International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 926

Energy Storage System for Thermal Load Fluctuation Balancing

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ABSTRACT

Cogenerative geothermal power plants can supply thermal energy required by energy-intensive activities, such as greenhouses heating. The required thermal load in these systems usually follows the daily temperature trend, leading to not negligible load fluctuations on the power plant side that need to be managed, in case a constant electric output from the plant is required (e.g. because the energy has been already sold on the day-head electric energy market). The supplied heat flow rate must be constant to avoid a fluctuating operation of the cogeneration system. This paper investigates the opportunity of using a thermal storage to manage this load fluctuations and keep the system stable. Results show that even an oversized storage tank may not be sufficient to reach the desired set point conditions, especially if the load forecasting is incorrect. For this reason, it is necessary to increase the supplied heat flow rate to reduce energy shortages and use a cooler to dissipate energy surpluses. Results show that it is possible to achieve setpoint conditions by increasing the supplied heat flow rate by 20 % and using a cooler do dissipate thermal energy surplus. This performance worsens when the load forecast is not accurate, though shortening the period with a fixed heat flow rate can be beneficial.

Keywords: thermal energy storage, geothermal energy, energy forecasting, thermal load fluctuations

NOMENCLATURE

Abbreviations	
HE-I	Primary heat exchanger
HE-II	Secondary heat exchanger
SOC	State of charge
Symbols	
c_P	Specific heat capacity (kj/kgK)
$C_X(x)$	Cumulative distribution function for the variable X
$\dot{m}$	Mass flow rate (kg/s)
T	Temperature (°C)
$\dot{Q}$	Heat flow rate (MW)
$\bar{\dot{Q}}$	Average heat flow rate (MW)
p	Supplied heat flow rate increase (%)
P_{cool}	Maximum cooler power (MW)
$p_{k\%}$	Statistical percentile relating to k percentage of occurrences
Δt	Time step used for discretization
Subscripts	
c	Cooler
r	Residual
st	Storage

1 INTRODUCTION

Geothermal energy can cover the consumption of energy-intensive processes. Taking advantage of these resources is helpful to supply significant energy demand by using a renewable source with a low environmental impact. Geothermal plants can cogenerate both electric and thermal energy at a useful temperature level. Several studies also investigated the use of different suitable fluids for cogeneration, e.g. [1]. Some energy-intensive activities use the heat flow rate produced by geothermal plants (both cogenerative and not) to satisfy the energy demand. Greenhouses heating is one of these processes whose requirement can be satisfied by a geothermal source [2] [3]. Geothermal cogeneration is easily manageable when the thermal load is constant, such that the plant operates with stable conditions. Frequently, the thermal demand follows the daily temperature trend, thus having a higher energy request during the night and a lower one during the day. Some undesired fluctuations can occur on the electric power

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

generation side as the operating point fluctuates frequently due to the thermal load fluctuation. Such fluctuations can be avoided by setting a given heat flow rate over a defined period and arranging a proper storage system to administrate energy surplus or shortages. As shown in [4] [5], thermal energy storages are helpful to reduce and shift load fluctuations keeping systems in more stable conditions.

2 SYSTEM LAYOUT

In the examined case study, a geothermal cogeneration power plant provides the required warming load to a large greenhouse. Referring to the scheme in Figure 1, hot water at the temperature T_1 = 90 °C circulates in the primary circuit and provides the requested heat flow rate to the water circulating in the secondary circuit in the heat exchanger HE-I. The temperature T_2 at the heat exchanger outlet must be as constant as possible to avoid fluctuating operating conditions on the geothermal plant side. To ensure A steady operation of the geothermal plant, the heat flow rate $\bar{\dot{Q}}$ provided to the greenhouse must be fixed over a defined period (from 7 up to 15 days). The thermal users (the greenhouses) absorb the heat introduced into the system with a secondary heat exchanger HE-II. Since the greenhouse consumption follows the daily temperature fluctuations, introducing a thermal energy storage in the system help maintain the desired inlet temperature $T_{set\ point}$. A preliminary analysis showed that arranging the storage as in Figure 1 yields the best performance. Positioning the storage parallel to the stream allows one to control the inlet mass flow rate, thus the charging or discharging rates. In this case, part of the water coming from HE-II at the temperature T_4, $\dot{m}_x$, can be diverted to the storage, according to its state of charge and the desired $T_{set\ point}$. An equal flow $\dot{m}_x$ leaves the storage so that the water level inside the storage does not change. Afterwards, $\dot{m}_x$ is mixed again with the main stream.

The storage operates only when its state of charge, i.e. its temperature, is adequate. In particular, if T_4 is higher than $T_{set\ point}$ – the stream needs to be cooled – but storage temperature T_{st} is higher than T_4, the storage is bypassed. The same situation occurs when T_4 is lower than $T_{set\ point}$ – the stream needs to be warmed – but T_{st} is lower than T_4. Furthermore, the temperature layering inside the tank is beneficial to the system. The hot zones are on the top of the tank, and the cold ones are on the bottom. Therefore, when the stream needs to be cooled, the hot water enters on the top, and cold water is sent to the main stream from the bottom and vice versa (Figure 2).

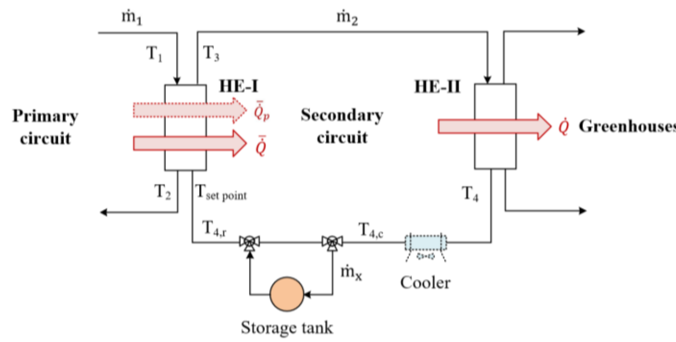

Figure 1. System Layout.

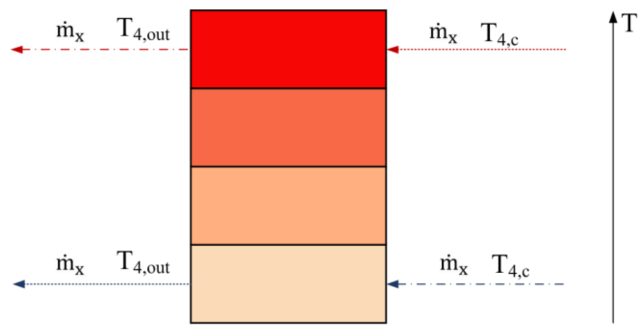

Figure 2. Stratified storage tank layout. Dashed lines are for the charging phase; dashed and dotted lines are for the discharging phase.

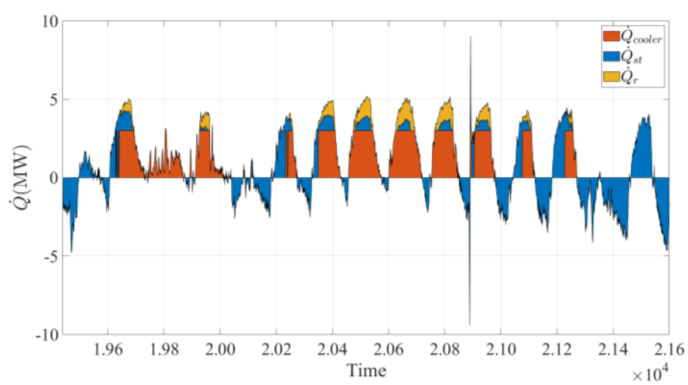

Figure 3. Thermal load management. Orange areas stand for heat flow rate supplied by the cooler; blue areas stand for heat flow rate supplied by the storage; yellow areas indicate residual power that cannot be managed.

A preliminary analysis showed that the system hardly reaches the set point conditions with the storage alone. This behaviour is due to the wide load fluctuations that storage cannot manage from day to night, even if it is oversized. According to this, some additional modifications are necessary. The proposed solution is to increase the heat flow rate supplied $\bar{\dot{Q}}$ by a factor p, to reduce the occurrences in which T_4 is colder than $T_{set\,point}$. Consequently, this modification brings to an increment of occurrences in which T_4 is hotter than $T_{set\,point}$; these deviations need to be managed by an auxiliary device, like a cooler. Dashed lines in Figure 1 show the modification brought to the system by introducing the cooler. The cooler must be managed with a defined strategy to optimize system operation. In particular, when T_4 is different from $T_{set\,point}$, one of these cases occur:

- If $T_4 > T_{set\,point}$ and $T_{st} \leq T_{set\,point}$, the cooler is off, since the storage can be discharged;
- If $T_4 > T_{set\,point}$ and $T_{st} \geq T_{set\,point}$, the cooler brings T_4 as close as possible to $T_{set\,point}$; if the new temperature obtained, $T_{4,c}$, is still hotter than $T_{set\,point}$, then the storage acts only if $T_{st} < T_{4,c}$;
- If $T_4 < T_{set\,point}$ the cooler is off, and the storage acts only if $T_{st} \geq T_4$.

Figure 3 shows how $\dot{Q}_r$ is typically managed by the storage and the cooler during the period with a constant heat flow rate $\bar{\dot{Q}}_p$.

3 METHODOLOGY

3.1 *General assumptions and examined parameters*

Without losing in generality, some assumptions have been made:

- Thermal losses are neglected for HE-I, HE-II and the storage;
- Temperature measurements every ten minutes are available for the plant. Consequently, this is the time step Δt used for the simulations.

The use of some statistical parameters can be helpful to understand the system behaviour and quantify the occurrences in which setpoint conditions are achieved. This approach will be described in the following paragraphs. The storage and the cooler provide $\dot{Q}_{st}$ and $\dot{Q}_{cool}$, respectively, and it is possible to define the remaining heat flow rate $\dot{Q}_r$ required to reach the setpoint as in Eq. 1.

$$\dot{Q}_r = \dot{m}_2 c_P (T_{4,r} - T_{set\,point}) \quad (1)$$

where $\dot{m}_2$ is the secondary circuit flow rate and $T_{4,r}$ the temperature obtained after storage and cooling operation. However, it is possible to accept a deviation from $\dot{Q}_r$ = 0 of ± 1.16 MW. Knowing $\dot{Q}_r$ for every time step, it is possible to analyze it with statistical indexes:

- The cumulative distribution function for the variable $\dot{Q}_r$. It indicates on the y-axis the probability $C_X(x)$ that the dimension X will take a value less than or equal to the x-axis value x (referring to Eq. 2); In this case, the variable X is $\dot{Q}_r$.

$$C_X(x) = P(X \leq x) \quad (2)$$

- Statistical percentile $p_{k\%}$. It represents the values below which a given percentage k of occurrences occurs; e.g., the 90th percentile $p_{90\%}$ is the value below which 90 % of the scores in the distribution may be found.

3.2 *Supplied heat flow rate over a fixed period*

Choosing the correct value of the supplied thermal energy over a fixed period is the most critical aspect of designing the plant. $\bar{\dot{Q}}$ will be the heat flow rate exchanged by HE-I over an entire week or more (up to fifteen days) and must be decided at the beginning of this settled period. This implies the exact knowledge of the heat flow rate $\dot{Q}$ required by greenhouses over the forthcoming period, which depends on meteorological conditions. Disposing of this accurate forecast is the optimal condition. In this case, $\bar{\dot{Q}}$ can be calculated as the average value of greenhouse consumption, as expressed in Eq. 3.

$$\bar{\dot{Q}} = \mathrm{mean}_{period}[\dot{m}_1 c_P (T_1 - T_2)] \quad (3)$$

When the plant does not use sophisticated forecasting methods and can not manage HVAC devices with predictive control strategies, some simple solutions are needed to set the best heat flow rate supplied by HE-I. By comparing a few naive forecasting methods, the best approach was that based on persistence. Therefore, the average value of heat flow rate during the previous period (i.e. 7 or 15 days) was used.

3.3 *Layered storage tank model*

Stratified storage tank modelling is comparable to a series of several perfectly stirred tanks. Here, four layers are used for the sake of simplicity. A reference scheme is shown in Figure 4. The storage tank is discretized in four equal volumes V_1, V_2, V_3, V_4, that are characterized by the temperatures $T_{st,1}$, $T_{st,2}$, $T_{st,3}$, $T_{st,4}$. It is possible to determine these temperatures by using the energy conservation law applied on each volume (Eq. 4, Eq. 5, Eq. 6, Eq. 7). In addition, the appropriate mass flow rate $\dot{m}_x$ to be diverted into the storage to reach the set point conditions is determined by the enthalpy balance on point A (Eq. 8).

$$T_{st,1}(t) = T_{st,1}(t-\Delta t) + \frac{\dot{m}_x[T_4 - T_{st,1}(t-\Delta t)]}{\rho V_1}\Delta t \quad (4)$$

$$T_{st,2}(t) = T_{st,2}(t-\Delta t) + \frac{\dot{m}_x[T_{st,1}(t-\Delta t) - T_{st,2}(t-\Delta t)]}{\rho V_2}\Delta t \quad (5)$$

$$T_{st,3}(t) = T_{st,3}(t-\Delta t) + \frac{\dot{m}_x[T_{st,2}(t-\Delta t) - T_{st,3}(t-\Delta t)]}{\rho V_3}\Delta t \quad (6)$$

$$T_{st,4}(t) = T_{st,4}(t-\Delta t) + \frac{\dot{m}_x[T_{st,3}(t-\Delta t) - T_{st,4}(t-\Delta t)]}{\rho V_4}\Delta t \quad (7)$$

$$\dot{m}_x(t) = \frac{\dot{m}_2(T_{set\,point} - T_4)}{T_{st,4}(t-\Delta t) - T_4} \quad (8)$$

$$T_{4,r}(t) = \frac{\dot{m}_x T_{st,4}(t-\Delta t) + (\dot{m}_2 - \dot{m}_x)T_4}{\dot{m}_2} \quad (9)$$

The storage system is not always able to provide the required heat flow rate to reach set point conditions since $\dot{m}_x$ is limited from 0 to $\dot{m}_2$. For this reason, the temperature reached after the mixing in point A is indicated as $T_{4,r}$ in Eq. 9. It is possible to calculate the SOC as expressed in Eq. 10, knowing the storage temperature profile:

$$SOC = \frac{T_{st,1}V_1 + T_{st,2}V_2 + T_{st,3}V_3 + T_{st,4}V_4}{V_{tot}T_{max}} \quad (10)$$

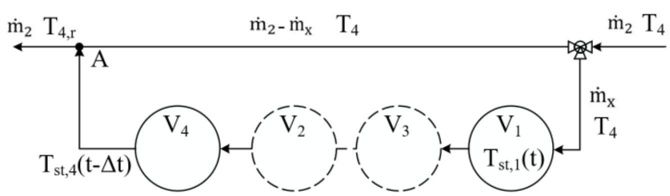

Figure 4. Stratified storage tank model

4 RESULTS

4.1 Storage system operation

Figure 5 shows the behaviour of the stratified storage for an exemplary period of two weeks. As T_4 changes, according to thermal load absorbed by greenhouses; $T_{set\,point}$ is fixed over the examined exemplary period. Moreover, the upper graph shows the variation of storage tank state of charge (SOC) as temperatures change. The equation for SOC is given by Eq. 10, where T_{max} is the maximum storage temperature reached during the whole year, and V_{tot} the sum of four volumes. As shown in Figure 5, if T_4 is higher than $T_{set\,point}$ and T_{st}, the SOC increases. Vice versa, if T_4 is lower than $T_{set\,point}$ and T_{st}, the SOC decreases. Lastly, the cases with a constant SOC indicate the occurrences in which heat flow rate should be dissipated but T_{st} is higher than T_4, or the cases in which heat flow rate would be required ($T_4 < T_{set\,point}$) but T_{st} is colder than T_4.

4.2 Cumulative distribution function for residual heat flow rate

The cumulative distribution function for the residual heat flow rate is shown in Figure 6. Cumulative distribution function for $|\dot{Q}_r|$ as the volume changes (left). Cumulative distribution function for both positive (surplus) and negative (defection) of $\dot{Q}_r$ for an exemplary volume of 10000 m^3 (right).. Five storage tank volumes have been investigated in a range between 2500 and 20000 m^3. By increasing the storage tank volume the percentage of occurrences in which the system reaches the setpoint (corresponding to the y value for x = 0) increases. However, as the volume increases, the relative improvement decreases. By using 10000 m^3 rather than 5000 m^3 allows an improvement of 3 %, whereas by using 20000 m^3 rather than 15000 m^3 allows an improvement of 1 %. This phenomenon indicates that the system behaviour is asymptotic as the volume increases.

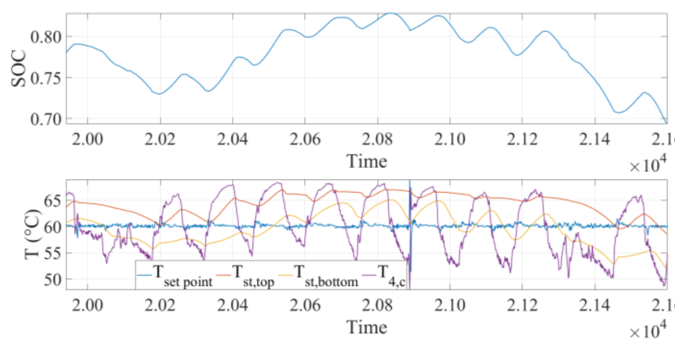

Figure 5. Storage system operation related to its state of charge and system temperatures

As a matter of fact, the storage effectiveness in reaching the set point conditions is driven by its internal temperatures. Hence, even if the tank had an infinite volume, its SOC may not be compatible with the cooling/warning duty required by the flow at certain times, so the system cannot reach the setpoint temperature.

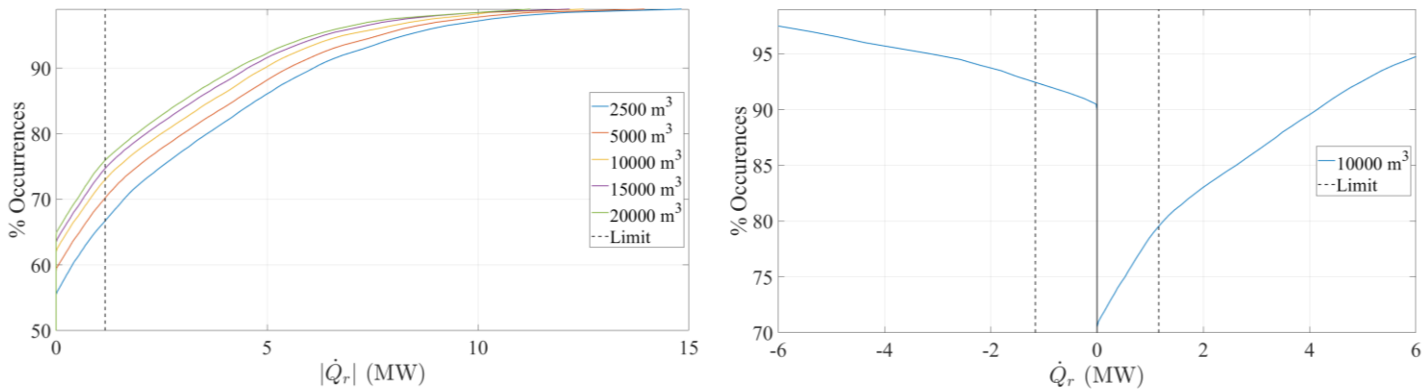

Figure 6. Cumulative distribution function for $|\dot{Q}_r|$ as the volume changes (left). Cumulative distribution function for both positive (surplus) and negative (defection) of $\dot{Q}_r$ for an exemplary volume of 10000 m^3 (right).

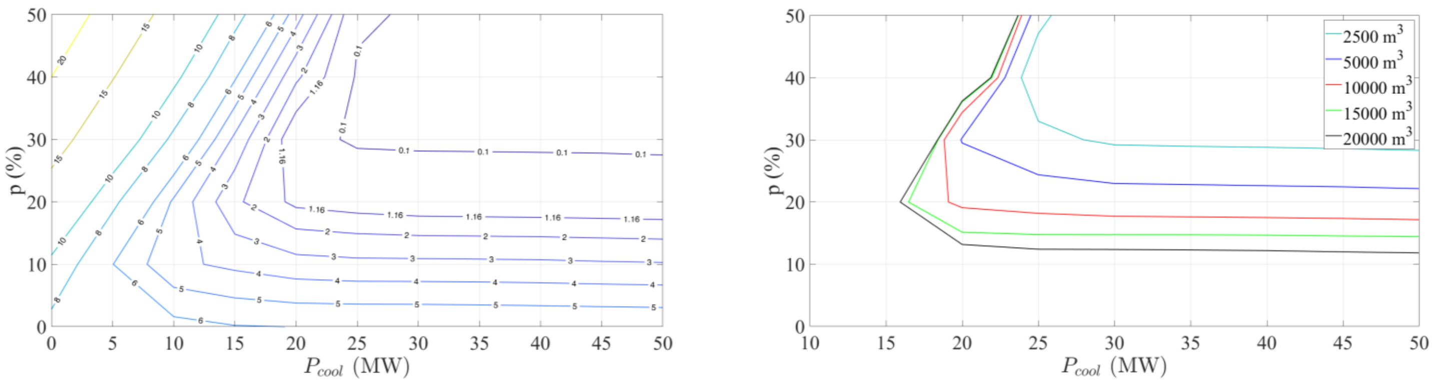

Figure 7. $p_{95\%}$ reached as P_{cool} and p change for an exemplary volume of 10000 m^3 (left). $p_{95\%}$ of 1.16 MW reached as P_{cool} and p change for a volumes in a range from 2500 m^3 to 10000 m^3 (right).

4.3 Operation maps-performance parameters

Results shown in the previous section 4.2 are valid for a given cooler power rating and increment of the heat flow rate supplied by the geothermal plant. As it resulted, in that case, setpoint conditions are not achieved in the 100 % of occurrences. However, different combinations of these two parameters can be investigated to obtain setpoint conditions for a higher percentage of cases. The contour lines represented in Figure 7 shows the value of the 95-th percentiles $p_{95\%}$ of $\dot{Q}_r$ obtained by varying P_{cool} and p for different tank volumes. As expected, the increase of *p* implies the use a more powerful cooler since the heat flow rate in excess increases. The almost horizontal part of the contours, instead, indicates that, for a given value of *p*, exists a $\mathrm{P_{cool}}$ value over which the rising of cooler power is unnecessary. Figure 7 shows how the $\mathrm{p_{95\%}}$ for the value 1.16 MW can be reached by varying the cooler power rating, energy supply increment and storage tank volume. As mentioned in Section 4.2, the system performance improves as the volume grows; however, by using a volume greater than 10000 does not imply a significant benefit.

4.4 Results varying the period and with forecast errors

Results discussed in the previous Section 4.3 shows that reaching a value of $\dot{Q}_r$ corresponding to a certain $p_{k\%}$ is possible by setting several couples of values for $\mathrm{P_{cool}}$ and p. Generally, by choosing a specific combination of $\mathrm{P_{cool}}$ and *p* is subject to economic and feasibility considerations. Table 1 gathers the most promising combinations of p and $\mathrm{P_{cool}}$. Such combinations are chosen from Figure 7 as the point that requires minimum p and minimum P_{cooler}.

The following considerations stemming from the results in Table 1 are worth to be observed:

- for the case with ideal forecast (no errors), changing the length of the period with fixed heat flow rate supply from seven to fifteen days does not significantly affect system performance;

- For the case with a non-ideal forecast, extending the period with a fixed heat flow rate supply leads to a significant deterioration of system performance. This behaviour is due to both the storage system and the cooler being unable to introduce energy into the system. Therefore, if the supplied energy is less than that that is required by the greenhouses, the system cannot operate properly due to incorrect forecasts. Furthermore, the storage can only shift energy over time, from periods of energy surplus to moments with energy shortages. For this reason, the storage system operates properly if surpluses and shortages are comparable, which does not occur when the future thermal demand of greenhouses is imperfectly forecasted.

Table 1. Values of *p* and P_{cool} necessary to reach some $p_{k\%}$ varying the length of period with assigned heat flow rate and considering forecasting errors

7 days	$p_{k\%}$	p (%)	P_{cool} (MW)
with an ideal forecast	95	20	21
	90	10	12
	85	10	9
	80	10	5
with forecasting error	95	50	34
	90	20	20
	85	20	14
	80	20	11
15 days	$p_{k\%}$	**p (%)**	P_{cool} **(MW)**
with an ideal forecast	95	20	17
	90	10	12
	85	10	8
	80	10	5
with forecasting error	95	-	-
	90	30	40
	85	20	20
	80	20	15

5 CONCLUSIONS

This paper examined the effects of using a storage system to manage load fluctuation. Some parameters have been investigated, like the storage volume, the length of the period with fixed heat flow, the maximum thermal power of the cooler and the increase of supplied power. The study of the mitigation of thermal load fluctuations with storage systems highlights the following observations:

- The storage ability to keep the thermal load constant over the prescribed period improves by increasing the storage tank volume. However, the relative improvement becomes negligible over a certain volume threshold. For the investigated plant, a volume of 10000 m^3 can be considered as acceptable;
- An incorrect prediction of the thermal load absorbed by greenhouses brings to a significant deterioration of working performance;
- Shortening the period over which the supplied heat flow rate must be a constant is not significant when power absorbed is perfectly forecasted, while it influences when there are forecasting errors.

Concluding, this study investigates the design of a storage tank to mitigate wide thermal load fluctuations without a forecast strategy. Some configurations that might be useful to this purpose have been defined. The addition of predictive forecast methods to foresee consumptions might improve the fluctuation mitigation by also reduce the tank size thank to predictive and optimized managing strategies for the storage.

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