AN EFFICICENT STRATEGY FOR THE OPERATION OF AN INTEGRATED THERMAL ENERGY STORAGE FACILITY AND CHP/DH PLANT

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Abstract— Combined Heat and Power (CHP) systems are of interest for District Heating (DH) networks due to their high conversion efficiency. The main challenge in implementing CHP/DH systems is in matching the inherent dynamic demand of residential thermal demand. In fact, the large mismatch between production and consumption profiles is issue of concern. Thermal Energy Storage (TES) can be used to cope with this issue. The operational strategy of an integrated CHP with TES plays a significant role in profitability of the whole plant and, as such, necessitates precise study. In this paper, different options for the operation of an integrated CHP/DH with TES are investigated, all based on the same concept, sending a constant hourly amount of energy to the TES/DH. In order to find the best constant flow rate, the performance of the TES facility has been investigated numerically. To find the best operation strategy, the objective function in simulations was to minimize thermal energy dumping due to the following sources: thermal energy degradation in the thermocline hot water storage tank and/or thermal energy dumping due to uncertainty of thermal demand. In all scenarios, hourly thermal energy supply is set at a constant average value for each month, but is varied from one month to another. Moreover, the amount of supplied energy varies between design options as it only covers a certain percentage of the thermal demand. Based on the proposed method of operation, the hourly full load operation mode is dictated to the CHP plant. This has been shown to allow CHP to have its best energetic performance in all scenarios. The results show that the best constant hourly thermal energy that should be supplied to the TES/DH should be equal to the monthly average of the maximum thermal demand. Furthermore, policies with fewer mismatches have resulted in better thermal performance of TES. Since all alternatives have been compared based on the same TES capacity, the best energetic scenario also represents the best economically one.

Keywords— Combined Heat and Power, Thermal Energy Storage, District Heating, Operation Strategy, Numerical simulations.

NOMENCLATURE

D	demand factor
Q_{CHP}	thermal energy production by CHP [kWh]
$Q_{DH\text{-}Direct}$	direct supplied energy to DH consumers [kWh]
Q_{DHW}	domestic hot water energy demand [kW]
$Q_{Dumping}$	dumped energy [kWh]
Q_{max}	maximum thermal energy demand [kW]
Q_{stored}	amount of the stored energy by TES facility [kWh]
Q_{TES}	thermal energy demand covered by TES [kWh]
Q_{min}	minimum thermal energy demand [kW]
Q_{ST}	supplied energy to steam turbines [kWh]
Greek symbols	
η	efficiency
Abbreviations	
CHP	Combined Heat and Power
CHP/DH	Integrated CHP and DH
CHP/TES/DH	Integrated CHP, TES, and DH
DH	District Heating
DHW	Domestic Hot Water
HRSG	Heat Recovery Steam Generator
HVAC	Heating, Ventilation and Air Conditioning
TES	Thermal Energy Storage

I. INTRODUCTION

As reported in [1], an efficient method for providing residential energy demand is a district heating (DH) network integrated with combined heat and power (CHP) plant. Uncertainty of residential thermal demand is an issue of concern for the CHP/DH. As discussed in [2], adding thermal energy storage (TES) into the system reduces the hourly mismatch between production and consumption profiles, allowing for better utilization of the plant and higher overall annual energy efficiency. Smith et al. [3] reported that a properly designed TES can reduce primary energy consumption and carbon dioxide emissions, while at the same time reducing the size of system components and costs.

Among the key factors affecting CHP profitability, a proper management of the energy flows between the prime mover and the storage subsystem should be considered. Investigators have studied different operation strategies for CHP/TES, but most of previous works focused on application of TES in

distributed generation (DG) systems, and when it comes to CHP/DH/TES, there are only a few works in this area. The maximum benefit of adding TES into CHP can only be obtained when intelligent operational strategies are employed. Though there have been many researches on analyzing the integrated CHP and TES plant from both technical and financial perspectives, many aspects of optimal operation are still under-developed, namely:

- Mismatch between production and consumption profiles should be minimized, but stochastic fluctuations and uncertainties in both of thermal and electrical demand are difficult to predict and satisfy [2, 4-6].
- Not all consumers require the same heat to power ratio. Those with high thermal demand will (logically) benefit more from thermal storage [3]. In the limit, the system can be designed to meet peak thermal loads [2]. Flexibility of a CHP plant is of great importance from both financial and technical viewpoints, and it can be increased by using TES and it is important to find the best way to capitalize on this flexibility [7,8]
- Since CHP systems operate most efficiently at a constant load, especially at full power, strategies for start-up/shut-down and interplay with TES are critical [2, 3, 7-9].

In order to address these in one operation strategy simultaneously, Mostafavi et al. [2] suggested an efficient way to decouple the operation of CHP and TES/DH. In this control scheme, the CHP plant provides the TES/DH systems with a constant hourly thermal production. Thus, the amount of delivered energy to TES/DH is constant during one month, but it varies from one month to another. The supplied amount was defined based on a linear function between the amount of supplied energy and thermal request. Although the effectiveness of this general strategy has been investigated technically and economically in [2], the actual optimum quantity for the constant hourly flow rate has not been defined yet. The current work will analyze different possible linear functions to find the best constant quantity for some characteristic cases. First, we will describe the proposed CHP/TES/DH plant together with all assumptions and applied simulation models. Secondly, different scenarios are proposed to quantify the steady hourly flow rates for each month. Then, a methodology is introduced for evaluating different alternatives from thermodynamic point of view. Finally, results are discussed and the most appropriate steadily flow rate is found.

II. PLANT DESCRIPTION

The schematic diagram of CHP/TES/DH system is shown in **Fig. 1**. The system is designed to match with the demand of Parand (DH plant), which is situated 35 km southwest from Tehran. This area is laid at longitude 51.04˚ and latitude 35.8˚, and at 1095 m height above sea level, with hot dry climate, and its area is about 1578 ha. As is described by Mostafavi et al. [2], thermocline hot water storage tank(s) were chosen to improve the performance of the DH network integrated with CHP station. The corresponding technical specifications of the thermocline TES facility are given in **Table 1**.

In order to investigate different options for the operation of CHP/TES/DH, the thermal demand must first be determined. The demand profile on the basis of the worst case condition is computed using eQUEST [10], and labeled as maximum demand. This profile is an upper range of thermal request. In the next step the lower range of thermal request is computed, and labeled as minimum demand. A ratio called monthly demand factor is defined in equation (1). Using this factor, the minimum demand profile is obtained from equation (2). DHW demand is approximately constant during the whole year, so it does not participate in finding monthly demand factor. As a matter of fact, the ratio of DHW to total thermal demand varies from one case study to another, and this ratio was found to be around 0.3 in this case study [1]. Moreover, since the HVAC load is negligible in May and November in the considered area, so the demand factor is not defined for these months.

$$D_{monthly} = \frac{Average(Q_{max} - Q_{DHW})_{hourly}}{Maximum(Q_{max} - Q_{DHW})_{hourly}} \quad (1)$$

$$Q_{min,hourly} = D_{monthly} \times (Q_{max} - Q_{DHW})_{hourly} + Q_{DHW,hourly} \quad (2)$$

The region between the upper and lower limits is considered as an uncertain thermal request. Since it is the responsibility of the CHP system to supply the maximum thermal demand, scenarios are defined based on covering the part of foregoing profiles directly or/and by using TES facility, and provide the uncovered uncertain part with peak boilers at demand side. It should be noted that when it comes to the TES facility, hourly simulation over a typical year of operation is required. Hourly simulation of the CHP plant (consisting of six gas turbines with HRSGs), and TES model is presented in [2]. The hourly amount of available energy for supplying either the steam turbines or DH network has been determined before, but this study advances the previous work by finding the best operation strategy to supply the TES/DH and steam turbines simultaneously. Details of energy production at the CHP plant and energy consumption at demand side are represented in **Table 2**.

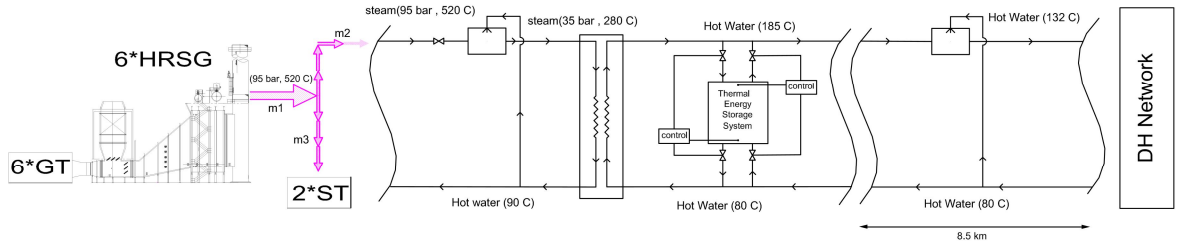


Fig. 1. Schematic diagram of CHP/TES/DH system.

III. OBJECTIVE/METHODOLOGY

Since the CHP plant feeds DH network and steam turbines simultaneously, interactions between them should be taken into account. Furthermore, it is not practical for the CHP plant to follow the fluctuating thermal load at demand side due to technical/economic issues. Therefore, a proper strategy for operation of a ST/TES/DH system should be considered. When there is a shortage of energy, an efficient operation of steam turbines can be guaranteed using supplementary firing; therefore, the best operation strategy is the one resulting in the best performance of the TES facility based on the fact that TES facility has no supply source but the energy from CHP plant. Moreover, according to the role of TES in CHP plants, the more TES facility discharges energy, the less energy will dump at demand side since TES covers the uncertain thermal demand region. Although Mostafavi et al. [2] have shown that a steady flow rate is an interesting practical (and efficient) general solution, the specific flow rate has not been found yet. Hence, in this study, this is determined as is illustrated by equation (3). The hourly amount of available energy for supplying either the steam turbines or DH network has been determined before (m_1) [2], and this study attempts to find the best operation strategy to supply the TES/DH and steam turbines simultaneously based on minimizing energy dumping. It is assumed that energy dumping in equation (3) has two main sources: uncertain thermal demand and energy losses at TES. Energy destruction at TES facility can be determined based on TES efficiency, so higher TES efficiency means less energy dumping. On the other hand, based the uncertain thermal demand region which is considered to be covered either by TES or peak boilers, maximizing Q_{stored} will minimize Q_{dumpig}.

where

$$m_1(\text{constant}) = m_2(?) + m_3(?)$$
$$Q_{CHP} = Q_{ST} + Q_{DH-Direct} + Q_{Stored} + Q_{Dumping} \quad (3)$$
$$\text{minimize} Q_{Dumping}$$

Table 1: Technical specifications of the TES tank.

Type of the storage tank	Thermocline hot water tank
Tank configuration	vertical cylinder, composed of stainless steel, well insulated
Tank dimensions	height=30 m, out diameter= 7 m, approximate volume = 1100 m^3
Number of tanks	1 up to 20 tanks
Inlet configuration	type of diffuser=Impingement, inlet port diameter= 0.4 m

Table 2: Details of energy production and consumption (95 bar steam, ton per hour).

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
$HRSG_s$ Maximum production	1260	1254	1250	1247	1212	1205	1203	1199	1208	1212	1248	1253
Maximum $_{\text{Max demand}}$	904	862	759	710	281	965	1036	1018	939	787	281	856
Maximum $_{\text{Min demand}}$	557	483	419	379	281	614	659	679	561	425	281	492
Monthly average $_{\text{Max. demand}}$	559	479	420	379	281	618	661	672	546	430	281	488
Monthly average $_{\text{Min. demand}}$	404	350	321	303	281	445	471	492	394	324	281	357
Average $_{\text{Monthly average Max. and Min. demand}}$	481	414	370	341	281	532	566	582	470	377	281	423

Based on **Table 2**, seven scenarios are defined to ensure that every possible option has been considered, see **Table 3** and Fig. 2. In each scenario, an hourly constant rate of heat is considered to feed the ST/TES/DH. The hourly thermal request in April together with supplied energy by different scenarios is presented in **Fig. 3**. In each alternative, the energy from the CHP plant (Q_{CHP}) can be deployed in three ways: 1-$Q_{DH-Direct}$: To directly supply a portion of the DH demand. 2- Q_{stored}: To charge the TES for later energy discharging. 3- Q_{ST}: To supply the steam turbines. Furthermore, shortage of steam for full load operation of steam turbines is provided by supplementary firing system at HRSGs. Peak boilers are also considered to supply uncovered thermal demand (Q_{PB}). It should be noted that the number of steam turbines has been defined in the way that there is always a demand for energy in steam turbines in

all scenarios, so there is no energy dumping at steam cycle.

As mentioned earlier, the advantage of TES is that is can help meet uncertain demand. Since the region between minimum and maximum profiles is assumed to be uncertain, minimizing the share of $Q_{DH\text{-}Direct}$ and Q_{PB} together with maximizing the portion of Q_{TES} in the foregoing region can result in the best energetic/environmental/financial case scenario (i.e. the objective of this paper).

Mismatch between production and consumption profiles means a great potential for applying TES at CHP/DH. Each scenario will lead to different mismatch profiles; take for example, scenario 1: the annual mismatch between available and shortage of energy for different scenarios are depicted in **Fig. 4**. Based on the TES capacity, a portion of available energy can be stored to compensate the energy shortage at demand side, while any 'not-stored' energy is used to feed steam turbines. The same framework has been used in other alternatives.

Table 3: Constant available energy to meet the thermal demand in different scenarios (95 bar steam, ton/hr.)

Scenario	Description
Sc. 1	Monthly average $_{\text{Max. demand}}$ or Maximum $_{\text{Min demand}}$
Sc. 2	0.5* Maximum $_{\text{Max. demand}}$
Sc. 3	0.6* Maximum $_{\text{Max. demand}}$
Sc. 4	0.7* Maximum $_{\text{Max. demand}}$
Sc. 5	1.2* Maximum $_{\text{Min. demand}}$
Sc. 6	0.8* Maximum $_{\text{Min. demand}}$
Sc. 7	Average $_{\text{Monthly average Max. and Min. demand}}$

As discussed before, the best alternative can be determined based on evaluating the overall performance of TES. In order to compare TES performance in different scenarios, two criteria are defined: annual TES discharge and annual TES efficiency. The annual TES discharged energy is the total delivered energy to DH during a year, and the annual TES efficiency is the annual total discharged energy divided by the annual total stored energy. Consequently, annual TES efficiency can be computed as equation. (3) [2, 11]:

$$\eta_{TES} = \frac{Q_{TES}}{Q_{stored}} \quad (3)$$

Annual TES discharge criterion compares different scenarios in terms of thermal energy delivered to DH by TES for the same storage capacity. Hence, the more one scenario uses the capacity of TES facility, the more efficient it is. TES annual efficiency determines the efficiency of TES facility regardless of the available potential in storage tanks. Although annual TES efficiency has a linear relation with overall CHP plant efficiency and primary energy saving [1, 2], in order to find the best case scenario, it cannot be used alone. In other words, both annual TES discharge and annual TES efficiency should be taken into account to determine the best energetic/economic solution. In fact, a TES facility with certain capacity can deliver less energy with higher annual efficiency in one scenario compared to delivering more energy with less annual efficiency in another one. Together with these criteria, the total operating hours of TES facility can be regarded as a secondary criterion to specify the best performance of TES facility. Obviously, the discussed criteria for analyzing the performance of TES facility have not the same priority, and following preferences should be regarded: annual TES discharge, annual TES efficiency, and operating hours.

IV. RESULTS

Performance of TES facility with the same capacity (1 tank to 10 tanks) in different scenarios is represented in **Fig. 5** to **Fig. 7**. It should be noted that destruction of available thermal energy in the TES facility has sources: 1) Heat loss in hot water storage tank(s) because of mixing hot and cold water, 2) Since there is no thermal energy for storage in May and November, TES facility is not used in these months and consequently portion of energy (if there is available) is dumped from the TES facility at the end of April and October. Based on the results obtained from the analysis, considering the annual discharge criterion, scenario 1, scenario 3 and scenario 7 resulted in the best performance of TES facility with different capacities, respectively. Annual TES working hours (aggregation of charging and discharging hours) for different scenarios are depicted in **Fig. 8**. As it can be seen, regardless of TES capacity, scenarios 1, 3, and 7 have had more working hours which means more justification for the application of TES.

In order to compare scenarios 1, 3, and 7 in more detail, results are extended to 20 storage tanks for these options, see **Fig. 9**. As it is expected, the annual TES discharged energy has been increased steadily by adding the number of tanks for all alternatives. However, annual TES efficiency had decreased slightly in options 1 and 3, while it improved for scenario 7. Although scenario 7 resulted in the best performance of TES system from annual TES efficiency point of view, it is not the best candidate considering the annual discharge factor, which is the most important criterion. Furthermore, although from annual TES discharge viewpoint, there is not a much difference between scenarios 1 and 3, from annual TES efficiency perspective, option 1 is by far better than option 3. These results show that in order to evaluate the performance of a TES facility, both annual criteria should be

considered. Finally, it can be concluded that TES application in CHP plants has justification only when amount of available and shortage of energy have not much difference. Therefore, operation strategies should be devised in a way to guarantee the mentioned limitation.

It should be noted that though different scenarios affects power generation of steam turbines differently, finding the best case scenario for the operation of TES/DH system does not need the aforementioned analysis. In fact, although the energy consumption at CHP plant for feeding steam turbines varies from one scenario to another, effectiveness of TES system under the certain operation strategies is independent. To summarize, the first step in the design process of a CHP/TES system is to find the most appropriate operation strategy which can be case specific (e.g. in this case study, scenario 1 has been found to be a best one), and then to find the optimum capacity of TES.

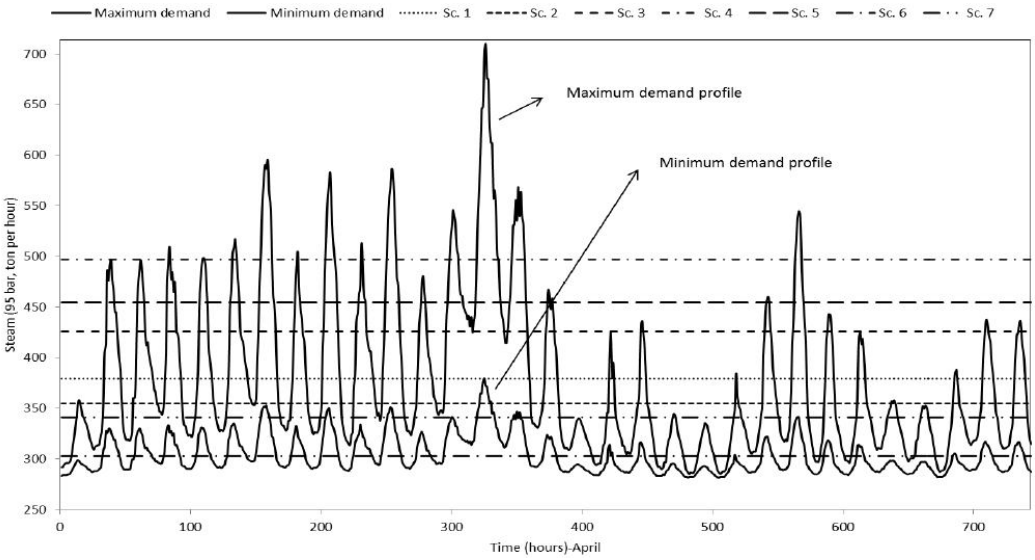


Fig. 2. Thermal request profiles and supplied energy to TES/DH by different scenarios in April.

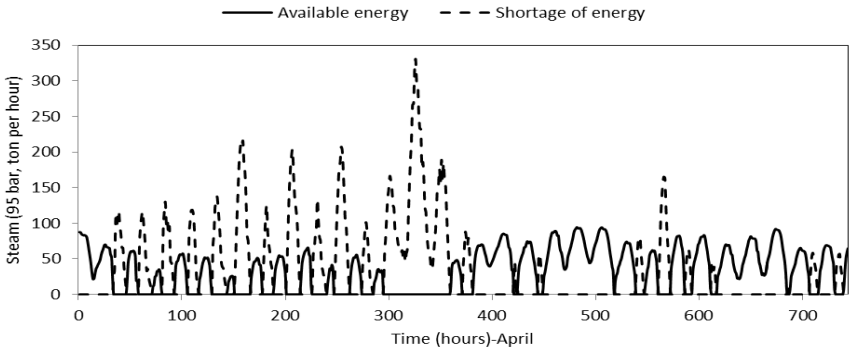


Fig. 3. Hourly mismatch between production and consumption profiles (scenario 1).

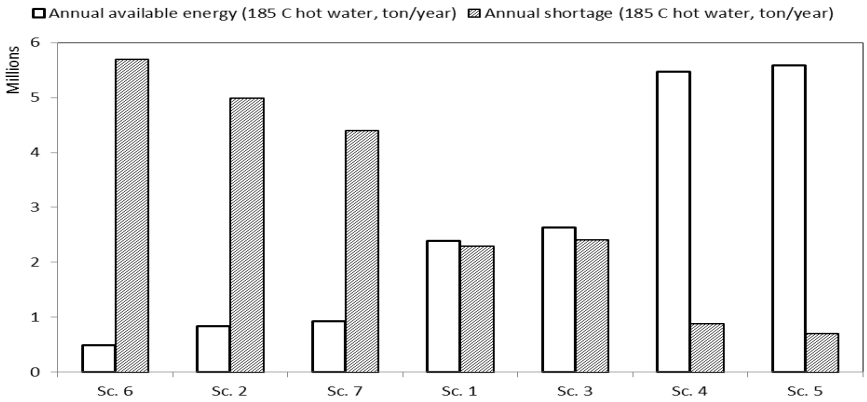


Fig. 4. Annual mismatch in different scenarios.

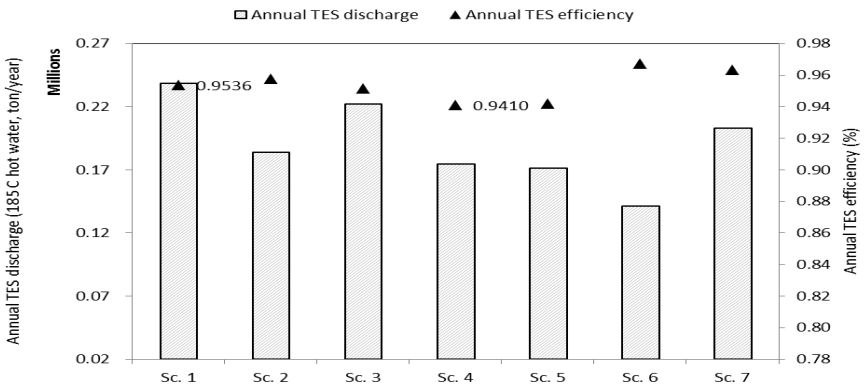


Fig. 5. Annual performance of TES facility with capacity of 1 tank.

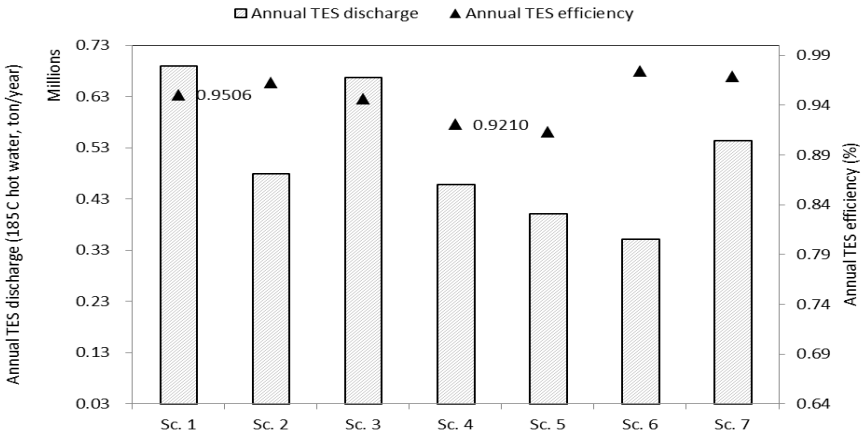


Fig. 6. Annual performance of TES facility with capacity of 5 tanks.

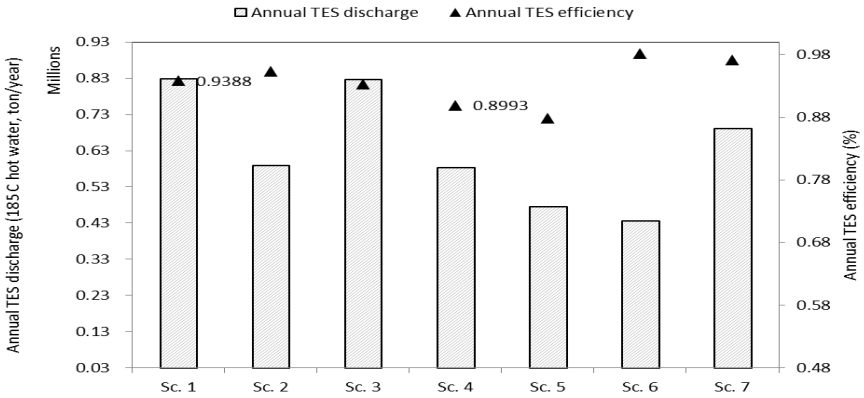


Fig. 7. Annual performance of TES facility with capacity of 10 tanks.

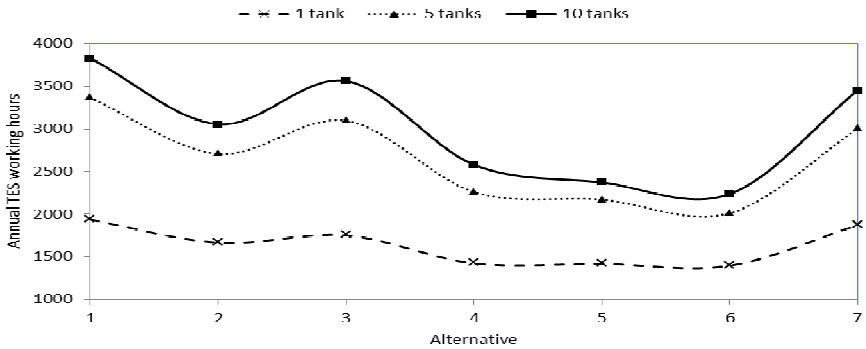


Fig. 8. Annual TES working hours with various capacities in different scenarios.

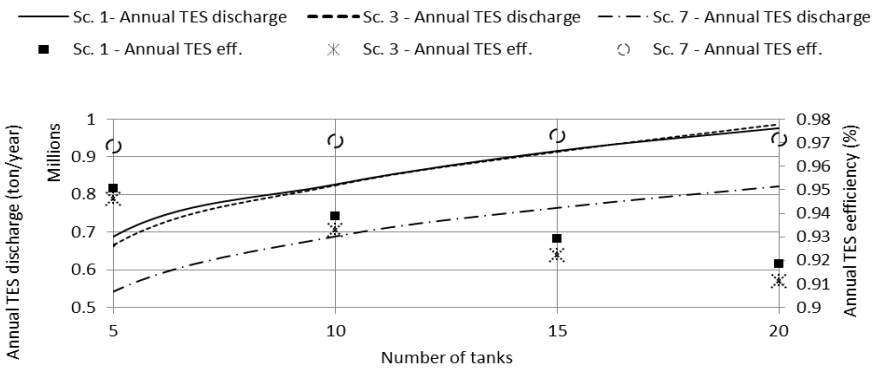


Fig. 9. Annual performance of TES facility with different capacities in the best case scenarios.

CONCLUSIONS

There are different operational strategies for a CHP/TES plant. In order to achieve the maximum potential of both CHP and TES systems, the hourly constant thermal energy that should be provided for TES/DH were examined in this paper using different linear functions between amount of supplied energy and the thermal demand profiles (maximum and minimum). Among the seven considered alternatives, the best hourly constant flow rate for supplying the TES/DH was found to be the one having the monthly average of the maximum thermal demand. Moreover, it was found that TES has justification only when CHP operates by strategies through which the minimum difference between amount of available energy for storage and shortage of energy for supplying end users is guaranteed. It should be noted that in order to assess the thermal performance of a TES facility, following criteria were evaluated respectively: annual TES discharge, annual TES efficiency.

The proposed mode of operation results in different advantages in CHP/TES/DH plants such as full load annual operation, more total annual efficiency, less emissions, more flexibility, to name but a few. In fact, without a well-integrated and controlled TES facility, CHP has no choice but to follow the fluctuating thermal demand profile, which has an adverse effect on the profitability of the whole plant. Although the analyses presented here refer to the case of residential consumers and to a CHP/TES integrated with a district heating network, the methodology could be extended to other CHP/TES systems. Needless to say, more thermal demand profiles in different regions should be considered to validate the aforementioned constant quantity.

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