C; the energy loss in each month is calculated by multiplying each monthly temperature difference by the ratio of 421/388.

The energy grade function R for natural gas is taken to be 0.913 throughout [32].

3.1. Performance of Operating Modes

3.1.1. Thermal Process Mode 1

In this mode, boilers are the only source of heating. Water does not circulate in the TES or solar collectors. Water with a temperature of 83°C flows into the thermal network, transfers heat to the thermal network, and returns from the thermal network outlet at 55.4°C to the boilers. The Friedrichshafen DE system operates in Mode 1 during November, December, January, and February, because the TES is discharged and the available solar energy is insufficient to satisfy the Friedrichshafen DE system's demand. The performance of the Friedrichshafen DE system in Mode 1 is evaluated with Equations (5) to (11) and depicted in (Table **2**).

Table 2. Performance of Friedrichshafen DE system for different operating modes.

Mode	Input of Natural Gas to the DE sys. (MWh)	Input of Solar Energy to the DE Sys. (MWh)	Energy Demand of the DE Sys. (MWh)	η (%)	Natural Gas Exergy (MWh)	Solar Exergy (MWh)	Demand Exergy (MWh)	Ψ (%)
1	F_1: 1464.92	na	Q_{net1}: 1222.18	83	ExF_1:1337.47	na	ExQ_{net1}: 305.17	23
2	F_2: 168.93	Q_{s2}: 350.72	Q_{net2}: 466.06	90	ExF_2: 154.06	ExQ_{s2}: 43.15	ExQ_{net2}: 70.00	35
3	F_3: 214.78	Q_{s3}: 611.92	Q_{net3}: 746.46	90	ExF_3: 196.10	ExQ_{s3}: 147.86	ExQ_{net3}: 125.30	36

3.1.2. Thermal Process Mode 2

In this mode, the TES operates with the boilers. Water in the TES is previously heated by surplus energy from the solar panels after feeding the DE system. This preheated water is discharged from the TES and enters the boilers when a significant demand for thermal energy exists. Mode 2 proceeds until the TES water temperature exceeds the thermal network temperature (55.4°C). The duration of Mode 2 is September and October. Energy and exergy parameters are evaluated with Equations (12) to (20) and listed in (Table **2**).

3.1.3. Thermal Process Mode 3

During Mode 3, solar thermal collectors and boilers both provide energy for the Friedrichshafen DE system, and the TES does not operate. Water from the solar collectors at 81°C flows directly to the boilers. Mode 1 occurs throughout the year. The DE system performance in Mode 3 is evaluated with Equations (21) to (30) and described in (Table **2**).

3.2. Total Efficiency

The total efficiency of the Friedrichshafen DE system can be estimated by using equations (33) and (34) for energy and exergy efficiencies. Energy efficiency of 87% and exergy efficiency of 27% are results of applying equations (33) and (34) on the Friedrichshafen DE system.

3.3. DISCUSSION

Energy and exergy efficiencies of the Friedrichshafen DE system in three different thermal process modes are tabulated beside the total Energy and exergy efficiencies of that DE system in (Table **3**).

Table 3. Energy and exergy efficiencies of the Friedrichshafen DE system.

Operation mode	η (%)	ψ (%)
Mode 1 (NG)	83	23
Mode 2 (NG & TES)	90	35
Mode 3 (NG & Direct Solar)	90	36
Total (Annual)	87	27

Operating Mode 1 is totally dependent on the natural gas as boilers are the only source of energy; this mode has the lowest energy and exergy efficiencies, 83% and 23% respectively, compared to the other modes. When solar collectors indirectly through the TES provide heat for the DE system in Mode 2 and, in this mode; the energy and exergy efficiencies boost up to 90% and 35% which is an improvement for the Friedrichshafen DE system relative to Mode 1. In Mode 3, solar energy directly assists the boilers and the energy and exergy efficiencies increase to 90% and 36% in compare with Mode 1 values. This comparison shows the positive impact of TES and solar panels in improvement of Friedrichshafen DE system.

The total energy and exergy efficiencies are driven with the concept of adding up the input and output energy in modes 1, 2, and 3, then to estimate the energy and exergy efficiencies during a typical year performance of Friedrichshafen DE system. The total energy and exergy efficiencies are also higher than the energy and exergy efficiencies of the DE system when is just working with the fossil fuels. This happens just because of applying solar collectors and TES in the thermal processes in Friedrichshafen DE system. Solar collectors and TES supply more efficient energy to the DE system, therefore the total energy and exergy efficiencies of the Friedrichshafen DE system increase.

The result of this study enforces the positive role of the TES in solar assisted DE system like the Friedrichshafen DE system.

CONCLUSION

Solar thermal technology and TES are two methods of modification of DE systems. Both are applied in the Friedrichshafen DE system to increase its performance. For determining the energy and exergy efficiencies of the Friedrichshafen DE system, it is divided into three thermal process modes. Each mode is analysed thermodynamically separately.

A comparison of the operating modes verifies that when Friedrichshafen DE system is working just with natural gas it has lower energy and exergy efficiencies. When solar collectors and TES assist the natural gas, the energy and exergy efficiencies are much higher (Table **3**). Note that this comparison is theoretical to demonstrate positive impact of solar energy and TES on the performance of the Friedrichshafen DE system in terms of the improvements to the energy and exergy efficiencies.

The actual performance of the Friedrichshafen DE system is a combination of three modes. In other words, the combination of the performances of the three thermal cycle modes defines the annual performance of the Friedrichshafen DE system. In the annual performance of Friedrichshafen DE system the total energy efficiency is 87% while the exergy efficiency in a typical year is 27%. These values are based on the energy and exergy efficiencies of the three thermal process modes of the Friedrichshafen DE system (Table **3**).

NOMENCLATURE

C_p	=	Specific heat at constant pressure, kJ/kg °C
ExF_1	=	Exergy supply by fossil fuel heater in Mode 1, kJ
ExF_2	=	Exergy supply by fossil fuel heater in Mode 2, kJ
ExF_3	=	Exergy supply by fossil fuel heater in Mode 3, kJ
ExF_{ng}	=	Energy supply by fossil fuel heater, kJ
ExQ_{net1}	=	Net exergy demand in Mode 1, kJ

ExQ_{net}	=	Net exergy demand, kJ
ExQ_{net2}	=	Net exergy demand in Mode 2, kJ
ExQ_{net3}	=	Net exergy demand in Mode 3, kJ
ExQ_{s2}	=	Exergy supply by solar energy in Mode 2, kJ
ExQ_{s3}	=	Exergy supply by solar energy in Mode 3, kJ
ExQ_{s}	=	Exergy supply by solar energy, kJ
F_1	=	Energy supply by fossil fuel heater in Mode 1, kJ
F_2	=	Energy supply by fossil fuel heater in Mode 2, kJ
F_3	=	Energy supply by fossil fuel heater in Mode 3, kJ
F_{ng}	=	Energy supply by fossil fuel heater, kJ
h_{in}	=	Inlet specific enthalpy, kJ/kg
h_{out}	=	Outlet specific enthalpy, kJ/kg
m	=	Mass of water transferring energy, kg
m_1	=	Mass of water transferring energy in Mode 1, kg
m_2	=	Mass of water transferring energy in Mode 2, kg
m_3	=	Mass of water transferring energy in Mode 3, kg
η_1	=	Energy efficiency in Mode 1
η_2	=	Energy efficiency in Mode 2
η_3	=	Energy efficiency in Mode 3
η	=	Energy efficiency by general approach
Q_1	=	Energy supply in Mode 1, kJ
Q_2	=	Energy supply in Mode 2, kJ
Q_3	=	Energy supply in Mode 3, kJ
Q_{net}	=	Net energy demand by Friedrichshafen DE system, kJ
Q_{net1}	=	Net energy demand by Friedrichshafen DE system in Mode 1, kJ
Q_{net2}	=	Net energy demand by Friedrichshafen DE system in Mode 2, kJ
Q_{net3}	=	Net energy demand by Friedrichshafen DE system in Mode 3, kJ
Q_{rec}	=	Energy recovered from TES, kJ
Q_s	=	Solar energy supply, kJ
Q_{s2}	=	Solar energy supply in Mode 2, kJ
Q_{s3}	=	Solar energy supply in Mode 3, kJ
R	=	Energy grade function
s_{in}	=	Inlet specific entropy, kJ/kg K
s_{out}	=	Outlet specific entropy, kJ/kg K
T	=	Ambient temperature, °C
ψ_1	=	Exergy efficiency in Mode 1
ψ_2	=	Exergy efficiency in Mode 2
ψ_3	=	Exergy efficiency in Mode 3
ψ	=	Exergy efficiency by general approach

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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