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Analysis of the influence of thermal energy storage on the optimal management of a trigeneration plant.

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Abstract

Safety, security, and sustainability of energy supply chains are among the main concerns of industrialized countries, and, therefore, distributed generation has significantly increased its share of the energy market, thanks to the possibility to simultaneously meet electrical, thermal and cooling demand, thus increasing the overall source-to-final-use conversion efficiency. The efficiency of a distributed generation system is influenced both by the individual performance of the plant components as well as by their interconnection, and is very sensitive to the control strategy adopted in the different plant sections. This last remark is particularly relevant for distributed generation systems, that are subject to rapid gradients in both the thermal and electrical loads, and in the values of the energy vector. In this respect, the introduction and the correct management of energy storage systems is a key point for trigeneration plants. In fact, energy storage brings on the one side advantages as for the reduced components sizes, but more importantly allows for a substantial decoupling of the thermal and electrical demands, making load following less of a stringent requirement. An optimization methodology, based on energy fluxes simulation, and on the application of the graph theory as in previous works by some of the authors, is used to identify the optimal set-points for each component. The optimization algorithm searches for the plant management envelope that minimizes a prescribed objective function. Specifically, two different optimization criteria are considered: i) economic optimization that minimizes the total daily operating cost and ii) primary energy use optimization, that minimizes the total daily amount of primary energy used by the plant. Since the paper focus is on the effects of energy storage, the trigeneration plant behavior will be analyzed both in terms of economical results and in terms of efficiency and primary energy use.

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Keywords: CHCP, trigeneration, optimization, thermal storage, distributed generation;

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Nomenclature

Abbreviations and symbols

AC	Absorption Chiller
CHCP	Combined Heat Cooling and Power
C	Cost
DG	Distributed Generation
I_0	Equipment capital cost
ICE	Internal Combustion Engine
L	Equipment expected life-time
LHV	Lower Heating Value
MC	Mechanical Chiller
N	Number
N_m	Number of equipments in the plant
N_{time}	Number of time-steps
PEC	Primary Energy Consumption
$\dot{Q}$	Thermal storage heat flux
Q_{max}	Thermal storage capacity
Q_0	Thermal initial state of charge
R	Revenues
c	Specific cost
k	Equipment set-point
$\dot{m}$	Mass flow
p	Power
pef	Primary Energy Factor
t	Time
u	Energy demand
Δt	Time step length
η	Efficiency
τ_{off}	Minimum duration of non-working intervals
τ_{on}	Minimum duration of working intervals
χ	Environmental power derating
ψ	Environmental efficiency derating

Subscripts and superscripts

ch	Chilling
el	Electrical
f	Fuel
g	Electricity demand index
$grid$	Grid
h	Thermal demand index
in	Input
l	Chilling demand index
m	Maintenance
n	Equipment index
on	Ignition
out	Output
r	Rated
th	Thermal
Tot	Total

1. Introduction

The potential advantages of trigeneration, i.e. the simultaneous generation of electricity, thermal, and chilling energy, by means of relatively small conversion units located close to the energy user, are well established. Among the recognized DG expectations there are: i) higher sources-to-final-use efficiencies [1], compared to separate production [2]; ii) reduction of pollutant and green house gases emissions, and fossil fuels depletion [1,3]; iii) deferring expensive investments on large size plants [1], and on transmission and distribution system [3]; iv) reducing the losses in the distribution system [3]; v) providing network support or ancillary services [3]; vi) promoting the use of alternative technologies and renewable sources [1,4,5]. Several applications of DG can be found on literature, both coupled with renewable sources [4,6,7], as well as based on fossil fuels [8–11].

CHCP management policy is a key aspect to ensure that the previous points are effectively met [12–15]. Specifically, the optimization of the set-point of each subsystem of a DG plant can significantly improve the energy system performance, as widely demonstrated in literature [11,12,15–17]. In particular in [15], building on the approach of [12,13,16], the authors developed an optimization procedure that permits the integration of a prescribed objective function over a predetermined time horizon, thus allowing to account for energy storage, and for the equipment dynamic behavior, through the introduction of ignition costs, and of turning on and off minimum time intervals.

Energy storage devices are often introduced in CHCP plans in order to reduce the components sizes, and to increase the heat recoverable from the prime mover, shifting in time the thermal demand to match the electrical one. More fundamentally, the introduction of thermal energy storage allows a substantial decoupling of electrical and thermal demand, increasing the CHCP degrees of freedom and making load following a less stringent constraint [18–20]. Thereafter, economic and energy optimization may benefit of the introduction of energy storage.

In this paper the methodology introduced in [15] is utilized to determine the optimal set-point for all the subsystems of a CHCP plant, in presence of thermal energy storage. Two different objective functions are considered, namely cost and primary energy consumption minimization, and the results are compared to rule-based strategies, such as load-leveling and load-shifting, to demonstrate the effectiveness of set-point optimization and dissect the role of energy storage for distributed generation. Moreover, a sensitivity analysis on the reservoir capacity is performed, to further analyze the energy storage effects on the energy conversion systems behavior, and to highlight the potential of using the optimization procedure also to support the plant design.

2. Plant Modeling

Following the approach in [12–15], all the equipments in the trigeneration plant are modeled through a black-box approach, which means that, they are considered as energy converters and characterized by means of one or more transfer functions (i.e. efficiency curves). The choice of a lumped model is dictated by the need to combine a sufficiently accurate description of the energy conversion processes with low computational costs. This allows the application of the proposed methodology to real industrial problems, where the optimization must be performed a very short time. Therefore, it is crucial that the experimental data used to define the equipment models are reliable, in order to ensure the reliability of the optimization. The fundamental model relations are reported in Tab. 1.

Rated power, efficiency curves, derating functions, and environmental conditions are model inputs. Moreover the minimum duration of time intervals where a generic machine is on or off are introduced to guarantee that the optimized regulation strategy is physically feasible [15].

Table 1. Plant equipment modeling.

Equipment	p_{el}	p_{th}	p_{ch}	p_{in}	$\dot{m}_f$
Trigenerative machinery	$k^n p_r^n \chi^n(t)$	$p_{in}^n(t,k^n)\eta_{th}^n(t,k^n)$	$p_{in}^n(t,k^n)\eta_{ch}^n(t,k^n)$	$\frac{p_{el}^n(t,k^n)}{\eta_{el}^n(t,k^n)\psi^n(t)}$	$\frac{p_{in}^n(t,k^n)}{LHV^n}$
Fuel boiler	—	$k^n p_r^n \chi^n(t)$	—	$\frac{p_{th}^n(t,k^n)}{\eta_{th}^n(t,k^n)\psi^n(t)}$	$\frac{p_{in}^n(t,k^n)}{LHV^n}$
Chiller	—	—	$k^n p_r^n \chi^n(t)$	$\frac{p_{ch}^n(t,k^n)}{\eta_{ch}^n(t,k^n)\psi^n(t)}$	—
Thermal Storage	—	$k^n p_r \eta_{ts_{out}}$ if $k \geq 0$	—	$\frac{k^n p_r}{\eta_{ts_{in}}}$ if $k < 0$	—

Internal and external energy fluxes, that represent the constraints that the plant must fulfill, are reported in eq. (1) [12,15].

$$0 \leq \sum_{n\in\mathcal{T}} p_{th}^n + \sum_{n\in\mathcal{B}} p_{th}^n + \dot{Q} - \left(\sum_{h=1}^{N_{th}} u_{th}^j + \sum_{n\in C_{\mathcal{A}}} p_{in}^n \right) \leq \Omega_{th} \ , \tag{1a}$$

$$0 \leq \sum_{n\in C} p_{ch}^n - \sum_{l=1}^{N_{ch}} u_{ch}^h \leq \Omega_{ch} \ , \tag{1b}$$

$$\sum_{n\in\mathcal{T}} p_{el}^n - \left(\sum_{g=1}^{N_{el}} u_{el}^g + \sum_{n\in C_{\mathcal{M}}} p_{in}^n \right) = P_{grid} \ , \tag{1c}$$

where the energy production and consumption of each subsystem are calculated using the relations in Tab. 1, while the parameters Ω_{th} and Ω_{ch}, introduced to account for all the situations where thermal and chilling power rejection to environment is limited, and the energy demands are model inputs. Similarly, $P_{grid} = 0$ for stand-alone power plants.

Note that, for positive values of $\dot{Q}$ the heat flux is directed from the storage system to the energy demand, and $\dot{Q} = p_{th}^n$. Conversely, when $\dot{Q} < 0$, the thermal energy produced by the energy conversion system exceeds the demand, being overproduction (or a part of it) used to charge the storage system, and $\dot{Q} = p_{in}^n$. Moreover, the following constraint is required by the thermal storage capacity:

$$0 \leq Q_0 + \sum_{t=1}^{T} \dot{Q}\Delta t \leq Q_{max} \qquad \forall T \in [1, N_{time}] \ . \tag{2}$$

3. Optimization algorithm and objective functions

The proposed methodology determines the optimal plant state minimizing the value of a prescribed objective function [12,15]. In particular, two optimization criteria are considered, in this paper:

1. Cost minimization. The objective function, that accounts for fuel, maintenance, and ignition costs, as well as for the results of thermal, chilling and electricity revenues/costs, reads

$$C(t, \boldsymbol{k}) = C_f(t, \boldsymbol{k}) + C_m(t, \boldsymbol{k}) + C_{on}(t, \boldsymbol{k}) - R(t, \boldsymbol{k}) \ . \tag{3}$$

2. Primary energy consumption minimization, that is characterized by the following objective function

$$\mathrm{PEC}(t, \boldsymbol{k}) = \sum_{n \in (\mathcal{T} \cup \mathcal{B})} \dot{m}_f^n(t, \boldsymbol{k}) pef^n \Delta t(t) + P_{grid} pef_{grid} \ . \tag{4}$$

The problem is discretized in time and plant state and represented as an acyclic weighted graph. Each node of the graph, represents the operations of the plant for a single time-step with a prescribed state, and the arcs weight is determined by the value of the selected objective function, at its origin node. The optimal plant state is then determined for each time-step, seeking the shortest (i.e. minimum overall weight) path across the graph, resorting to the Bellmann optimality [21] condition and using backward dynamic programming [22,23]. This algorithm allows to determine the sequence of plant states that minimizes the value of the objective function integrated over the whole observation period, as required by the presence of energy storage, τ_{on}, τ_{off}, and ignition costs. For a detailed description of the algorithm, the reader can refer to [15].

4. Case Study

4.1. Energy demand

A typical hospital energy demand is considered as a case study. Energy loads for three different climatic conditions (i.e. winter, summer, and a transitional season) are retrieved from [24] and represented in Fig. 1.

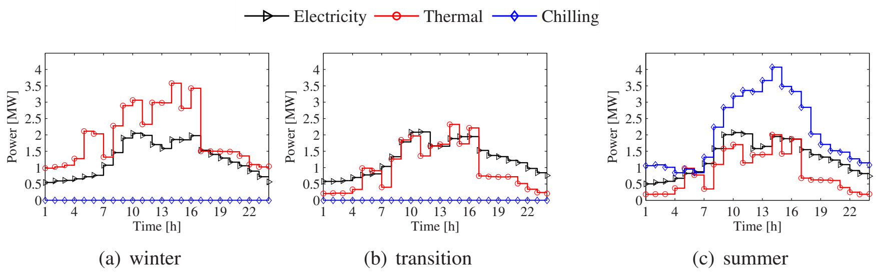
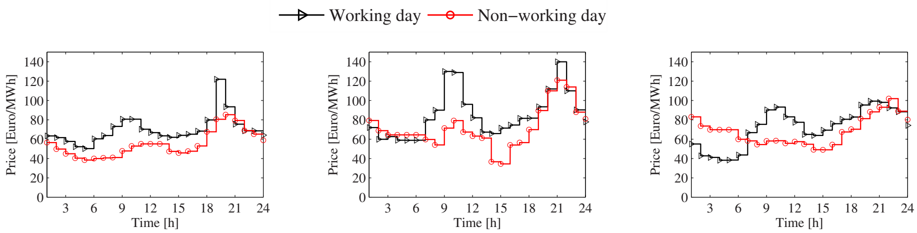


Fig. 1. Energy demand time traces [24].

The winter demand can be considered the most favorable for cogenerative applications thanks to its high heat to power ratio that allows the complete heat recovery from the prime mover, and lower variability of the heat demand, compared with the other situations, thus facilitating the plant power regulation. If absorption chillers are adopted, a very high degree of heat recovery is also possible during summer, improving the total efficiency of the plant. Nevertheless, in this situation, the regulation strategy appears more critical compared to winter.

Thermal and chilling energy productions are self-consumed, and do not generate revenues but act as constraint for the energy system. Similarly, electricity is transfered to the hospital without charges, but power exchange are also possible with the grid in both directions. Electricity selling revenues are calculated according to the Italian regulation, with the procedure reported in [26,27], and the selling rates, determined by the enrgy market [26], are reported in



(a) winter (b) transition (c) summer

Fig. 2. Time traces of the electricity value sold to the grid [25].

Fig 2. The price of electricity bought from grid is equal to 150 €/MWh for peak hours (8-19) and 90 €/MWh during off-peak hours (20-24 and 0-7), and weekends. Values are estimated on the basis of Eurostat data [28].

4.2. *Trigeneration plant*

The energy demand is satisfied using a trigeneration plant composed of: i) a cogenerative internal combustion engine; ii) a fuel boiler; iii) a mechanical chiller; iv) a single effect absorption chiller. A hot water thermal storage is also considered in the plant. The main design characteristics of the each component of the plant are reported in Tab 2.

The ICE is chosen so that its rated thermal output equals the highest daily average thermal demand among the considered situations. In particular, summer is characterized by the highest thermal demand, having assumed that chilling load is satisfied using absorption chillers. Therefore the total heat demand is estimated as

$$u_{th}^{Tot} = u_{th} + \frac{u_{ch}}{COP_{ref}} , \tag{5}$$

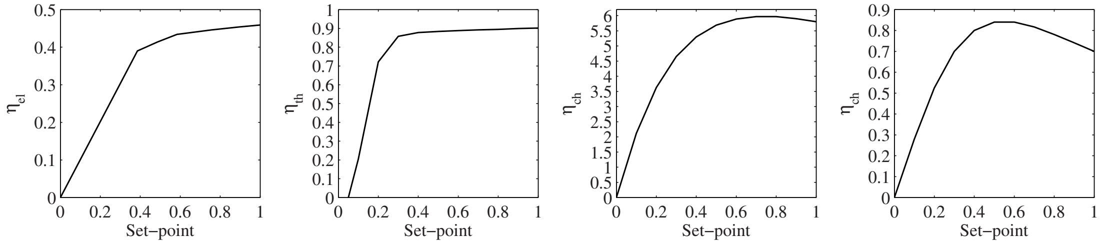
where $COP_{ref} = 0.7$ is the rated coefficient of performance of the absorption chiller. The ICE design and off-design performances are retrieved from [29] and [30]. According to [29,30], environmental derating is significant only for very high values of external temperature and altitude. Therefore their effect can be safely discarded in this application. Engine maintenance costs are estimated according to the survey in [2].

A 24 MWh capacity hot water storage is also included in the plant and acts as a compensation reservoir, being its capacity designed in order to allow a complete load leveling during the hot season. The charge and discharge efficiencies of the storage are both set to 0.95 [31]. Having considered a relatively low storage time (lower than one day) the thermal storage energy loss, that is usually comprised in the range 1-2% of the storage capacity per day, is neglected.

Table 2. Main design parameter of the CHCP plant.

		ICE	boiler	MC	AC
Rated Power P_r	[MW]	4.560	3.500	4.200	4.200
η_{el}	[/]	0.459	—	—	—
η_{th}	[/]	0.400	0.900	—	—
η_{ch}	[/]	—	—	5.800	0.700
Fuel cost c_f	$\left[e/\mathrm{Sm}^3\right]$	0.37	0.37	—	—
Maintenance cost c_m	[€/h]	22.00	1.00	6.00	10.00
Ignition cost c_{on}	[€]	22.00	1.00	6.00	10.00
τ_{on}	[h]	2	0	0	0
τ_{off}	[h]	2	0	0	0

A 3.5 MW natural gas boiler, is also included both to guarantee that the hospital thermal load is always satisfied also during ICE off-duty periods, as well as to increase the CHCP plant flexibility. Finally, two chillers, (one absorption and one mechanical chiller), both dimensioned on the peak chilling demand are included. The AC guarantee an optimal heat recovery from the ICE also during the hot season, while the presence of the MC releases the ICE from the production the heat demand necessary to feed the AC, and acts as a back-up solution.



(a) ICE [29] (b) boiler [32] (c) mechanical chiller [32] (d) absorption chiller [32]

Fig. 3. Efficiency curves for all the plant equipments.

Design and off-design performances of boiler and chillers are estimated using relations and data in [32], while maintenance costs are estimated as $c_m = I_0/L$, where the capital cost I_0 is a function of size and technology, as reported in [32], and the equipment useful life is hypothesized equal to 200,000 hours. Fuel costs are retrieved from eurostat statistics [28], and ignition costs are hypothesized equal to one hour of maintenance for all the equipments.

4.3. Rule based management vs. optimized strategies

The energy system state is optimized according to the two objective functions described in section 3. Such strategies are compared to traditionally employed rule-based policies [33], in terms of total cost and daily primary energy consumption. Two different rule-based strategies are identified based on the energy demand time trace. Specifically, *load leveling* [33] is used for the summer load. According to this strategy the engine operates at full load for the whole day, and the thermal storage compensates all the demand variations. Conversely, the energy necessary to satisfy winter and spring heat demand can be produced exploiting the ICE for a reduced number of hours (about 12 hours in winter and 8 hours in spring). Thereafter, *load shifting* [33] is adopted for these situations, meaning that energy is produced only during peak hours (i.e. when electricity value is higher) and stored for deferred usage.

It is worth pointing out that, for all the management strategies, without loosing generality, the state of charge of the storage at the end of the last time-step is constrained to be equal to the initial one. Therefore, costs and energy consumptions of the different strategies can be directly compared.

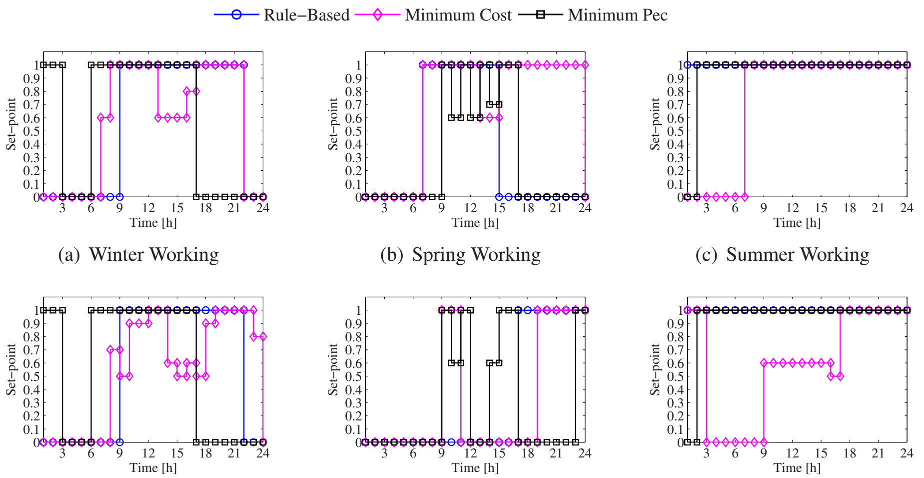
Table 3. Daily Cost: rule based strategy vs. optimized management.

	Summer		Spring		Winter	
	Working	WeekEnd	Working	WeekEnd	Working	WeekEnd
Rule-based [€]	3772	3811	2964	2403	3102	3605
Minimum Cost [€]	3085	3496	1945	2341	2820	3397
Minimum PEC [€]	3618	3764	3015	3076	3516	4020

Table 4. PEC: rule based strategy vs. optimized management.

	Summer		Spring		Winter	
	Working	WeekEnd	Working	WeekEnd	Working	WeekEnd
Rule-based [GJ]	339	339	269	269	298	298
Minimum Cost [GJ]	335	345	302	269	289	293
Minimum PEC [GJ]	331	331	269	269	282	282

Daily costs and PEC for all the energy demand and electricity value combinations are reported in Tab. 3 and Tab. 4, respectively. The minimum cost optimized management yields significantly lower overall costs with respect to rule-based, and minimum PEC strategy. Specifically, the relative difference ranges between approximately 2.5% and 35%, with respect to the rule based policy, and between 8% and 55% compared to the minimum PEC management. On the other hand minimum PEC optimization guarantee a reduction of PEC that varies from 0.1% to 2.5%, with respect to rule based strategy, and between 1.1% to 11%, compared to cost minimization. It is noted that, generally speaking, cost minimization does not generate primary energy savings, and vice-versa. Indeed, plant efficiency is only one among the large number of parameters that determine the electricity rates, that, in turn, have a crucial influence on economic optimization. For instance, electrical grid congestions, difficulties related to operate large plants at part load, or the necessity to integrate non-controllable renewable sources on the grid can be considered as key factors for electricity rates determination. In this respect economic optimization responds to an industrial vision of maximizing the single plant profitability, while PEC minimization would be more coherent with a socio-economic objective seeking to minimize the environmental impact. PEC minimization is achieved maximizing the overall energy system efficiency. Thereafter, as depicted in Fig. 4, the engine mainly works at full load (part load occurs only during transition days), and thermal reservoir is used to compensate between thermal demand and production, as shown in Fig. 5. On the other hand, economic optimization is fundamentally driven by the electricity price time series. Thus, according to this management criterion, the engine is allowed to operate a part load when electricity production cost is comprised between sold and acquired electricity values. Moreover, comparing Fig. 2, and Fig. 5 it can be noted that thermal energy is mainly stored during the morning and evening electricity price peaks. Finally, comparing Fig. 1, and Fig. 4, it is noted that the usage of energy storage effectively releases the prime mover from load following, allows the optimization algorithm to meet the objective function minimization with the highest number of degrees of freedom.



(a) Winter Working (b) Spring Working (c) Summer Working

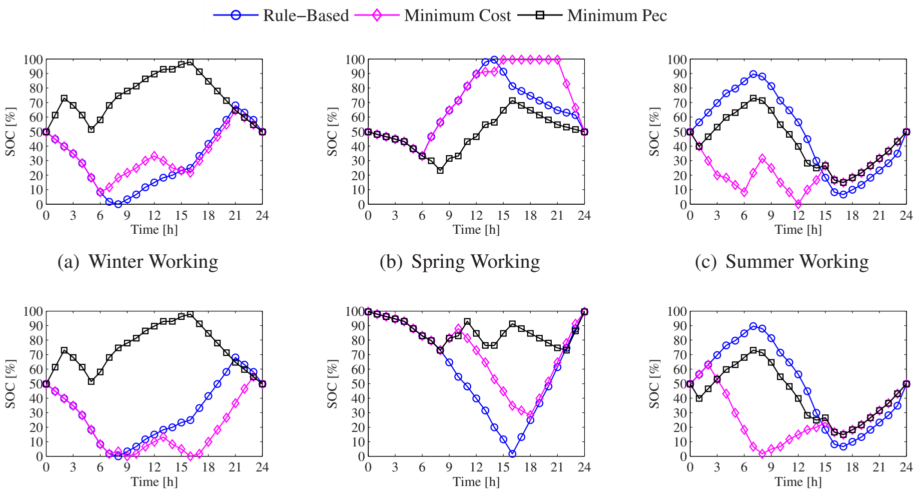
(d) Winter Weekend (e) Spring Weekend (f) Summer Weekend

Fig. 4. Engine set-point for optimized and rule based strategies for different energy demands and electricity values.

Table 5. Engine utilization factor: rule based strategy vs. optimized management.

	Summer		Spring		Summer		Average
	Working	WeekEnd	Working	WeekEnd	Working	WeekEnd	
Rule-based	0.541	0.542	0.333	0.333	1.000	1.000	0.625
Minimum Cost	0.537	0.550	0.675	0.333	0.750	0.615	0.576
Minimum PEC	0.541	0.542	0.288	0.300	0.958	0.958	0.598

Generally speaking, the usage of optimized strategies reduces engine utilization factor compared to the chosen rule-based policy, as evidenced in Tab. 5. In particular, cost minimization leads to the lower average utilization factor, thus maximizing the cash flow while reducing maintenance costs and increasing the engine useful life, at the same time. This trend is basically respected for all the considered cases except for the transitional working day. This behavior is explained, observing that the high rates of electricity that characterize this case (see Fig. 2(b)), promote electricity selling to the grid, that requires high engine load, irrespectively of electrical and thermal self-consumption. This is also evidenced if we compare Fig. 5(b) and Fig. 4(b), and observe that from 12 hours to 21 hours the engine is operated at almost full load, despite storage of excess thermal production, is not allowed as the reservoir is saturated. On the other hand, the relatively low heat demand hamper heat recovery from the prime mover, thus reducing the overall plant efficiency and the engine utilization factor, if PEC minimization is required.



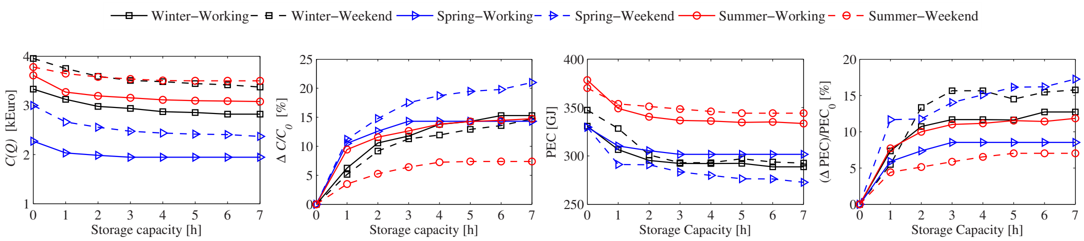
(a) Winter Working (b) Spring Working (c) Summer Working

(d) Winter Weekend (e) Spring Weekend (f) Summer Weekend

Fig. 5. Thermal storage SOC for optimized and rule based strategies for different energy demands and electricity values.

4.4. Sensitivity analysis on the thermal storage capacity

After having demonstrated the effectiveness of the proposed optimization methodology, a sensitivity analysis on the thermal storage capacity is performed. For the sake of clarity the thermal storage capacity is scaled by the maximum thermal output of the cogenerative engine. Therefore the storage dimension will be expressed in hours. Eight values of Q_{max}, ranging from 0 h to 7 h are considered. For each of these values the optimal policy is determined, varying the energy demand and electricity value profiles.



(a) Cost (b) Relative cost variation (c) PEC (d) Relative PEC variation

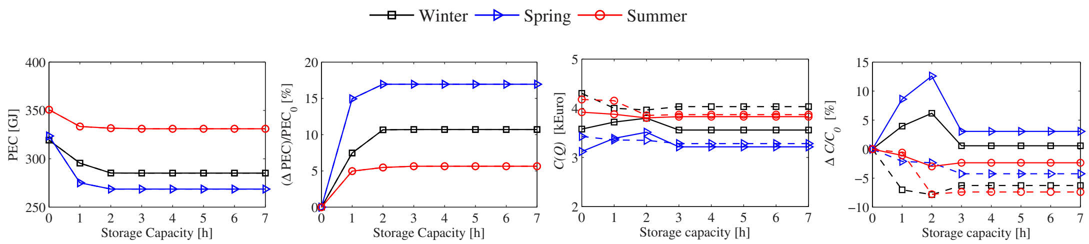
Fig. 6. Influence of the thermal storage capacity on the daily cost. C_0 stands for cost obtained with zero thermal storage capacity.

Results for economic optimization, reported in Fig. 6, evidence that both the cost, and the PEC, decrease as the storage capacity is increased. Moreover, both cost, and PEC functions show a tendency to saturate for storage capacity higher that 3 hours, thus significantly lower compared to the value identified hypothesizing the load leveling strategy. Cost savings saturate at values comprised between 7% (summer non working day) and 20% (spring non working day) of the total cost with no energy storage. Analogous results are obtained also in terms of primary energy savings. Economical aspects related to thermal storage capacity design can be further dissected through a net present value analysis. The annual cash flow, generated by the introduction of a given capacity thermal storage is estimated as the summation of the avoided costs relative of each of the representative days considered, over the whole year, and reported in Tab. 6 as function of the thermal storage capacity. The investment for a given capacity thermal storage can be estimated using the data from [31], and ranges between 0.1 and 10 €/kWh. Thereafter, safely considering the highest value in the range, the investment cost of a 3 h capacity (i.e. about 12 MWh) storage would be about 120 k€, and could be recovered in 10 months. On the other hand the cost of installing a 7 h capacity thermal storage, as required by the system design based on load leveling concept, is about 280 k€, and its pay-back time would be approximately 20 months. Moreover, as demonstrated in Tab. 6, the maximum values for the 5 and 10 years net present values, are reached for reservoir capacity between 3 and 4 hours.

Table 6. Net present value analysis as function of the storage capacity.

Q_{max} [h]	1	2	3	4	5	6	7
Cash flow [k€/year]	93	125	143	153	158	162	165
Pay back period [months]	5	8	10	13	15	18	20
5 years NPV [k€]	321	406	435	436	413	388	362
10 years NPV [[k€]	464	701	771	797	785	769	752

Similar results are obtained if the sensitivity analysis is performed following the minimum PEC criterion, as highlighted in Fig. 7. Specifically, in this case, PEC functions reach an asymptote for lower values of the storage capacity, with respect to economical optimization (i.e. for $Q_{max} = 2$ h). It is also noted that according to PEC minimization cost is not a monotone decreasing function of the storage capacity, unlike the minimum cost policy that generates substantially decreasing PEC as the reservoir capacity is increased (see Fig. 6).



(a) PEC (b) Relative PEC variation (c) Costo (d) Relative cost variation

Fig. 7. Influence of the thermal storage capacity on the daily PEC.

5. Conclusions

In this paper we studied the behavior of a trigeneration plant, under different energy demand and prices, with particular reference to thermal energy storage dynamics. The plant was designed to maximize the amount of self-produced energy, recognizing the distributed generation represents a valuable instrument to meet the increasing energy demand, avoiding expensive investments on large plants and grid infrastructure, while increasing the overall energy system efficiency. We focused on the effects of the plant management strategy on the energy system economical and energetic performances. In particular we utilized an optimization methodology, previously introduced by some of the authors [12–15], to determine the optimal plant state, according to different objective functions (i.e. minimum costs, and minimum PEC), and compared the result to rule based strategies (i.e. load-leveling and load-shifting). This study confirmed that a proper management policy is a key point to exploit all the expected advantages of distributed generation, and that equipment set-point optimization is a viable option also in presence of thermal energy storage. Specifically, socio-economic externalities can be significantly reduced through PEC minimization, while economical optimization significantly improves the plant profitability, avoiding massive investments that would be necessary to seek the same objective updating the plant components.

Moreover, we demonstrated that the usage of plant management optimization, besides improving the economical and/or energetic performances of a given plant, can also usefully support its design. In fact, the thermal storage capacity suggested by the sensitivity analysis (3 hours), is less than a half with respect to the one identified by the traditional design concept (7 hours), thus reducing the initial investment as well as the pay back period, without significantly affecting the long term net present value.

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