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Optimization of time-of-use tariffs demand side management coupled with cold Thermal Energy Storage (TES) and solar PV to reduce on-peak demand

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Abstract

Industries are responsible of emitting 40% of total energy-related CO_2 emissions and about one third of total final energy consumption. Introducing energy management systems allow companies to manage and control their energy use, enabling them to lower energy costs, and enhance productivity and competitiveness. Demand side management using thermal energy storage and off-grid solar photovoltaic technologies could enhance the performance of energy systems and reduce on-peak demand for industries. In the present paper, the feasibility of reducing the annual electricity bill mainly by peak shifting will be studied by applying cold TES and off-grid solar PV along with a proper time-of-use tariff structure. Simulations results have shown that adopting a proper time-of-use tariff structure in combination with cold TES coupled with off-grid solar PV can considerably increase annual energy savings mainly by shifting electricity demand to nighttime off-peak period. Additionally, it was estimated that for the analyzed case study (450 kW of electrical demand 9 hours/day for cooling processes) 5000 € to 75000 € of annual energy bills can be saved by applying TES and solar PV with different capacities. Moreover, it was found that the combination of TES and solar PV technologies based on time-of-use tariff structure can improve the economic savings by 3% to 9% in comparison to using the two mentioned technologies separately.

Keywords: *cold storage, thermal energy storage, solar PV, demand side management, optimization.*

1. Introduction

Industry accounts for about one third of total final energy consumption and almost 40% of total energy-related CO_2 emissions which are expected to rise by 46% by 2040 (Makridou et al., 2016). The European Union´s (EU) Energy Roadmap 2050 explores solutions towards decarbonisation by 2050 by over 80% while at the same time guaranteeing security of energy supply and competitiveness (European Commission, 2011). On this basis, the European commission (European Commission, 2011) is placing increasing priority on energy savings in all decarbonisation scenarios and furthermore, supporting the significant increase of renewable energy sources. Electricity storage in a large scale is not feasible; therefore electricity has to be consumed in real time covering the demand. On the other hand, since generation plants with different supply sources such as thermal, solar photovoltaic (PV), hydro, wind and other renewables of variable efficiency are used to meet demand, the cost of electricity varies hour to hour, day to day, and month to month (Faruqui et

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al., 2010). Additionally, variability in both demand profiles and renewable energy sources makes the energy management of the grid more difficult and increases the cost of electric power generation (Batalla-Bejerano and Trujillo-Baute, 2016).

Peak electricity demand is a global policy concern which causes transmission constraints and congestion, and increases the cost of electricity for all end-users. Further on, a huge investment is needed to upgrade electricity distribution and transmission infrastructure, and build generation plants to provide power during peak demand periods (Strengers, 2012). Furthermore, commonly service suppliers charge a higher price for peak-time services than for off-peak services in order to compensate for the costly electricity generation at peak hours (Kim et al., 2016). So that, cutting off some of this peak demand would benefit the whole energy system since, on one hand, it would eliminate the need to install expensive extra generation capacity such as combustion turbines for peak hours which are less than a hundred hours a year (Faruqui et al., 2007) and on the other hand, consumers can eliminate penalties due to exceeding power demands in their electricity bill. In addition, due to infrequent use of peak plants, making them more efficient is not fair. So that, normally it is cheaper to feed peak electricity generators by oil which results in more CO_2 emissions (Faruqui et al., 2010). Accordingly, even a small percentage of peak demand reduction can promise substantial savings in generation, transmission, and distribution costs (Faruqui and Sergici, 2010). Using flexible resources in the power system such as renewable generation, storage, and demand management could be a solution to increase the security and satiability of the whole energy system, to save energy and to reduce the hazardous emissions (European Commission, 2011).

Demand side management (DSM) is a proactive way to make customers energy-efficient in the long-term (Barbato and Capone, 2014). The most prominent DSM methods include reducing peak loads, shifting load from on-peak to off-peak , increasing the flexibility of the load and reducing energy consumption in general (Müller et al., 2015) where load shifting has been found as the most effective load management technique (Esther and Kumar, 2016). DSM can reduce both the electricity peak power (kW) and the electricity consumption (kWh) (Warren, 2014; Zhou and Yang, 2015). Further on, some countries have adopted or are investigating time-of-use distribution network tariffs such as Spain (Real Decreto 1164/2001, 2016), which aim at shifting consumption to off-peak hours to avoid grid constraints (European Commission, 2015). Time-of-use tariffs can encourage customers to take advantage of price variations in different periods of time to regulate their electricity use. In such schemes, a group of prices are determined in advance and they apply to different periods of time, where the electricity prices are discriminated by patterns and rates (Li et al., 2016). Thus, based on the information provided by suppliers, high energy consumers can decide how to distribute their loads according to variable electricity tariffs using different technologies (Buryk et al., 2015; Yalcintas et al., 2015). They will be able to shift their electricity consumption away from times of high prices (peak hours) to times of low prices (off-peak hours) and by that reduce their energy bill.

Energy storage technologies can have a valuable role to play in any energy system, including those with high and low proportions of renewable generation (e.g. solar PV) with variable nature due to weather conditions (Kousksou et al., 2014). Thermal energy storage (TES) has been the center of attention of many researchers during the past decades (Zalba et al., 2003). In particular, 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 to temporally shift the increasing cooling demand, reducing the stress on the energy system (International Energy Agency, 2011) and on the other hand, reduce the greenhouse gas emissions (Cabeza et al., 2015; Yau and Rismanchi, 2012). Refrigeration systems producing artificial cold with electrical or heat driven chillers, infrequently operate at full capacity. They usually operate during day to meet the cooling demand and are designed to satisfy the maximum cooling demand, which occurs only a few days each year. A wide range of economic, technical and energetic advantages are attainable by integration of a cold storage in such a system to supply cold such as: energy cost reduction, investment cost reduction by selecting a smaller chiller, possibility of using off-peak cheap electricity tariffs, increasing the flexibility of the system, reduction of peak electricity loads on the grid (if compression chiller is used), improving energetic efficiency (COP) of chiller, etc. (Mehling and Cabeza, 2008; Oró et al., 2014). However, further research and advancement are required for electric load management (Arteconi et al., 2012) to address the potential energy savings and peak load shaving regarding 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. On this ground, numerous studies have focused on DSM applying optimization techniques (Ikeda and Ooka, 2016; Muralitharan et al., 2016). The present study is an attempt to address the potential for implementation of incentive time-of-use tariffs (according to the Spanish electricity tariff structure) by an industrial consumer to reduce the electricity bill. However, it should be noted that, this method could be implemented in other countries with incentive time-of-use tariff structure. Particularly of interest are, on one hand, to reduce contracted power demands and to shift electrical chiller peak loads from high price times (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 find out the optimum combinations of power demand contracts with TES and solar PV technologies to reduce final electricity bill and comparing that with a conventional energy system.

2. Methodology

To have a better understanding of the methodology an overview is presented in this section. In section 2.1 the case study is described; section 2.2. is dedicated to the solar PV simulation; in section 2.3. the cold TES model is explained; section 2.4. focuses on the time-of-use tariff structure; and eventually section 2.5 defines the optimization procedure. Figure 1 shows a schematic of the implemneted approach.

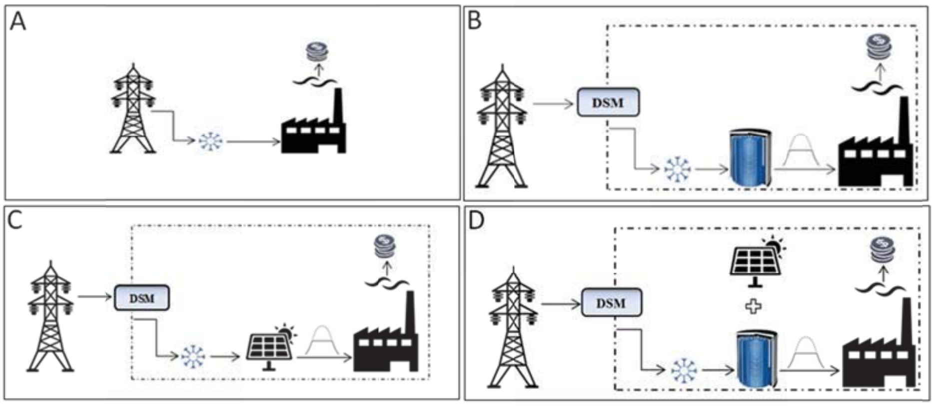


Figure 1. Schematic view of the methodology.

2.1. Case study

To give an estimate of the annual energy bill for an industrial consumer it has been assumed that for running the industrial processes of this industrial unit, a conventional energy system with no demand management facilities and with a conventional tariff structure has been used. So that, the industrial consumer directly uses the electricity network to provide electricity for its processes whenever it is required without considering the on-peak demand and off-peak demand periods (Figure 1.A). The industrial processes take place from 8:00 to 17:00 all days except Saturdays and Sundays requiring 450 kW of electrical demand for cooling processes. On this basis, the monthly electricity bill was calculated according to the Spanish electricity tariff structure (6.1A plan) which is divided into six different tariff periods (according to month and hourly basis) and is explained in detail in section 2.4.1.The annual electricity bill can be calculated using eq.1. Moreover, it is assumed that for all tariff periods the industrial consumer contracts 450 kW power demand with 100% of load factor during operational hours.

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

$$E_p = \sum_{i=1}^{i=6} (P_i \times CP_{pi})$$

$$E_e = \sum_{i=1}^{i=6} (P_i \times CEp_i \times h)$$

Where $Elec_{tot}$ is annual electricity bill, E_p is power demand cost, E_e is energy consumption, VAT stands for value added taxes; P stands for different tariff periods; CP and CE are cost of power [kW] and energy [kWh] for different periods according to Table 2, respectively. Investigation will be made into the possibility of shifting peak loads from daytime to nighttime by integrating a tariff-based DSM system with three different energy system designs. 1. tariff-based design coupled with a cold TES system (Figure 1.B), 2.tariff –based design coupled with an off-grid solar PV (Figure 1.C), and 3.tariff-based design coupled with both cold TES and off-grid solar PV systems (Figure 1.D). In case 1 (Figure 1.B), the cold TES tank has to be charged at nighttime during the cheapest tariff period and later on, it has to be discharged during day especially at expensive hours of electricity rates. In case 2 (Figure 1.C), the feasibility of applying only off-grid solar PV to reduce the energy bill will be assessed. Eventually, in case 3 (Figure 1.D) the possible energy benefits due to coupling both cold TES and solar PV and their mutual impacts on each other will be investigated.

2.2. Simulation of PV module

In order to analyze the solar PV electrictiy generation in the desired climate, TRNSYS 17 (transient system simulation tool) (Klein, 2010) was used. This software has an extensive library of components in which appropriate models (called types) could be selected for simulating thermal and electrical energy systems. In the present study, Type 15.3 (weather file reader), Type 16a (radiation processor), Type 94a (crystalline solar PV module), Type 25c (printer), and Type 65d (online printer) were selected and appropriately interconnected to carry out the solar PV simulation.

The potential solar-generated electricity 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 (Figure 2) (Sunrise, 2016) technical data as shown in Table 1 was introduced to Type 94a and four different nominal installation power of 25, 50, 80, and 100 kWp were considered. Further on, all the solar PV modules were considered to have 40º of array slope and 0º of azimuth.

Figure 2. Sunrise SR-M672315 module (Sunrise, 2016).

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 (Voc) [V]	45.42
Short circuit current (Isc) [A]	9.24
Maximum power voltage (Vm) [V]	36.69
Maximum power current (Im) [A]	8.59
Module efficiency [%]	16.20
Solar cell efficiency [%]	18.85
Cell type [mm]	156x156(Mono-Crystalline Silicon)
Number of cells [Pcs]	72(6x12)
Maximum system voltage [V]	DC1000
Temperature coefficient of Voc [%/ºC]	-0.35
Temperature coefficient of Ise [%/ºC]	0.05

Temperature coefficient of Pm [%/ºC]	-0.45
Operating temperature [ºC]	-40 to 85
Nominal operating cell temperature (NOCT) [ºC]	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	

Simulations were performed using time steps of 15 minutes for fifteen consecutive years (1991-2005) using historical solar radiation data of Denver international airport, Colorado, US (Köppen-Geiger classification: BSk) which was derived from NREL data base (National Renewable Energy Laboratory, 2007). This climate was selected because of two reasons, first, because we did not have historical weather data of the desired climate and second, the climate classification of the desired city which is in Lleida provice, Spain presents the same climate classification as Colorado.

2.3. Cold TES model

Cold TES system was included into the design to shift both the electric demand (kW) and the energy consumption (kWh) from higher cost (on-peak) and middle cost (partial-peak) periods to the lower cost (off peak) period. This design was based on an operating schedule with two modes: mode (1) charging the cold TES during the nocturnal period (the cheapest period); and mode (2) discharging the cold TES tank during the diurnal period (avoiding or reducing compressor operation), with assumed peak capacities ranging from 2 to 250 kW. The cold TES was sized to hold different storage capacities (25 to 3000 kWh) in order to evaluate the effect of the storage capacity in the economic benefits. Commonly, standby heat gains occur in storage tanks due to the heat conduction, convection and infiltration. These losses are very dependent on the indoor and outdoor boundary conditions, insulation level of storage tanks etc. On this basis, in order to take into account these heat losses, some heat loss values corresponded to cold storage tanks were derived from experimental results available in literature (Stovall, 1993; Therese K. Stovall, 1991; Therese K.Stovall, 1991a, 1991b). Afterwards, standby heat losses values of 0, 0.50, 1, 1.5 kW were considered to be implemented into a model with 50 kWp solar PV to see the impact of heat losses on the final energy cost.

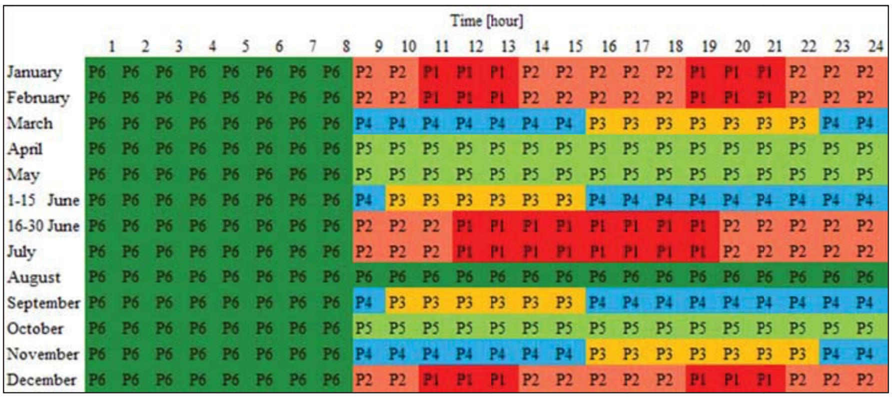
2.4. Time-of-use tariff structure

2.4.1. Electricity tariffs

The electricity tariffs used in this case study are based on the Spanish current prices. Spain has several major electricity companies, of which Endesa S.A. (“Endesa S.A.,” 2016) is the holding company for the active players in the electricity market. These players include generation, transmission, and customer relations. Transmission includes the network which delivers electricity from generators to customers. They are responsible for constructing and servicing this grid. This service is charged via a network charge priced in €/kW. These charges are regulated by government legislation and therefore transparent. Generators are large conventional power stations which generate power and either sells it to the electricity market or through contract with customer relations. The electricity spot market involves bids and purchases by generators and customer relations, and prices are cleared every period. Customer relations are the principle agent by which households and businesses interact with the electricity grid. They pass on transmission charges at cost, and an energy price charged per kWh usage. The energy price is negotiated but there are standard prices publicly available. Many large customers have their own transformer and make Endesa transmission manage it. Alternatively, Endesa transmission pays for the transformer and manages it, and this is negotiated.

2.4.2. The electricity bill

The electricity bill consists of an energy charge, peak demand charge, and taxes. Taxes are significant and include an electricity tax of 5.1% and a value-added tax (VAT) of 21%. The charges depend on your demand category as followings: 2.0 A: demand less than 10 kW; 2.1 A: 10 < demand < 15 kW; 3.0 A: demand > 15 kW; 3.1 A: demand < 450 kW; and 6.1 A: demand > 450 kW. Depending on which demand category the consumer fits in, it determines how many charge categories are applied to the contract. The residential sector has P1 and P2 charge categories, where the 6.1A demand categories vary from P1 to P6. In each charge category a peak and energy charge is applied. For category 6.1, the one contracted by the case study of the present paper and by most of the industrial applications, the applied incentive time-of-use tariffs are shown in Figure 3.



Time [hour]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
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 3. Hourly distribution of electricity rates.

Figure 4 shows the hourly and monthly periods during which each tariff structure is applied. PX refers to the tariff price profile consisting of a peak, off peak and middle peak price. P6 refers to all prices at off peak rates. The tariff consists of both an energy price and a demand price per period (see Table 2).

Table 2.Incentive time-of-use electricity prices ("Endesa S.A.," 2016).

	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

2.4.3. Charges due to power excess

In case that an industrial consumer requires more demand that it is 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) (see (eq.2) and (eq.3)), and it is measured every 15 minutes.

$$F_{ep} = \sum_{i=1}^{i=6} K_i \text{ x } 1.4064 \text{ x } A_{ei} \qquad \text{(eq. 2)}$$

Where F_{ep} stands for charges in Euros and A_{ei} is a factor that weights excess of demand depending on the period (Real Decreto 1164/2001, 2016), K_i is the coefficient that takes the values depending on the tariff period i as shown in Table 2, A_{ei} is calculated according to the following formula:

If $Pdj <= Pci$

$A_{ei} = 0$

Else if

$Pdj > Pci$

$$A_{ei} = \sqrt{\sum_{j=1}^{j=6} (Pdj - Pci)^2} \qquad \text{(eq. 3)}$$

Where Pdj is demanded power in each quarter of hour which is excessed (higher than Pci), Pci is contracted power in each period and in the considered period.

Table 2. Ki coefficients according to the tariff periods.

Period	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 overpasses the contracted power during one hour, the penalty is charged four times.

2.5. Optimization

A large and growing body of literature has been published on optimization techniques for DSM based on TES and solar PV to reduce energy-related costs of residential buildings and industrial processes (Barbato and Capone, 2014; Lee et al., 2009; Muralitharan et al., 2016). Some of these optimization methods are namely, mixed integer linear programming (MILP) and dynamic programming for a global optimal solution. Further on, metaheuristic methods such as particle swarm optimization and evolutionary algorithms have been implemented by many researchers (Müller et al., 2015). 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. On both cases, Constraint Integer Programming (CIP) has been used as a novel paradigm that integrates constraint programming (CP), mixed integer programming (MIP), and satisfiability (SAT) modeling and solving techniques in order to model and solve our problem (Achterberg, 2009, 2008; Achterberg et al., 2008). Without PV production, 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 1 in €/kWh; $K_i, i \in \{1..6\}$ is the coefficient as defined in Table 2; *SL* is the cold TES storage limit 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 4; $C_i, i \in H$, is the required energy during an hour. However, in our particular case:

$$C_i = \begin{cases} 450 kW \cdot h, & i \in 8..17 \\ 0, & Otherwise \end{cases}$$

It should be noted that for a constant energy demand, $C_i = 4 \cdot P_{dj}$, being P_{dj} the demanded power in each quarter of hour as stated in eq.3.

$$f(x) = \begin{cases} x, & x > 0 \\ 0, & x \le 0 \end{cases}$$

$PC_i \in \mathbb{R}, i \in 1..6$, is the contracted power for tariff P_i; $S_t \in \mathbb{R}, t \in T$, is the supplied energy from the grid in time *t*. When suitable, one can also denote S_t as $S_{h,d,m}$. Therefore, the cost of contracting power (*CP*) can be expressed as:

$$CP = \sum_{i=1..6} CP_i \cdot PC_i \qquad \text{(eq. 4)}$$

and the cost of the consumed energy is:

$$CE = \sum_{t\in T} S_t \cdot CE_{Period(t)} + K_{Period(t)} \cdot 1.4064 \cdot f\left(S_t - PC_{Period(t)}\right) \quad \text{(eq. 5)}$$

Finally, the following assumptions have been made: 1. PCM storage period ranges from hour 00:00 to 07:00. This is an obvious optimal assumption because those are the cheapest periods 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 $PC_i \in \mathbb{R}, i \in 1..6$, that minimizes CP+CE, which could be written as:

$$\min_{PC_i}(CP + CE) \quad \text{(eq. 6)}$$

subject to the following constraint:

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

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.6 and eq. 7 with SCIP version 3.2.0 ("SCIP Optimization Suite," 2015) in a 1.9 GHz processor. The problem results in 581 variables and 484 constraints, being solved in less than 2 seconds. When solar PV production is considered, it can be taken into account as a multivariate random variable $PV_y = \left(pv_{1,y}..pv_{|T|,y}\right)$, being $pv_{i,y}$ the PV production at hour $i \in T$ in year *y*. Then, for a given year *y*, eq.7 becomes:

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

When PV production is available over a set *Y* of years, we compute the expected optimization as:

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

subject to constraint as in eq.8. 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. DSM economic benefits

3.1.1. Influence of time-of-use DSM with cold TES capacity

Optimization results due to the use of only cold TES with different capacities are shown in Figure 4. Note that the y-axis is logarithmic base 10 scale; otherwise the correlation between energy savings and storage capacity will be misinterpreted as a linear trend. It can be seen that energy savings sharply increase by adding storage of about 200 kWh and this trend continues gradually up to approximately 500 kWh. After this point, the increase of storage capacity has a very little impact on energy bill savings, despite being upward.

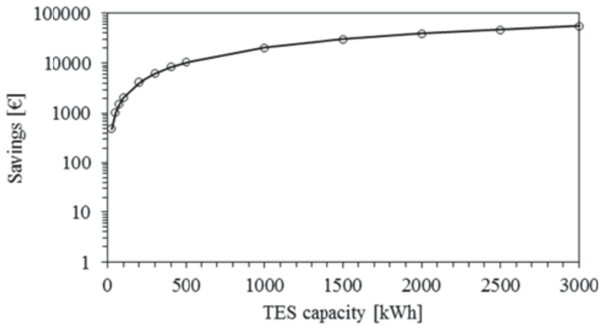


Figure 4. Energy savings by using DSM and cold TES.

3.1.2. Influence of time-of-use DSM with solar PV

The energy impact of tariff-based DSM coupled with off-grid solar PV system has been compared with a conventional energy system and the results are shown in Figure 5. It could be seen that energy savings vary from approximately 2% to 10% (4300 to 17000 euros) depending on the nominal installation capacity. However, it should be taken into account that the saving trend line is sharper from 25 to 80 kW of solar PV capacity and by increasing the solar PV to 100 kW this trend increases slightly. It should be considered that in previous results the impact of heat losses was not considered, on this basis calculations have been carried out taking into account three different levels of heat losses (0.50, 1, 1.50 kW/h) of the storage tank. It was found that 0.2 to 1% of the final energy bill could be increase due to heat losses of storage tank.

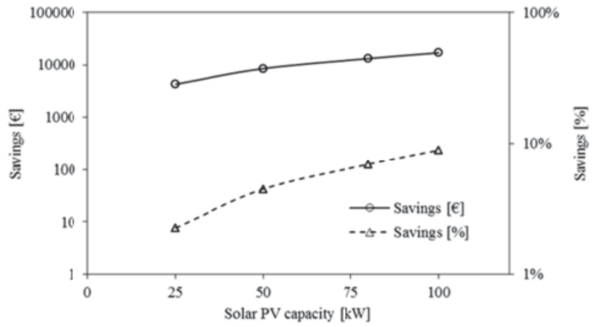


Figure 5. Energy savings by using only solar PV.

3.1.3. Influence of time-of-use DSM with cold TES coupled with solar PV

An important issue that should be discussed herein is how the combination of solar PV and short-time cold TES technologies coupled to a proper time-of-use DSM can shift peak demands and eventually improve the energy system and save final energy bill. To determine benefits due to interconnection of these two systems, savings due to integration of only cold TES and only solar PV should be summed and then subtracted from savings due to coupling cold TES with solar PV. For example in case of integrating PV 50 kW and TES with storage capacity of 1000 kWh, the benefits will lead to savings of about 8500 euros due to PV (see Figure 5) and 20600 euros due to storage (see Figure 4), however, the coupling of these two technologies achieved savings of 30400 euros.

Figures 6 and 7 show energy improvements ratios and energy savings (logarithmic base 10 scale), respectively, due to interconnection of solar PV and cold TES. It could be seen that the energy improvement is not linear and it is highly depends on the storage size and the solar PV power. For example, by looking at the trend line of solar PV with 25 kW power in Figure 6 it can be seen that the peak energy improvement occurred when storage with less than 200 kWh was coupled to the system and the increase of storage capacity decreased the performance of the whole system. Actually, when the solar PV share of the system is smaller, lower storage capacity is needed to provide the smoothness in the system. On the other hand, when higher shares of solar PV considered, higher short-term TES storage was required which is consistent with findings of Bussar et al. (Bussar et al., 2016). This could be also seen in Figure 8, in case of 25 kW PV savings sharply increase by coupling TES in the range of 50-200 kWh; after this point by the increase of TES capacity further savings could be achieved, however, it would not be as beneficial as the efficient range of 25-200 kWh. 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. Further on, it can be derived from Figure 7 that adding energy storage has the potential to further improve the performance of the whole system by reducing demand charges during periods when the solar PV system is not producing enough power due to weather conditions. Also, it can be derived that higher demand shifting is feasible by integration of cold TES, whereas, off-grid solar PV can reduce the energy consumption when solar radiation is available.

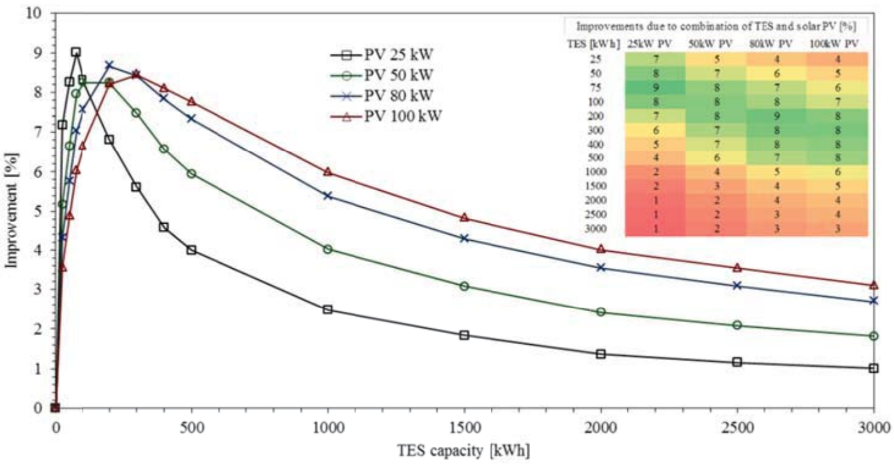


Figure 6. Improvements due to combination of solar PV & TES.

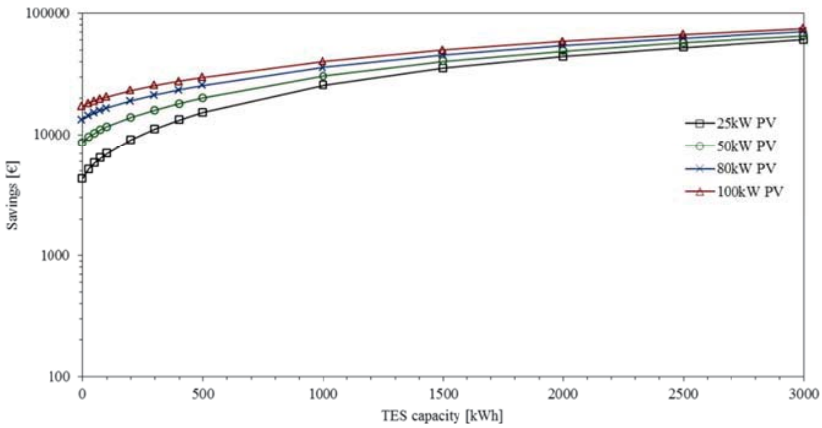


Figure 7. Energy savings due to combination of solar PV & TES.

4. Conclusions

The present paper is a simulation-based optimization study which investigates the implementation of time-of-use DSM combined with short-term TES and off-grid solar PV technologies to shift on-peak demand of an industrial electricity consumer under a certain climate zone. Through numerical optimization and simulation it has been found that both the cold TES and the off-grid solar PV coupled to an appropriate tariff structure can yield savings in final energy bills. Analyzing the results, it could be derived that savings attributed to the integration of TES are generally higher than those achieved by only off-grid solar PV. This is basically because of variability of solar radiation intensity and climate condition since when the expected solar power is not achieved; excess power is demanded from the consumer by cost of considerable charges. In addition, solar PV without storage can reduce the energy term and not significantly the power term of the energy bill. However, it should be highlighted that when an interconnected TES and solar PV energy system was analyzed, it was found that further energy improvements are attainable due to combination of these two systems. By this, it could be explained that the implementation of TES not only can shift the on-peak load but also can improve the performance of the off-grid solar PV system.

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