Price-based demand side management (DSM) coupled with cold thermal energy storage (TES) and solar PV for peak-load reduction

Mohammad Saffari[1], Alvaro de Gracia[2], Cèsar Fernández[1], Martin Belusko[3], Dieter Boer[2], Luisa F. Cabeza[1]*

[1]GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Lleida, Spain

[2]Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Tarragona, Spain

[3]Barbara Hardy Institute, University of South Australia, Mawson Lakes Boulevard, Mawson Lakes, South Australia, Australia

*Corresponding author: lcabeza@diei.udl.cat

Abstract

Peak electricity demand has become a global concern. It causes grid transmission constraints and congestion, and also increases the cost of electricity for all users, specifically industrial consumers with high peak demands. Time-of-use demand side management coupled with thermal energy storage and off-grid solar PV can be an alternative to increase the flexibility and security of the whole energy system. The aim of the current paper is to study the potential of implementing time-of-use demand side management coupled with thermal energy storage and solar PV technologies using optimization techniques for shifting electricity peak loads of cooling processes in an industrial unit. It was found that considerable reductions can be achieved in electricity power demands in different tariff periods using optimization-based demand side management (DSM) together with thermal energy storage and off-grid solar PV. In addition, it was seen that coupling cold thermal energy storage and solar photovoltaic technologies is more energy-beneficial than using them separately.

Keywords: Thermal energy storage, solar PV, time-of-use DSM, optimization, peak-load shifting.

1. Introduction

In developed nations electricity plays an important role to economic growth. A considerable rise in electricity demand can be seen in all end-use sectors, and further on, the share of electricity is steadily increasing in all sectors (IEA, 2016). In addition, increasing wealth in developing nations are likely to lead to bigger demand for energy services using electricity, such as cooling and refrigeration. The industry sector is one of the major energy-consuming sectors in the world with about one third of total final energy consumption and almost 40% of total energy-related CO_2 emissions. Reducing these hazardous emissions due to high non-renewable generations is an important issue in the global climate system. For this reason, many governments in the world are exploring alternatives to slow down the global warming by enforcing new rules and regulations for different sectors.

Peak electricity demand is a global policy concern which creates transmission constraints and congestion, and raises the cost of electricity for all end-users (Strengers, 2012). In addition, a considerable investment is required to upgrade electricity distribution and transmission infrastructure, plants and build non-renewable power generation to provide power during peak-demand periods (Strengers, 2012). For this reason, commonly service suppliers charge a higher price for services at peak-time than for off-peak time to compensate for the costly electricity generation at peak hours (Kim et al., 2016). So that, reducing some of this peak demand would benefit the whole energy system (Faruqui et al., 2007).

Solar PV is becoming an important technology in the world energy market for electricity generation, and it has proven its capability to reduce energy costs and hazardous energy-related emissions over time and this is projected to continue. However, in systems with high shares of PV generation, variability and uncertainty in electricity generation within the system may occur because of weather conditions. To overcome this uncertainty energy storage could be a solution to match energy supply and demand. As an example, battery storage technologies could be used to store generated electricity by solar PV, however, currently large-scale electricity storage technology is expensive and needs further technology development (Hameer and van Niekerk, 2015), as a result, electricity storage has limited potential and the generated electricity has to be consumed instantly

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(Faruqui et al., 2010).

Demand side management (DSM) is a proactive way to increase the energy efficiency among customers in the long-term (Barbato and Capone, 2014), and can reduce both the electricity peak power demand (kW) and the electricity consumption (kWh) (Warren, 2014; Zhou and Yang, 2015). Among DSM methods techniques load shifting is the most effective load management technique (Esther and Kumar, 2016) which can enhance the demand flexibility without compromising the stability and continuity of the process and, furthermore, a highlighted feature of DSM is that it can be 100% efficient, since no energy conversion to and from an intermediate storable form is required (Lund et al., 2015). However, in order to shift loads from high-demanding hours (on-peak hours) to low-demanding hours (off-peak hours), specifically for industrial and commercial units with considerably high power demand profiles due to their industrial processes, high-capacity energy storage is an essential component to provide an effective and continuous load shifting.

A considerable number of studies have been devoted to investigate the benefits of thermal energy storage (TES) for renewable energies applications and system integration. As an example, Alva et al. (Alva et al., 2017) extensively reviewed the application of TES materials and systems for solar energy applications. Additionally, Li and Zheng (Li and Zheng, 2016) studied different methods of TES system integration for building and industry applications. However, the application of cold storage systems has been broadly developed in the power generation sector, the building sector, and the industrial sector because of their high potential of cooling load shifting (Oró et al., 2012), and decreasing greenhouse gas emissions (de Sisternes et al., 2016). For this reason, there is growing interest in using DSM techniques together with TES, battery storage, and solar PV technologies for industrial and commercial sectors. However, there has been little discussion about coupling DSM together with solar PV and cold TES technologies to reduce peak loads in the industry sector and enhancing the overall performance of the energy system through interconnection of these technologies (Arteconi et al., 2017). Therefore, further research and technology advancement are required for electric load management to address the potential peak load shifting and energy savings considering the new time-of-use tariff structure and elevated electricity prices, high surplus demand charges, and variable solar PV share and its uncertainties in the energy system (Arteconi et al., 2012).

The objective of the current study is to address the potential for applying optimization-based time-of-use DSM in the industry sector to reduce peak electricity demands and eventually to decrease the annual electricity bill. Particularly of interest are, on one hand, to reduce contracted power demands and to shift electrical chiller peak loads from high-price times (on-peak hours) to low-price times (off-peak hours), by taking advantage of cold TES (sensible systems, ice or phase change materials) and off-grid solar PV; and on the other hand, to determine the optimum combinations of contracted power at different tariff periods by integrating TES and solar PV technologies with different capacities, and considering the solar PV variations and surplus charges of power demand.

2. Methodology

2.1. Case study

To give an estimation of the annual energy bill for an industrial consumer, it was assumed that for running its industrial processes, a conventional energy system with no demand management facilities, neither solar PV nor TES system is used. So that, the industrial consumer directly uses the electricity from the grid to run its processes whenever it is required and without considering the on-peak, mid-peak and off-peak demand and energy tariff periods (Figure 1a). The industrial processes take place from 8:00 to 17:00 all days except Saturdays and Sundays, requiring 450 kW of electric demand for cooling processes. To calculate the electricity consumption, the Spanish electricity tariff structure (6.1A time-of-use tariff structure) (Real Decreto 1164/2001, 2016) has been used. The tariff structure is divided into six different tariff periods, and consumers pay through the bill the energy cost and the demand cost. Further explanations of the above-mentioned tariff structure are provided in Section 2.4.1. Assuming that for all tariff periods the reference industrial unit contracts 450 kW power demand with 100% of load factor, the annual electricity bill for operational hours can be calculated using eq. 1:

$$Elec_{tot} = (E_p + E_e) + [(E_p + E_e) \times \text{VAT}] \qquad \text{(eq. 1)}$$

$$E_p = \sum_{i=1}^{i=6} \left(P_{demand_i} \times CP_{P_{demand_i}} \right) \quad \text{(eq. 2)}$$

$$E_e = \sum_{i=1}^{i=6} \left(P_{energy_i} \times CE_{P_{energy_i}} \times h \right) \quad \text{(eq. 3)}$$

where $\mathrm{Elec_{tot}}$ is annual electricity cost, $\mathrm{E_p}$ is power demand cost, $\mathrm{E_e}$ is energy consumption, VAT stands for value added taxes; P_{demand_i} stands for power contracted in different tariff periods; P_{energy_i} stands for consumed energy in different tariff periods; CP and CE are cost of power in kilowatt (kW) and cost of energy in kilowatt-hour (kWh), respectively, for period I, as explained in details in Section 2.4.1.

Three different optimization scenarios were considered to optimally analyze the possibility of shifting on-peak loads from daytime to nighttime by adopting DSM system on the basis of time-of-use tariffs and compare them with the reference model (Figure 1a):

- Scenario 1. time-of-use tariff DSM coupled with only cold TES system (Figure 1b).
- Scenario 2. time-of-use tariff DSM coupled with only off-grid solar PV (Figure 1c).
- Scenario 3. time-of-use tariff DSM coupled with both cold TES and off-grid solar PV systems (Figure 1d).

In Scenario 1 (Figure 1b), the cold TES tank has to be charged at nighttime during off-peak period and be discharged during day especially at on-peak period or the most expensive hours of the electricity tariff. In Scenario 2 (Figure 1c), the feasibility of reducing the energy costs by applying off-grid solar PV has been assessed. In the current study the off-grid solar PV was considered because in the selected tariff structure there is insufficient incentive for grid-connected solar PV system. Eventually, in Scenario 3 (Figure 1d) the possible economic benefits by coupling both cold TES and off-grid solar PV have been investigated. In addition, in should be noted that in the present study the costs of equipment and payback period as well as its environmental impact are not taken into account and might be covered in future studies. Figure 1 illustrates a scheme of the optimization scenarios.

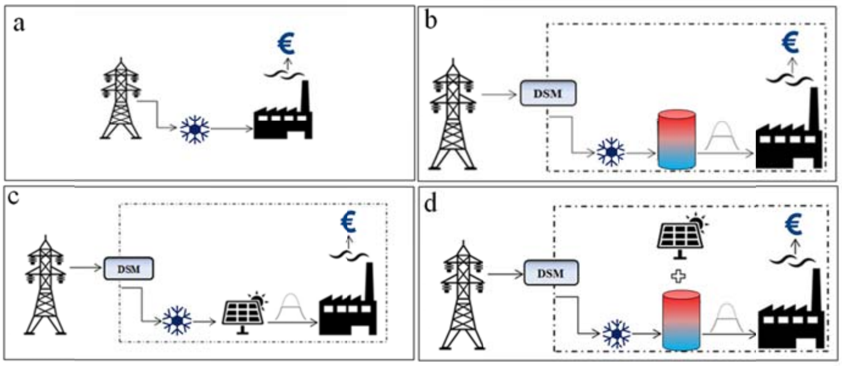

Figure 1. Schematic view of the methodology.

2.2. Simulation of PV module

The electricity generation by solar PV, was simulated using TRNSYS v17 (Klein, 2010). This software has an extensive library of components in which appropriate models could be selected for simulating thermal and electrical energy systems. The potential electricity generation from PV modules can be calculated using Type 94a which models the electrical performance of a photovoltaic array and could be used in simulations involving electrical storage batteries, direct load coupling, and utility grid connections. It applies equations for an empirical equivalent circuit model to predict the current-voltage characteristics of a single module. This circuit consists of a DC current source, diode, and either one or two resistors. The strength of the current source is dependent on solar radiation, and the IV characteristics of the diode are temperature-dependent (TRNSYS 17, 2016). Sunrise SR-M762315-B solar PV (Sunrise, 2016) technical data as shown in Table 1 was introduced to Type 94a and four different nominal power of 25 kWp, 50 kWp, 80 kWp, and 100 kWp were considered. Further on, an array slope of 40º and azimuth of 180º were taken into account. Simulations were performed using time steps of 15 minutes for fifteen consecutive years (1991-2005) using historical solar radiation data of Denver derived from National Renewable Energy Laboratory (NREL) weather data base (National Renewable Energy Laboratory, 2007). Denver, Colorado is dominated by BSk climate classification according to Köppen

Geiger classification and could be representative of climate condition of Lleida province, Spain.

2.3. Thermal energy storage model

A cold thermal storage was integrated into the system with the aim of shifting the electric demand (kW) and the energy consumption (kWh) from on-peak and mid-peak to off-peak hours. The storage model and corresponding charging/discharging modes are similar to the method presented by Ihm et al. (Ihm et al., 2004). The storage capacity can be characterized by a charge/discharge rate as shown in eq. 4. In addition, to convert thermal load to electrical load an average coefficient of performance (COP) of 3 was considered. Then, the electrical acquired energy could be calculated using eq. 5.

Table 1. Sunrise SR-M672315 module specifications (Sunrise, 2016).

Maximum power [W]	315
Module area [m^2]	1.94
Tolerance [%]	0~+3
Open circuit voltage (V_{oc}) [V]	45.42
Short circuit current (I_{sc}) [A]	9.24
Maximum power voltage (V_m) [V]	36.69
Maximum power current (I_m) [A]	8.59
Module efficiency [%]	16.20
Solar cell efficiency [%]	18.85
Cell type [mm]	156x156 (Mono-Crystalline Silicon)
Number of cells [P_{cs}]	72 (6x12)
Maximum system voltage [V]	DC1000
Temperature coefficient of Voc [%/°C]	-0.35
Temperature coefficient of Ise [%/°C]	0.05
Temperature coefficient of Pm [%/°C]	-0.45
Operating temperature [°C]	-40 to 85
Nominal operating cell temperature (NOCT) [°C]	45±2
Maximum series fuse [A]	15
Wind bearing [Pa]	2400
Pressure bearing [Pa]	5400
Standard Test Conditions (STC):1000W/m^2 AM=1.5 25 ºC	

$$\dot{Q}_{storage} = x \frac{SL}{\Delta t} \quad \text{(eq. 4)}$$

$$COP_{ave} = \frac{SL}{Elec_{ac}} \quad \text{(eq. 5)}$$

$$f(x) = \begin{cases} inactive\ mode, & x = 0 \\ charging\ mode, & x > 0 \\ discharging\ mode, & x < 0 \end{cases}$$

where $\dot{Q}_{storage}$ is the TES charge (+)/discharge (−) rate (kW), SL is the cold TES capacity (kWh), x the charge/discharge rate (fraction), Δt the simulation time step (15 minutes), COP_{ave} the average thermal to electrical load conversion COP, $Elec_{acq}$ the acquired electric energy (kWh).

The design is based on three operation schedules over the continuity of charge/discharge rates:

- Inactive mode: when the TES system is not working, for instance at the weekends, the charge/discharge rate is set to zero in a sub-hourly schedule defined specifically for the TES operation.

- Charging mode: the dedicated TES chiller integrated in the TES module produces cold at the charging rate, *x*, during off-peak hours (the cheapest period) with the maximum charging rate of 375 kW.
- Discharging mode: in this stage the TES system supplies cooling at different capacities to meet the cooling demand during on-peak and mid-peak hours (avoiding or reducing compressor operation). In the present study, the economic impact due to the use of various TES capacities (75-9000 kWh) on the final electricity bill will be analyzed.

The steady-state storage model does not take into account the external weather conditions such as dry bulb temperature, humidity, etc. Moreover, charging and discharging efficiencies were kept a constant value of 100% throughout time steps.

2.4. Time-of-use tariff structure

2.4.1. The electricity bill

In many countries the electricity bill consists of an energy charge, peak demand charge, and taxes. In Spain, taxes are significant and include an electricity tax of 5.1% and a value-added tax (VAT) of 21%. Depending on which demand category the consumer fits in, it determines how many charge categories are applied to the contract. The industry sector has 6.1A demand category which is classified in periods P1 to P6. In each charge category a peak and energy charge is applied. Further on, for this demand category incentives are applied. Figure 2 shows the hourly and monthly periods during which each tariff structure is applied. PX refers to the tariff price profile consisting of an on-peak, mid-peak and off-peak price and P6 refers to all prices at off-peak rates. The tariff consists of both an energy price and a demand price per period as shown in Table 2.

Month/Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
February	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
March	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P3	P4	P4
April	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
May	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
1-15 June	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
16-30 June	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
July	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
August	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
September	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
October	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
November	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P3	P4	P4
December	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2

Figure 2. Incentive time-of-use electricity tariff structure.

Table 2. Incentive time-of-use electricity prices [59].

	P1	P2	P3	P4	P5	P6	---	---
Power	39.139	19.586	14.334	14.334	14.334	6.540	€/kW/ year	Regulated price
Energy	0.120	0.096	0.092	0.074	0.0708	0.065	€/kWh	Standard free price

2.4.2. Charges due to power excess (surplus charges)

In case that an industrial consumer requires more demand that it has contracted in each determined time interval (for some minutes or even hours), a penalization due to power excess is charged to the bill. This penalization is calculated according to the power contracted in each tariff period and, if applied, depending on each tariff period, the actual demanded power rates are metered using electricity metering equipment. The billing of the excesses of power for the 6.1 tariffs is calculated according to the formula established in Royal Decree 1164/2001 (Real Decreto 1164/2001, 2016) (eq. 6 and eq. 7), and it is measured every 15 minutes:

$$F_{ep} = \sum_{i=1}^{i=6} K_i \times 1.4064 \times A_{ei} \qquad \text{(eq. 6)}$$

where F_{ep} stands for charges in € and A_{ei} is a factor that weights excess of demand depending on the period, K_i is the coefficient that takes the values depending on the tariff period i as shown in Table 3, A_{ei} is calculated according to the following conditional equation:

$$A_{ei} = \begin{cases} 0, & \mathrm{P_{dj}} <= \mathrm{P_{ci}} \\ \sqrt{\sum_{j=1}^{j=6} (\mathrm{P_{dj}} - \mathrm{P_{ci}})^2}, & \mathrm{P_{dj}} > \mathrm{P_{ci}} \end{cases} \quad \text{(eq. 7)}$$

where $\mathrm{P_{dj}}$ is demanded power in each quarter of hour which is excessed (higher than $\mathrm{P_{ci}}$), $\mathrm{P_{ci}}$ is contracted power in each period and in the considered period.

Table 3. K_i coefficients according to the tariff periods.

Period (i)	1	2	3	4	5	6
K_i	1	0.5	0.37	0.37	0.37	0.17

These powers are expressed in kW and the excesses of power are billed monthly. For tariffs 6.1 at every breach is charged a penalty i.e. every 15 minute breach. Thus, it means that if the user demands over the contracted power during one hour, the penalty is charged four times. However, there is an optimum contracting demand that reduces the energy cost taking into account the penalties. The application of optimized DSM together with TES and PV can optimally find the contracting demands in each period and can improve the overall performance of the energy system.

2.5. Optimization

It could be understood that for given electricity consumption requirements, an optimization problem can be derived based on the power contracting plan, i.e. how much power is contracted for each one of the 6 period tariffs. The optimization problem results deterministic when no PV production is considered. Otherwise, PV uncertainty will lead to stochastic optimization. In both cases, constraint integer programming (CIP) was used as a novel paradigm that integrates constraint programming, mixed-integer programming (MIP), and satisfiability modeling and solving techniques in order to model and solve this problem (Achterberg, 2008; "SCIP Optimization Suite," 2017). Without PV generation, the system may be described as sets, parameters and functions as follows:

$P = \{P_1..P_6\}$, is the set of tariff periods; $CE_i, i \in \{1..6\}$ is the cost of energy consumption during period P_i according to Table 2 in €/kWh; $K_i, i \in \{1..6\}$ is the coefficient as defined in Table 3; *SL* is the cold TES storage capacity in kWh; *H*, *D* and *M* are the set of hours, days and months respectively; *T=H*D*M* is the set of hour periods in a year; $Period: T \rightarrow P$, is a function that maps an hour period to its corresponding tariff as corresponding to Figure 2; $C_i, i \in H$, is the required energy during an hour as shown in eq. 8:

$$C_i = \begin{cases} 450 kW \cdot h, & i \in 8..17 \\ 0, & otherwise \end{cases} \quad \text{(eq. 8)}$$

Therefore, the cost of contracting power (*CP*), and the cost of consumed energy can be expressed as eq. 9 and eq. 10, respectively:

$$CP = \sum_{i=1..6} CP_i \cdot PC_i \quad \text{(eq. 9)}$$

Subjected to these constraints: $CP_6 \geq CP_5 \geq CP_4 \geq CP_3 \geq CP_2 \geq CP_1$

$$CE = \sum_{t \in T} S_t \cdot CE_{Period(t)} + K_{Period(t)} \cdot 1.4064 \cdot f\left(S_t - PC_{Period(t)}\right) \quad \text{(eq. 10)}$$

Subjected to the surplus charge constraint of $f(x)$ that is applicable when supplied energy from grid at time t is higher than the contracted power in period i (PC_i) as shown in eq. 11:

$$f(x) = \begin{cases} x, & x > 0 \\ 0, & x \leq 0 \end{cases} \quad \text{(eq. 11)}$$

where $PC_i \in R, i \in 1..6$, is the contracted power for tariff P_i; $S_t \in R, t \in T$, is the supplied energy from the grid in time t. When suitable, one can also denote S_t as $S_{h,d,m}$.

Finally, the following assumptions have been made: 1. The TES operation hours is between 00:00 to 07:00. This is an obvious optimal assumption since it is the off-peak period and no demand exists. 2. The stored energy can only be consumed during the same day. The objective is to find an optimum assignment of $PC_i \in R, i \in$

1..6, that minimizes CP+CE, which could be written as eq. 12, subject to constraint shown in eq. 13:

$$\min_{PC_i}(CP + CE) \quad \text{(eq. 12)}$$

$$SL > \sum_{h=0}^{7} S_{h,d,m} > \sum_{h=8}^{17} C_h - S_{h,d,m}, \forall(d,m) \in D * M \quad \text{(eq. 13)}$$

For example, for each day, the stored energy must not surpass the storage limit and must supply the eventual lack of obtained energy from the grid. In order to reduce the number of variables, symmetries may be considered. As energy requirements are invariant from day to day (C_i), the number of variables can be drastically reduced. More specifically, $S_i$can be indexed in $H*M$ instead of T. We encoded and solved eq. 12 and eq. 13 with SCIP version 3.2.0 [64] in a 1.9 GHz processor. The problem results in 581 variables and 484 constraints, being solved in less than 2 seconds.

However, when solar PV production is considered, it can be taken into account as a multivariate random variable $PV_y = (pv_{1,y}..pv_{|T|,y})$, being $pv_{i,y}$ the PV production at hour $i \in T$in year y. Then, for a given year y, the eq. 14 could be written as:

$$SL > \sum_{h=0}^{7} S_{h,d,m} > \sum_{h=8}^{17} C_h - S_{h,d,m} - pv_{h,d,m,y}, \forall(d,m) \in D * M \quad \text{(eq. 14)}$$

When PV production is available over a set Y of years, we compute the expected optimization using the cost function presented in eq. 15:

$$E\left[\min_{PC_i}(CP + CE)\right] = \frac{1}{|Y|}\sum \min_{PC_i}(CP + CE) \quad \text{(eq. 15)}$$

subject to constraint as stated in eq. 14. Under this scenario, symmetry reduction as previously stated is no longer feasible and each year optimization problem results in 16469 variables and 16846 constraints, with a resolution time from 5 to 25 minutes depending on SL value.

3. Results

3.1. Economic benefits of optimized DSM with cold TES (Scenario 1)

In this section, the economic benefits due to the use of optimization-based DSM with only cold TES are presented. Figure 3 shows that the amounts of economic savings increase linearly with the increase of TES capacity. From Figure 3 it is apparent that with the increase of storage capacity the annual economic savings increase correspondingly from 418 € (below 1%) per year, in case of 75 kWh capacity of TES, to 53670 € per year (about 30%), in case of 3000 kWh TES. For example, adding 1500 kWh of TES can lead to about 8945 € per year cost savings, and when the storage capacity increases to 6000 kWh these savings rise to 3578 € per year.

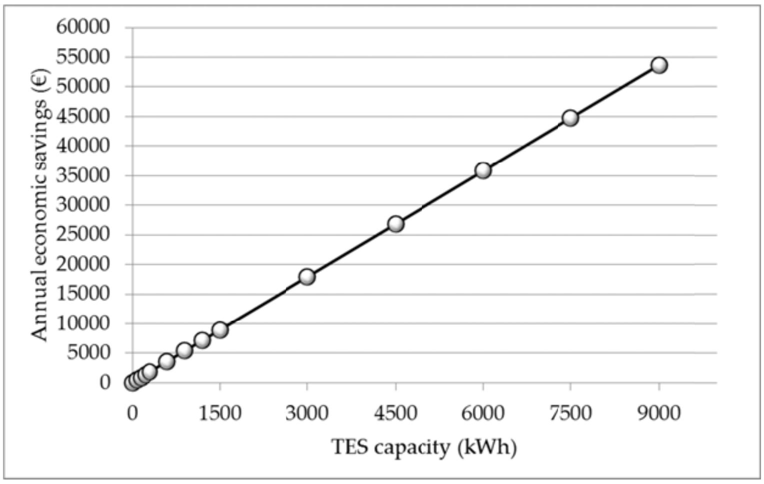

Figure 3. Economic benefits by using DSM and cold TES.

3.2. Economic benefits of optimized DSM with solar PV (Scenario 2)

In this section, the economic benefits due to the use of optimization-based DSM with off-grid solar PV system are presented and the results are shown in Figure 4. Off-grid solar PV yields economic benefits ranging from 4200 € to 16900 € in Denver.

It can be seen that adding 50 kW of off-grid solar PV could achieve annual cost savings of 8465 € in Denver. Compared to TES, lower savings could be achieved using off-grid solar PV. Actually, due to variable PV generation, the electric power demand contract cannot be decreased considerably, since in occasions of poor electricity generation from PV surplus penalties may apply to the electricity bill. However, solar PV can yield to substantial savings when there is enough solar radiation to produce electricity and reduce the real-time energy needs.

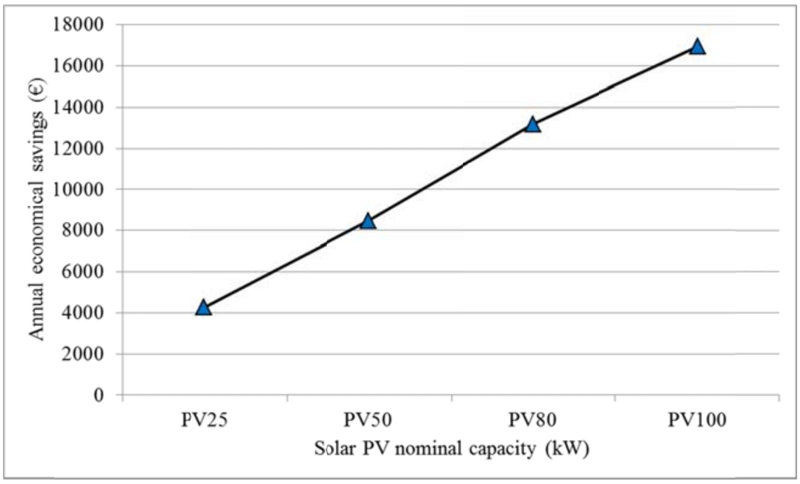

Figure 4. Economic benefits by using DSM and off-grid solar PV.

3.3. Economic benefits of optimized DSM coupled with cold TES and solar PV (Scenario 3)

In this section, the economic benefits due to the use of optimization-based DSM with cold TES coupled with off-grid solar PV system for an industrial consumer have been presented (Figure 5). In general, it can be seen that the annual cost savings have a linear correlation with TES capacity and solar PV nominal capacity. With the increase of TES and PV capacities the annual economic savings increase correspondingly.

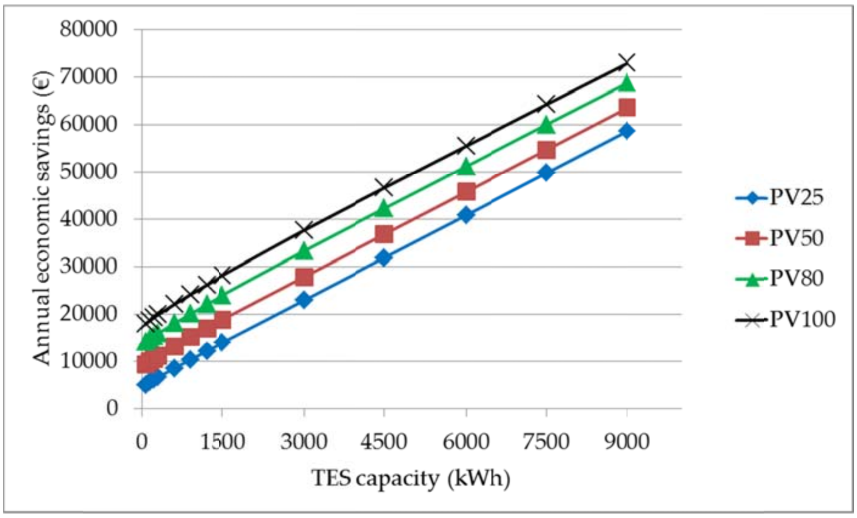

Figure 5. Economic benefits by using DSM coupled with cold TES and solar PV, Denver.

An interesting and very important issue that can be obtained from the results presented in this section is that when TES and PV technologies coupled together higher reductions in power contract demands could be achieved. Accordingly, coupling PV and cold TES together with an optimized DSM led to higher annual electricity cost reductions both for demand and energy terms. Further on, the authors would like to mention that important annual demand cost savings were achieved thanks to the application of TES, nevertheless, it was not limited to only the demand term, but also, considerable cost savings can be observed for the energy term which mainly comes from renewable solar PV generation.

3.4. Improvements by coupling cold TES and solar PV technologies

An important issue that should be discussed herein is how the combination of solar PV and short-time cold TES technologies coupled to an appropriate time-of-use DSM can shift peak demands and reduce energy consumption and eventually improve the whole energy system. To find economic benefits due to interconnection of these two technologies, annual cost savings due to integration of only cold TES (Scenario 1) and only off-grid solar PV (Scenario 2) should be summed; and then, subtracted from annual cost savings due to coupling cold TES with solar PV (Scenario 3). Actually, these cost savings demonstrate how the interconnection of two renewable technologies together with an optimized DSM, can be energy-beneficial compared to when they are used individually.

The results presented in Figure 6 show the annual cost saving improvement ratios in Denver. In fact, when the solar PV share of the system is smaller, lower storage capacity is needed to provide the continuity and smoothness of supply in the system. The warm color area in the color map highlights the maximum improvement that could be achieved by coupling cold TES and solar PV technologies together. In general, by the increase of solar PV share higher short-term TES is required. In other words, the higher the dependency of energy system on the solar PV, the higher the storage is needed to ensure the security of electricity supply of the system without intermittency and hence avoid possible penalties.

For instance, in case of using 1500 kWh of TES a total annual savings of 8945 € could be achieved. On the other hand, when only off-grid solar PV of 50 kW is considered savings of 8465 could be achieved in Denver. On the other hand, when TES and solar PV technologies are coupled together these savings increase to 18803 €, which is about 7% higher than the sum of benefits achieved by using them separately (Figure 6).

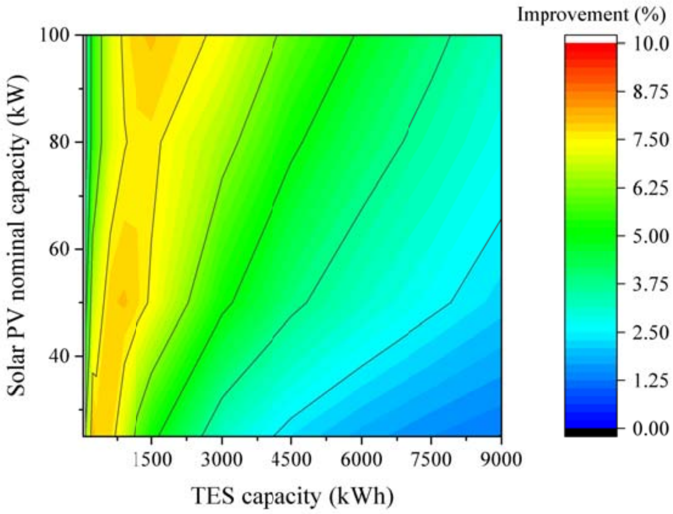

Figure 6. Annual electricity saving improvement by coupling cold TES and solar PV technologies, Denver.

4. Conclusions

In the present study, an optimization-based time-of-use DSM combined with short-term cold TES and off-grid solar PV technologies is used to shift on-peak electricity demand of an industrial consumer. Using numerical optimization and simulation it was found that both cold TES and off-grid solar PV coupled with an appropriate tariff structure can lead to annual electricity cost savings. However, savings attributed to the integration of cold TES are generally higher than those achieved by only off-grid solar PV. In addition, solar PV without storage can reduce the energy term but not significantly the power term of the energy bill. However, it should be highlighted that when cold TES and solar PV are coupled together, further economic benefits could be achieved in comparison with using these two technologies independently.

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