Optimized demand side management (DSM) of peak electricity demand by coupling low temperature thermal energy storage (TES) and solar PV

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

Cooling in the industry sector contributes significantly to the peak demand placed on an electrical utility grid. New electricity tariff structures include high charges for electricity consumption in peak hours which leads to elevated annual electricity costs for high-demanding consumers. Demand side management (DSM) is a promising solution to increase the energy efficiency among customers by reducing their electricity peak demand and consumption. In recent years, researchers have shown an increased interest in utilizing DSM techniques with thermal energy storage (TES) and solar PV technologies for peak demand reduction in industrial and commercial sectors. The main objective of the present study is to address the potential for applying optimization-based time-of-use DSM in the industry sector by using cold thermal energy storage and off-grid solar PV to decrease and shift peak electricity demands and to reduce the annual electricity consumption costs. The results show that when cold thermal energy storage and solar PV are coupled together higher annual electricity cost savings can be achieved compared to using these two technologies independently. Additionally, considerable reductions can be seen in electricity power demands in different tariff periods by coupling thermal energy storage with off-grid solar PV.

Keywords: Thermal energy storage (TES); solar PV; demand side management (DSM); optimization; energy management.

Nomenclature

Δt	simulation time step
A_{ei}	excess demand factor
C	required energy during an hour [kW]
CE	cost of energy [€]
COP_{ave}	average coefficient of performance
COV	coefficient of variation
CP	cost of contracting power [€]
D	set of days
DNI	direct normal irradiance [W/m^2]
DSM	demand side management
E_e	energy use [kWh]
$Elec_{tot}$	annual electricity cost [€]
$Elec_{acq}$	acquired electric energy [kWh]
E_p	power demand cost [€]
F_{ep}	charges [€]
h	hour
H	set of hours
I_m	maximum power current [A]
I_{sc}	short circuit current [A]
K_i	coefficient depending on the tariff period
M	set of months
MILP	mixed integer linear programming
MIP	mixed integer programming
NOCT	nominal operating cell temperature [$^{\circ}$C]
P_{demand}	power contract in different tariff periods [kW]
P_{energy}	energy consumed in different tariff periods [kWh]
P1-P6	tariff periods
Pc_i	contracted power for a specific tariff period [kW]
Pcs	number of cells
Pd_i	demanded power in each tariff period [kW]
Q_{str}	TES charge/discharge rate [kW]
SL	cold TES capacity [kWh]
t	time
T	set of hour periods
TES	thermal energy storage
V	maximum system voltage [V]
VAT	value added taxes
V_m	maximum power voltage [V]
V_{oc}	open circuit voltage [V]
x	fraction

Subscripts

Acq	aquired
d	day
e	energy
h	hour
i	period i (1, …, 6)
m	month
p	power
y	year

1. Introduction

In modern societies electricity is an important factor and plays a crucial role to economic growth. Globally, a vigorous increase in electricity demand can be seen in all end-use sectors. Additionally, the share of electricity is steadily growing in all sectors (Figure 1). On the other hand, increasing wealth in developing nations is likely to lead to higher demand for energy services using electricity, such as cooling and refrigeration [1]. 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 which are expected to grow by 46% by 2040 [2]. Reducing these elevating hazardous emissions due to high non-renewable generations is an important issue in the global climate system.

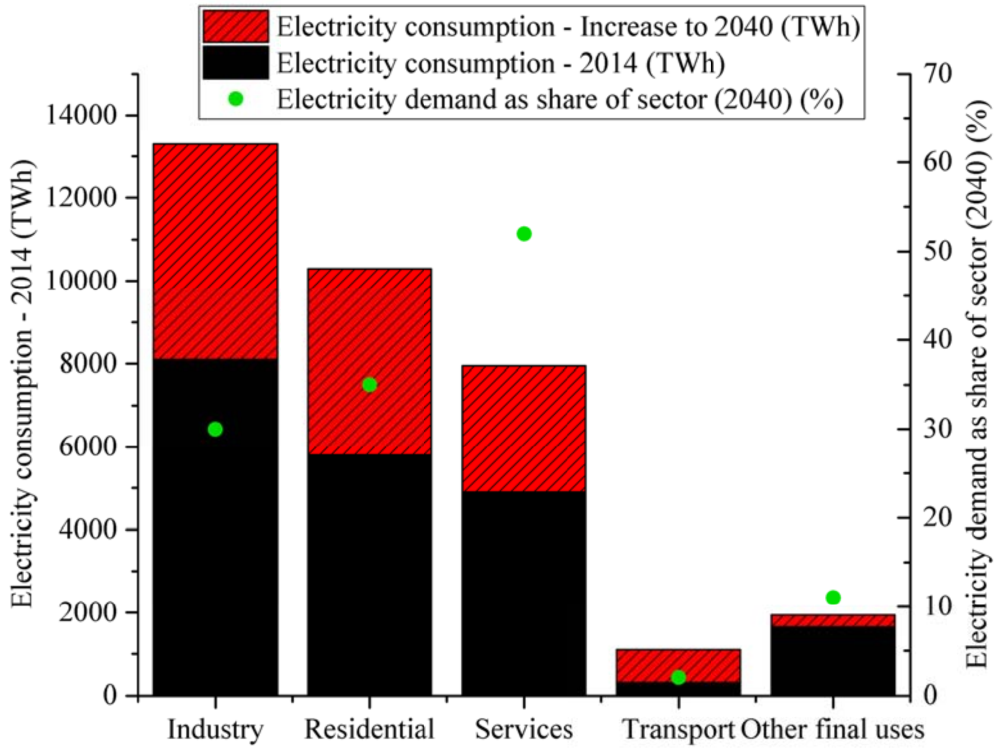

Figure 1. Growth in global electricity demand by sector and electricity´s share of sector demand in New Policies Scenario, adopted from [1].

Many governments in the world are exploring alternatives to slow down the global warming by enforcing new rules and regulations for different sectors. The Paris Agreement on climate change [3], which entered into force in November 2016, is among them which is an agreement focusing on energy. Countries should increase their ambition of applying new energy policies across both the supply side and the demand side. An important change is necessary in the pace of decarbonization and increasing the energy efficiency in the 450 Scenario [4]. This energy scenario deploys an energy solution consistent with the objective of reducing the global rise in temperature to 2°C by restricting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2 [1]. In this scenario, the power sector is highly decarbonized and nearly 60% of the power generated in 2040 is planned to come from renewable energy sources, around half of this from solar photovoltaic (PV) and wind.

Peak electricity demand is a global policy concern which creates transmission constraints and congestion, and raises the cost of electricity for all end-users [5]. In addition, a considerable investment is required to upgrade electricity distribution and transmission infrastructure, and build generation plants to provide power during peak-demand periods [6]. 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 [7].

So that, scaling down some of this peak demand would benefit the whole energy system [8]. On one hand, it can 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 [9], and on the other hand, consumers can eliminate penalties due to exceeding power demands in their electricity bill. As an example, in Italy and Spain 5.3% and 6.8% of installed capacities are only used about 1% of the time [10]. Furthermore, because of occasional use of peak plants, making them more efficient is not feasible from economic point of view. So that, normally it is cheaper to run peak electricity generators by fossil fuels. As a result, these inefficient plants increase greenhouse gas (GHG) emissions and other air pollutant emissions per unit of electricity produced [11].

Using flexible resources in the power system such as solar photovoltaic (PV), storage, and demand management can offer a unique solution to increase the security and stability of the whole energy system, to bring economic benefits, and to make low-carbon transition achievement possible [13].

Solar PV is fast becoming a key technology in global energy market [15]. The market of solar PV is expanding from a record high 49 GW in 2015 to almost 90 GW per year by 2040 in the New Policies Scenario, and cumulative capacity additions to 2040 amount to over 1400 GW [1]. However, there is a challenging aftereffect of increased levels of solar generation share which is the variability and uncertainty of electricity generation due to weather condition. In fact, integrating large shares of PV requires technical and economic flexibilities from the rest of the system [16].

Demand side management (DSM) is a proactive way to increase the energy efficiency among customers in the long-term [19], and can reduce both the electricity peak power demand (kW) and the electricity consumption (kWh) [20,21]. The most prominent DSM methods include reducing peak loads (peak clipping or peak shaving), shifting load from on-peak to off-peak (load-shifting), increasing the flexibility of the load (flexible load shape), and reducing energy consumption in general (strategic conservation), as stated by Müller et al. [22].

In order to avoid grid constraints, time-of-use distribution network tariff structure has been adopted by some countries such as Spain to shift their consumption from on-peak hours (expensive hours) to off-peak hours (cheap hours) [23,24]. Time-of-use tariffs can encourage customers to benefit from price variations in different periods of time and to regulate their electricity use based on their needs. In such schemes, a group of prices are determined in advance and applied to different periods of time, where the electricity prices are discriminated by patterns and rates [25]. So that, based on the information provided by electricity supplier, energy-intensive customers such as commercial and industrial units can decide how to distribute their loads according to variable electricity tariffs, and available financial resources using different technologies [26,27] with the objective of reducing their final energy bill.

Among the other DSM techniques mentioned above, load shifting is the most effective load management technique [28] since it enhances the demand flexibility without compromising the stability and continuity of the process and, additionally, 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, as mentioned by Lund et al. [29]. 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.

Energy storage could be classified in major categories of mechanical storage, electromagnetic storage, chemical storage (battery storage), biological storage, and thermal energy storage (TES) [30]. 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 [31,32].

Thermal energy storage (TES) is an increasingly important area, which has been the center of attention of many authors during the past decades [33]. A large and growing body of literature has investigated the benefits of TES for renewable energies applications and system integration.

For example, Guruprasad et al. [34] extensively reviewed the application of TES materials and systems for solar energy applications. In another attempt, Li and Zheng [35] studied various methods of TES system integration for building and industry applications. 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 [36], and on the other hand, reduce the greenhouse gas emissions [37,38].

For instance, Naranjo Palacio et al. [39] analyzed the application of cold TES for cooling applications and its impacts on reducing power system operation costs by cutting down peak demands and smoothing out the load profile of large-scale commercial buildings. In another study, Sehar et al. [40] studied the application of ice TES technology to shift peak electrical cooling load to off-peak periods in large and medium-sized office buildings. It was shown that the ice TES can reduce the cooling load in peak hours, nonetheless, it was reported that the ice TES systems have higher chiller energy consumptions than the conventional systems without ice TES due to the day and night chiller operation because of climatic conditions. Similarly, Arcuri et al. [41] investigated the application and effectiveness of ice TES technology to shift air conditioning peak cooling demand from on-peak hours to off-peak hours in commercial buildings in Brazil. It was found by them that ice TES system can be more economically beneficial in cities with hotter climates and higher energy costs. Additionally, they concluded that the attractiveness of the ice TES system to shift peak cooling loads in commercial buildings varies considerably depending on the weather condition and energy tariffs.

Recently, researchers have shown an increased interest in using DSM techniques together with TES, battery storage, and solar PV technologies for peak load management in industrial and commercial sectors. This is a step change taking place in energy management technologies which is tied with technology advancements, increase of electricity prices, appearance of new incentive tariff structures, substantial decrease in solar PV price, and new energy policies.

For example, Wand and Dennis [45] studied the potential of coupling TES with different types of phase change material (PCM), battery storage, and PV to reduce the peak cooling load of a PV-based cooling system of a residential building under different climate conditions. For their specific case they found that, higher primary energy saving ratio could be achieved using battery storage than cold TES mainly because of heat losses in the storage tank and low temperature chiller set point. In another study, Sehar et al. [46] investigated the potential of applying ice TES and solar PV technologies in demand responsive commercial buildings for reducing the plug-in electric vehicles active loads during charging and mitigating the network constraint. It was shown in their research that coupling ice TES and PV can fully absorb plug-in electric vehicles penetration, and result in 13.4% reduction in the peak load; about 11% improvement in the load factor; and 11.6% reduction in feeder losses. Further on, Ban et al. [47] proposed a methodology based on ice TES and grid-connected solar PV technologies to reduce the peak cooling loads in office buildings, and also to solve the intermittency problem of solar PV generation, especially when cooling storage is integrated into district cooling systems. It was concluded that the most cost-beneficial solution was to charge ice TES during night and to sell PV generation by building-integrated PV to the grid. Park and Lappas [48] investigated the application of solar PV and battery storage to reduce peak demand charges in commercial scale. They found that the utilization of solar PV could reduce the maximum demand by 0.05% to 1.5% under Australian electricity network tariffs. However, when 12 kWh battery storage was coupled with the solar PV the savings increase to 1.31% to 2%. In addition, Comodi et al. [49] analyzed the possibility of shifting loads from on-peak hours to off-peak hours using sensible TES. They studied different scenarios for load shifting and found that 14124 $ and 23427 $ of annual economic savings could be achieved by shifting 3531 kWh and 6436 kWh of electricity from on-peak to off-peak hours, respectively. However, it was mentioned by them that due to sensible TES high space is required for the storage tank and one should bare it in mind when adopting this technology.

Recently, numerous studies have focused on DSM applying simulation and optimization techniques [50–54]. As an example, Muralitharan et al. [51] applied a multi-objective evolutionary optimization method for DSM in a residential home with the objective of reducing the energy cost. Their results showed reductions in both electricity cost and delay time of execution of electrical appliances for consumer. Further on, Shakouri and Kazemi [54] used a DSM method based on mixed-integer multi-objective linear programming to minimize electrical peak load and electricity cost for a residential area with multiple households considering the on-peak, mid-peak, and off-peak electricity prices. Their results show the effectiveness of using optimization-based DSM for peak load reduction and reducing the energy bill.

So far, 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 with high electric demand and enhancing the overall performance of the energy system through interconnection of these technologies [55]. For instance, in a recent study, Sehar et al. [56] used DSM technique using TES coupled with solar PV to reduce the peak power cooling loads in an office building using dynamic simulation. For their specific case study they found that using only solar PV, only DSM, or their combination can reduce both building peak load and energy consumption. Also, they concluded that using ice storage increases the overall building energy consumption;

however, it can provide substantial peak load savings.

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 structures and elevated electricity prices, high surplus demand charges, and variable solar PV share and its uncertainties in the energy system [57]. Previous studies related to DSM in industry and building sectors show that simulation-based optimization can play an important role to improve energy efficiency in the energy sector [58–60].

Today, the energy policies are shifting towards integration of different technologies. The central issue of the present 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 PCM) 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. The results of the present study can be used by customers with large-scale electric demands to apply incentive electricity tariffs for reducing their final energy cost. Additionally, the results presented herein can help the industry sector in the decision making of applying TES and solar PV with appropriate capacities to exploit the maximum benefits due to use of these technologies which can improve the overall performance of the energy system.

The novelty of the present paper is reflected by the fact that it shows how the interconnection of TES and solar PV technologies along with an optimized DSM based on Spanish electricity tariff structure can effectively reduce the peak electric loads in the industry sector compared to when these two technologies are used individually.

2. Methodology

2.1. Case study

The case study is a dairy factory producing high quality dairy products located in Lleida province of Spain. The dairy processes approximately 30 000 liters of milk per day, five days per week into cheese and yoghurt products. Refrigeration is needed to fast freeze yoghurt products in a cool tunnel, and store within a cool room. This is achieved with a 5-year old Freon direct expansion refrigeration system. The facility also produces water at 0°C for the process plant using an ice making ammonia refrigeration plant. Investigation will be made into the possibility of replacing the direct expansion refrigeration system with an ammonia plant with a thermal storage coupled to off-grid solar PV.

Initially a conventional energy system with no demand side management facilities, neither solar PV nor TES system was considered, to give an estimation of the annual energy bill for ~~an~~ above-mentioned industrial consumer. 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 2a). 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 for high-demanding consumers (6.1A time-of-use tariff structure) [24] was 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. As derived from the realistic annual electricity bill of the industrial consumer it can be seen that for all tariff periods the reference industrial unit contracts 450 kW electric power demand and in almost all periods significant surplus charges can be seen. The annual electricity bill for operational hours of the dairy factory can be calculated using Eq. (1):

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

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

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

where $Elec_{tot}$ is annual electricity cost, E_p is power demand cost, 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 different periods as explained in details in Table 2.

Three different optimization scenarios have been 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 2a): Scenario 1. time-of-use tariff DSM coupled with only cold TES system (Figure 2b), Scenario 2. time-of-use tariff

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

In Scenario 1 (Figure 2b), the cold TES tank has to be charged at nighttime during off-peak period and later on, it has to be discharged during day, and especially at on-peak period or the most expensive hours of the electricity tariff. In Scenario 2 (Figure 2c), the feasibility of reducing the energy costs by applying off-grid solar PV has been assessed. Eventually, in Scenario 3 (Figure 2d) 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 2 illustrates a scheme of the optimization scenarios.

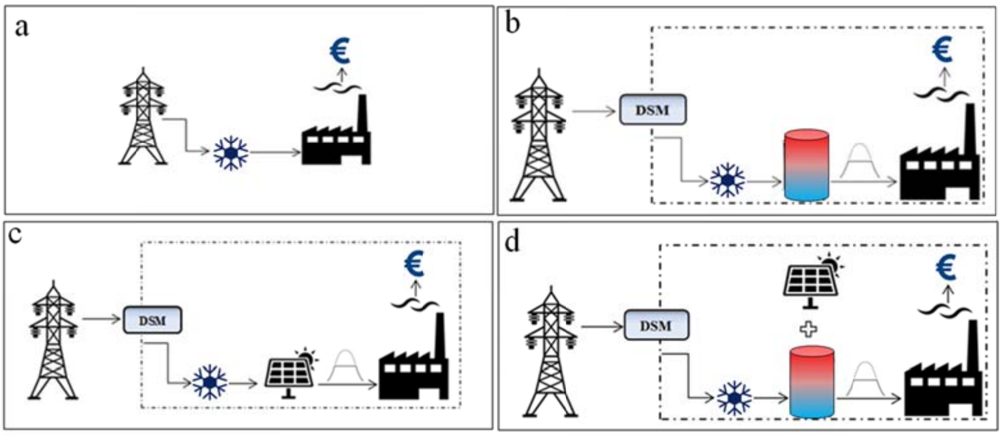

Figure 2. Schematic view of the methodology.

2.2. Simulation of PV module

The electricity generation by solar PV, was simulated using TRNSYS v17 [61]. This software has an extensive library of components in which appropriate models 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 run the simulation.

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 [62]. Sunrise SR-M762315-B solar PV (Figure 3) [63] technical data as shown in Table 1 was introduced to Type 94a and four different nominal power of 25 kW_p, 50 kW_p, 80 kW_p, and 100 kW_p were considered. Further on, in all cities a fixed array slope of 40º and azimuth of 180º were taken into account. Simulations were performed using time steps of 15 minutes for a period of one year. Also, it should be noted that the PV export in hours with surplus generation was not considered. Further explanations about the weather data are provided in Section 2.3.

Table 1. Sunrise SR-M672315 module specifications [63].

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	

2.3. Weather data and solar variation

For simulating solar PV generation under climate condition of Lleida where the case study is located, solar radiation and ambient temperature data for several years was required to be introduced into the simulation program. Actually, selecting weather data and mainly solar irradiance of different consecutive years help to understand the solar PV generation under different solar intensities and intermittencies over a long period of time. Since finding historical weather data for several years was unfeasible for the considered climate, weather data for fifteen consecutive years (1991-2005) of Denver, Colorado, US were derived from National Renewable Energy Laboratory (NREL) weather data base [64]. According to Köppen-Geiger climate classification both Lleida and Denver are categorized in BSk climate classification. Further on, it was of interest to analyze how the solar intensity variations affect the solar PV generation, specifically at on-peak hours and eventually the annual economical savings in other climates. For this reason, two more climates of Nebraska (Köppen-Geiger classification Dfa), and Syracuse (Köppen-Geiger classification Dfb) were considered. Although a major part of Spain has warm temperature (Köppen-Geiger classification C) and arid (Köppen-Geiger classification B) climate condition but in some regions Köppen-Geiger classification D is prominent [65].

An important factor to improve the design of a system is the solar variability. For instance, by adding sufficient storage capabilities and understanding the performance of a solar conversion system [66]. In the present study, the solar irradiance variability method developed by Wilcox and Gueymard [66] was used. According to their method, the solar irradiance variability could be expressed by interannual coefficient of variation (COV) for direct normal irradiance (DNI) in percentage (Figure 3). In the current study three different climate classifications of BSk, Dfa, and Dfb were selected with 1-2%, 4-5%, and 9-10% COVs, respectively. The reason for this is to understand how the solar variability influences the electricity generation by off-grid solar PV and respectively the overall economic benefits of the system. On the other hand, it is intended to show how and to what extents the integration of TES can improve the performance of the solar PV in situations with low to high solar variations.

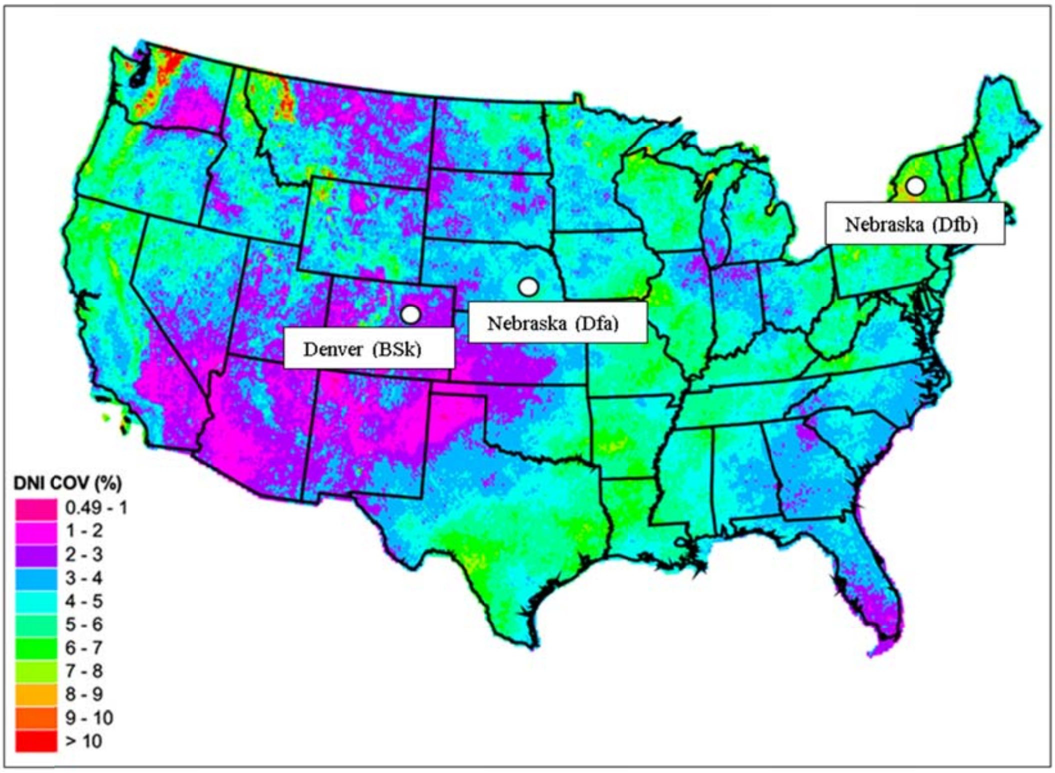

Figure 3. Interannual coefficient of variation (COV) for direct normal irradiance (DNI) (%) 1998-2005 [66].

2.4. 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. [67]. The capacity of storage model can be characterized by a charge/discharge rate as shown in Eq. (4) [67]. 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) [68].

$$\dot{Q}_{str} = x \frac{SL}{\Delta t} \quad (4)$$

$$COP_{ave} = \frac{\dot{Q}_{str}}{Elec_{acq}} \quad (5)$$

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

where $\dot{Q}_{str}$ 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.

It should be considered that 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. However, for the storage efficiency some heat losses were considered. 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. For this sake, in order to take into account these heat losses, some values corresponding to cold storage tanks were derived from experimental results available in literature [69–71]. Accordingly, four different standby heat loss values of 0 kW, 0.50 kW, 1 kW, and 1.50 kW were considered for the storage tank and implemented into TES model to see how the final economic benefits could be affected by these heat losses.

2.5. Time-of-use tariff structure

2.5.1. The electricity bill

In many countries 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 the 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 and by most of the industry sectors, the applied incentive time-of-use tariffs are shown in Figure 4.

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 4. Incentive time-of-use electricity tariff structure.

Figure 4 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. P6 refers to all prices at off-peak rates. The tariff consists of both an energy price and a demand price per period (Table 2).

Table 2. Incentive time-of-use electricity prices [72].

	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

2.5.2. 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 [24] (Eq. (6) and Eq. (7)), and it is measured every 15 minutes.

$$F_{ep} = \sum_{i=1}^{i=6} K_i \times 1.4064 \times A_{ei} \tag{6}$$

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:

$$A_{ei} = \begin{cases} 0, & \mathrm{Pd_j} <= \mathrm{Pc_i} \\ \sqrt{\sum_{j=1}^{j=6} (\mathrm{Pd_i} - \mathrm{Pc_i})^2}, & \mathrm{Pd_i} > \mathrm{Pc_i} \end{cases} \tag{7}$$

where $\mathrm{Pd_j}$ is demanded power in each quarter of hour which is excessed (higher than $\mathrm{Pc_i}$), $\mathrm{Pc_i}$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.

2.6. 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 [73–75]. 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 [22]. 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 [76–78]. 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 use 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; $T = H \times D \times M$ 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 as shown in Eq. (8):

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

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

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

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

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

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):

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

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 operating hours are 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 used 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), considering Eq. (9) and Eq. (10), and subject to constraint shown in Eq. (13):

$$\min_{PC_i}(CP + CE) \tag{12}$$

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

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 [79] 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:

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

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

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

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. It should be noted that for three climates of Denver, Nebraska, and Syracuse, identical efficiency and heat loss values were considered for the storage model and the corresponding results are not affected by the external weather conditions, so that, the results presented in Figure 5 do not differ from one climate to another. Generally, from Figure 5 it can be seen that the amount of economic savings increase linearly by the increase of TES capacity. From Figure 5, it is apparent that by the increase of storage capacity the annual economic savings increase correspondingly from 418 € (below 1%) per year, in case of 75 kWh of TES, to 53670 € per year (about 30%), in case of 9000 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.

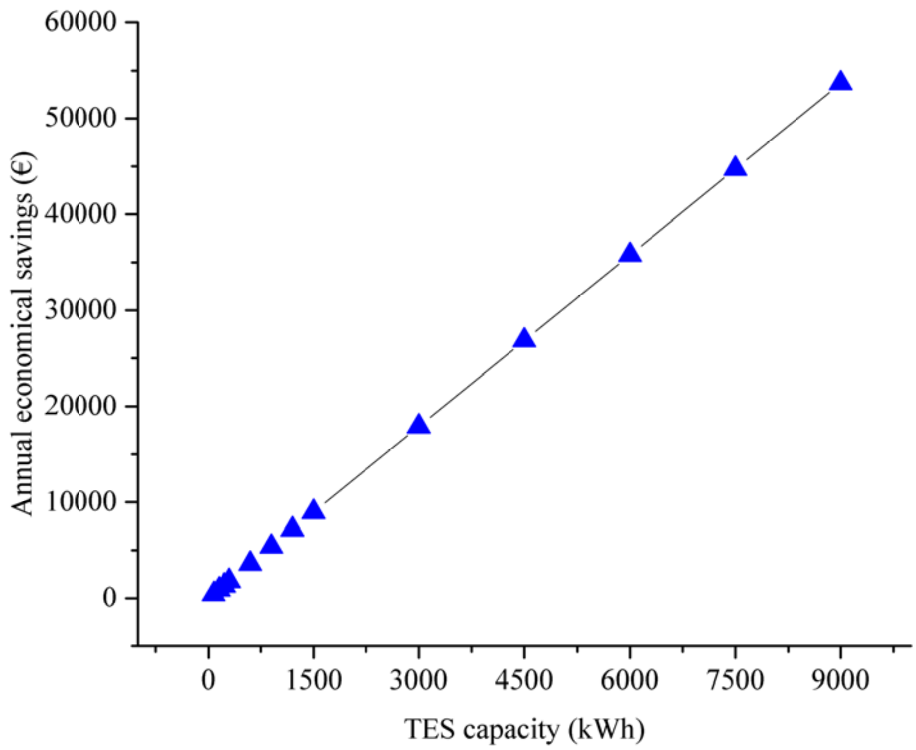

Figure 5. Economic benefits by using DSM and cold TES.

To have a more detailed view of the savings one can consider savings contributed to both power demand and energy consumption. Table 4 shows the optimum contract demands in six different tariff periods and the corresponding savings both for demand and energy in Denver. It can be seen that when only cold TES was used (No PV-1500 kWh TES) the power contract demands in all on-peak and mid-peak tariff periods (P1-P5) decreased form 450 kW to 400 kW compared to the reference case. Table 4 shows optimum contract demands in different tariff periods and the corresponding cost savings. It can be seen that above 8900 € of annual electricity cost could be saved parts of which come from demand costs and energy costs. Optimization results show 5086 € demand cost savings and 3859 € of energy cost savings. From these results it could be understood that using TES coupled with an optimized DSM can save both demand and energy costs, however, savings contributed to the power demand are higher than those achieved for energy consumption.

Table 4. Optimum power contract demands and cost savings; (No PV-1500 kWh TES), Denver.

Tariff periods						Cost savings (€)			Cost savings (%)		
P1	P2	P3	P4	P5	P6	Demand	Energy	Total	Demand	Energy	Total
400	400	400	400	400	450	5086	3859	8945	10%	3%	5%

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 have been presented and the results are shown in Figure 6. Generally, off-grid solar PV yields economic benefits in all climate regions; nonetheless, as expected the amount of cost savings depends on the solar radiation availability. From the results it is apparent that higher economic benefits can be achieved in Denver ranging from 4200 € to 16900 € (2-9%) with lower COV (1-2%), and in contrast, lower economic benefits can be obtained in Syracuse with about 3100 € to 12300 € (1.5-6.5%) with high COV (9-10%), however, the amount of cost savings in Nebraska which are about 3900 € to 15600 € (2.5-8.6%) are between the savings corresponding to Denver and Syracuse. This could be justified because the percentage of COV in Nebraska is between 4-5%, which is higher than Denver and lower than Syracuse.

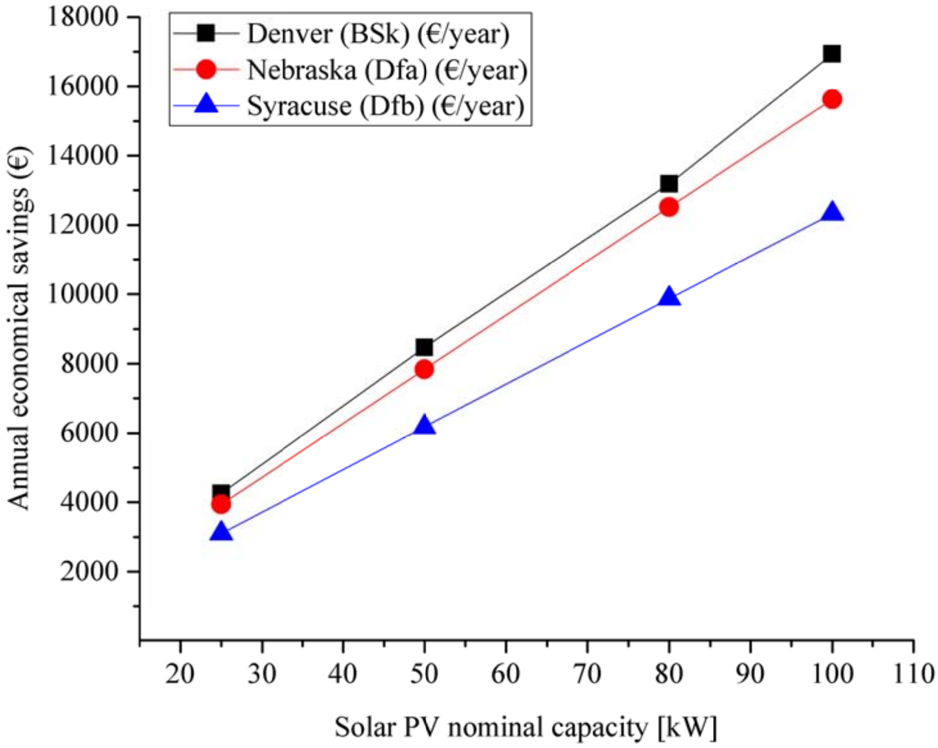

Figure 6. Economic benefits by using DSM and off-grid solar PV.

Further results regarding the benefits of using only off-grid solar PV together with an optimized DSM can be seen in Table 5. It can be seen that adding 50 kW of off-grid solar PV could achieve annual cost savings of 8465 €, 8100 €, and 6602 € in Denver, Nebraska, and Syracuse, respectively, with higher savings in Denver with lower COV.

By looking at the power contract demands it can be seen that using off-grid solar PV can slightly decrease the power contract demands in period P1. From the results presented in Table 5, it can be seen that only 2 kW reductions of electric power demand obtained in P1 period. However, it should be highlighted that solar PV showed substantial energy costs savings in all three climates despite of very low capability to reduce the power demands. The energy costs savings achieved in these climates are higher than those achieved by only using TES. Further explanations for this is that due to variable PV generations the electric power demand contract cannot be reduced substantially, since in occasions of poor electricity generation from PV surplus penalties may apply to the electricity bill. However, PV is energy-beneficial when there is enough solar radiation to produce electricity and reduce the real-time energy needs. In should be added that, the annual electricity savings may increase further by using more advanced solar

PV technologies such as solar tracking systems, and optimizing the performance of the solar PV system.

Table 5. Optimum power contract demands and cost savings in case of 50 kW PV-No TES for three different climates.

	Tariff periods						Cost savings (€)			Cost savings (%)		
	P1	P2	P3	P4	P5	P6	Demand	Energy	Total	Demand	Energy	Total
Denver	448	450	450	450	450	450	156	8308	8465	0.3%	5.8%	4.4%
Nebraska	447	450	450	450	450	450	117	7983	8100	0.2%	5.6%	4.2%
Syracuse	447	450	450	450	450	450	117	6485	6602	0.2%	4.5%	3.4%

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. Since the annual cost savings trends were very similar in three climates, only the annual electricity cost savings for Denver climate region are illustrated in Figure 7. In general, it can be seen that the annual cost savings have linear correlation with TES capacity and solar PV nominal capacity. By the increase of TES and PV capacities the annual economic savings increase correspondingly. However, generally higher annual electricity cost savings could be obtained in Denver in comparison with Nebraska and Syracuse. This is because of lower PV generation variability, and accordingly less demand surplus charges in Denver.

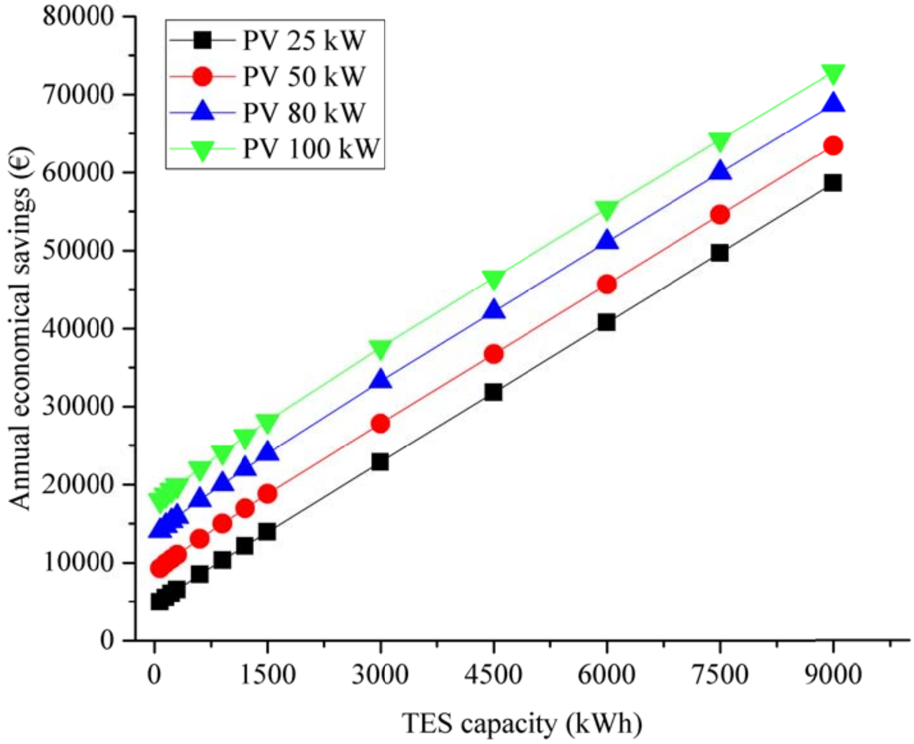

Figure 7. Economic benefits by using DSM coupled with cold TES and solar PV, Denver (BSk).

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.

For instance, in Table 6 the results obtained by optimization-based DSM coupled with TES and solar PV are presented in case of PV 50 kW-TES 1500 kWh for three different climates of Denver, Nebraska, and Syracuse with different annual solar radiation patterns. By looking at the power contract demands in P1 to P6 periods, it is apparent that coupling TES and solar PV technologies can considerably contribute to reduction of electricity demands compared to using these two technologies separately and without coupling. As explained in previous sections, P1 period is the most expensive period, in which, reductions of demand and energy can substantially reduce the annual electricity bill. From Table 6 it can be seen that power contract demands in P1 period reduced from 450 kW in case of reference model to 358 kW, 370 kW, and 381 kW in Denver, Nebraska, and Syracuse, respectively. Moreover, important reduction of power demands achieved for periods P2 to P5 in all three climates, according to results presented in Table 6.

Table 6. Optimum power contract demands and cost savings in case of 50 kW PV-1500 kWh TES for three different climates.

	Tariff periods						Cost savings (€)			Cost savings (%)		
	P1	P2	P3	P4	P5	P6	Demand	Energy	Total	Demand	Energy	Total
Denver	358	409	409	409	409	450	6167	12636	18803	12.7%	8.8%	9.8%
Nebraska	370	409	409	409	409	450	5697	12526	18223	11.7%	8.8%	9.5%
Syracuse	381	404	404	404	404	450	5580	10834	16414	11.5%	7.6%	8.6%

Further on, the authors would like to put shed on the cost savings achieved for demand and energy terms in all three climates due to coupling TES and solar PV technologies with assist of optimization techniques. In all three climates, important annual demand cost savings were achieved thanks to the application of TES, however, it was not limited only to demand term, but also, considerable cost savings can be observed for energy term which mainly comes from solar PV generation.

From these results, one can understand the significance of integration and economic benefits due to interconnection of technologies and the corresponding economic benefits that could be achieved using these advanced control and innovative materials and strategies.

In general, in all three climates the solar PV could increase the economic benefits by reducing the energy term of the electricity bill. On the other hand, the cold TES could substantially reduce the demand term of the electricity bill, and eventually when cold TES and solar PV technologies were used together, more cost savings observed in the annual electricity bill.

To have a detailed understanding about the benefits of integration, the hourly results of the optimization-based DSM together with charging/discharging control are presented in Figures 8 and 9 for a winter day and a summer day, respectively, under weather conditions of Denver. From Figure 8, it can be seen that at off-peak hours (00:00-08:00) about 60 kW of electricity is consumed to charge the TES with a capacity of 1500 kWh. Then, from 08:00 to 11:00 when there is poor solar radiation, the TES discharges about 132 kW of thermal energy (equivalent to 44 kW of electric energy), however, at 10:00 due to climatic condition the solar radiation drops considerably where higher discharge from TES can be observed (about 390 kW of thermal energy which is equivalent to 130 kW of electric energy), further on, 10:00 to 12:00 are the most expensive hours since they are in the P1 tariff period.

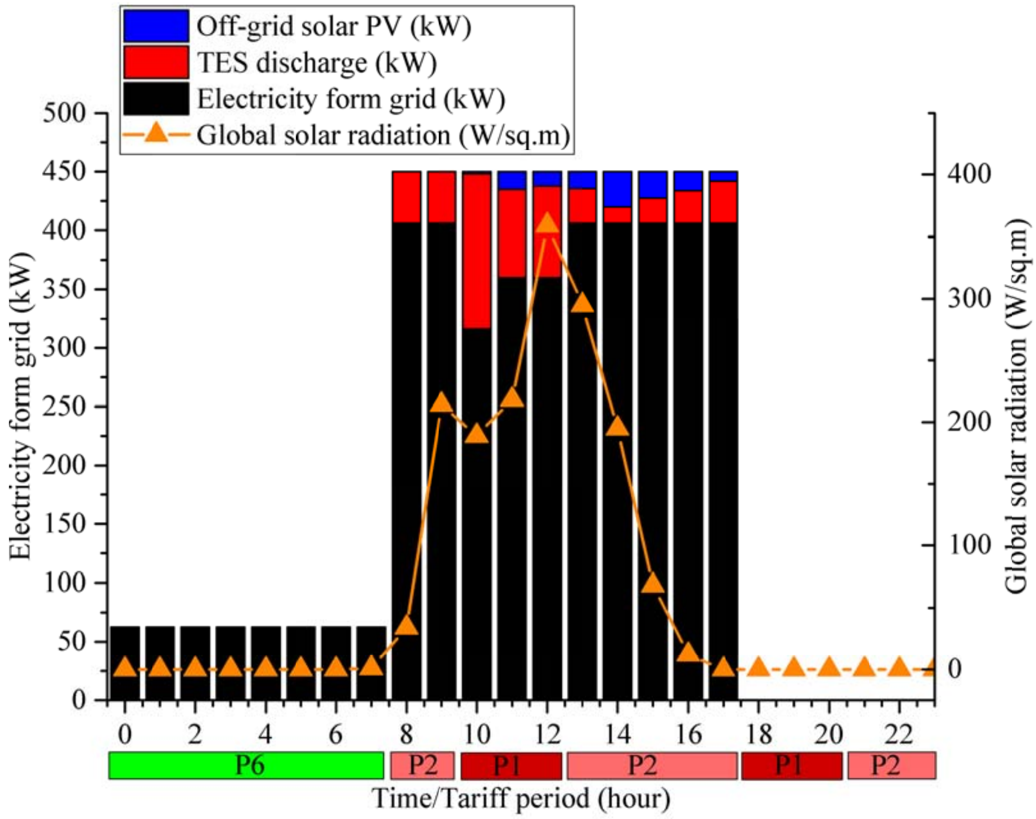

Figure 8. Charging/discharging control of TES/solar PV in a winter day, (12/01/1999), Denver (BSk).

On the other hand, by looking at the results presented in Figure 9, it could be seen that in a summer day and when there is a high amount of solar radiation (more than two times compared to the maximum solar radiation available in January 12th), the amount of purchased electricity from the grid reduces, specifically at on-peak hours (from 11:00 to 16:00). Later on, at 17:00 when lower solar radiation is available, the control system demands higher discharge from TES (about 465 kW thermal energy equivalents to 155 kW of electric energy). On the other hand, it should be considered that when higher solar radiation is available the stored energy in the TES could be kept for hours when there is a need for discharging from TES.

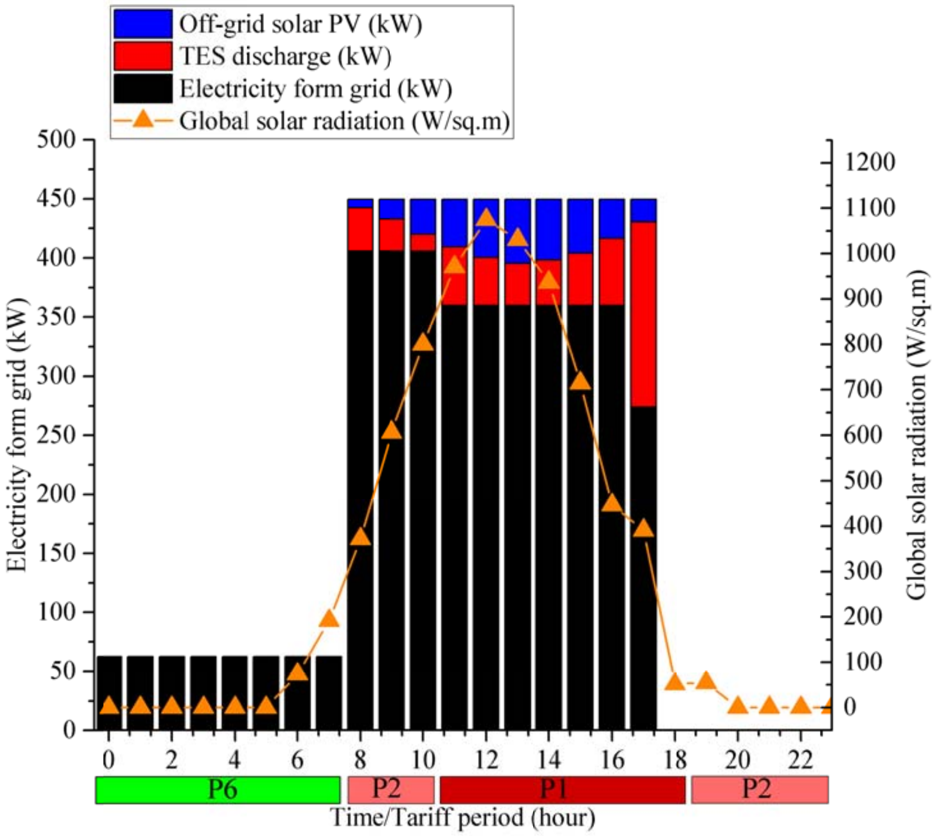

Figure 9. Charging/discharging control of TES/solar PV in a summer day, (21/07/1999), Denver (BSk).

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 determine 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 after subtracted from annual cost savings due to coupling cold TES with solar PV (Scenario 3). Actually, these cost savings demonstrate that 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 10 to Figure 12 show the annual cost saving improvement ratios in three different cities. Actually, 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 which is also consistent with findings of other researchers [80]. 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 €, 8100 €, and 6602 € could be achieved in Denver, Nebraska, and Syracuse, respectively. However, when TES and solar PV technologies are coupled together these savings increase to 18803 € in Denver, 18223 € in Nebraska, and 16414 € in Syracuse, which are higher than the sum of the economic benefits achieved by only TES and only solar PV technologies. For example, 8945 € annual savings can be achieved in case of using only TES, and 8465 € by using only solar PV in Denver. However, when these two technologies coupled together the total annual cost savings increased to 18803 € in Denver, which is about 7% higher than the sum of benefits achieved by using them separately (Figure 10).

In general, from Figure 10 to 12 in can be derived that in climates with lower COV such as Denver, higher system performance improvement could be achieved by coupling TES and solar PV, and in contrast, in climates with higher COV such as Syracuse lower system performance improvement can be achieved due to solar variability, nevertheless, the presence of TES prevents the whole system to suffer from discontinuity of supply and surplus demand charges.

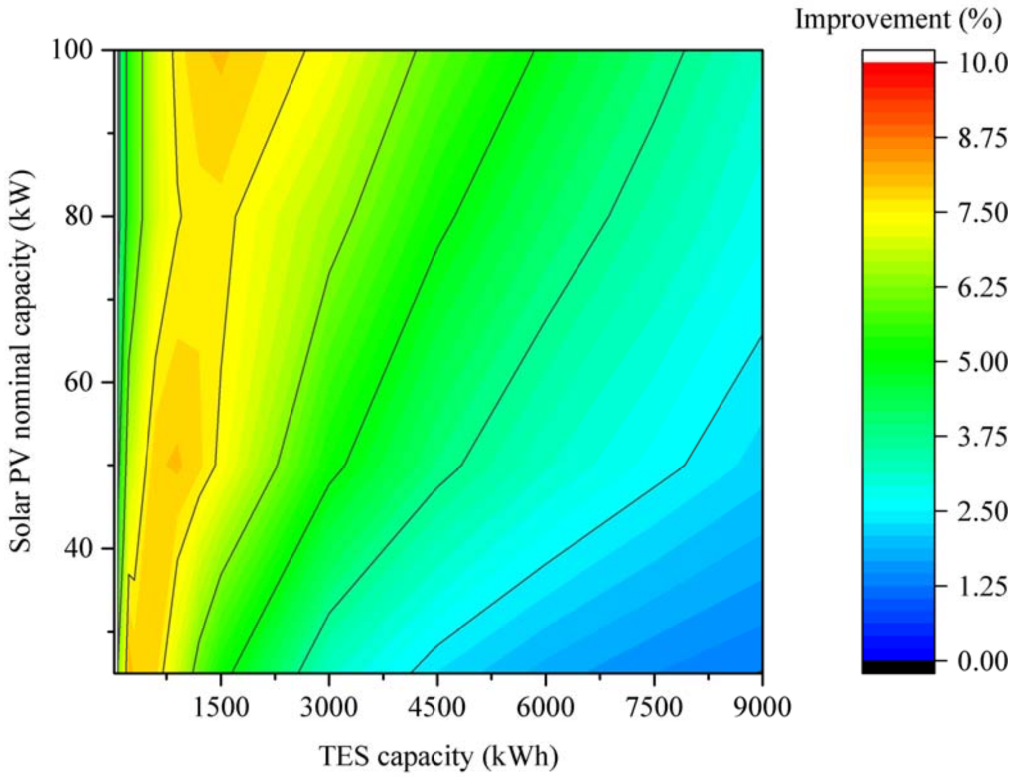

Figure 10. Annual electricity saving improvement by coupling cold TES and solar PV technologies, Denver (BSk).

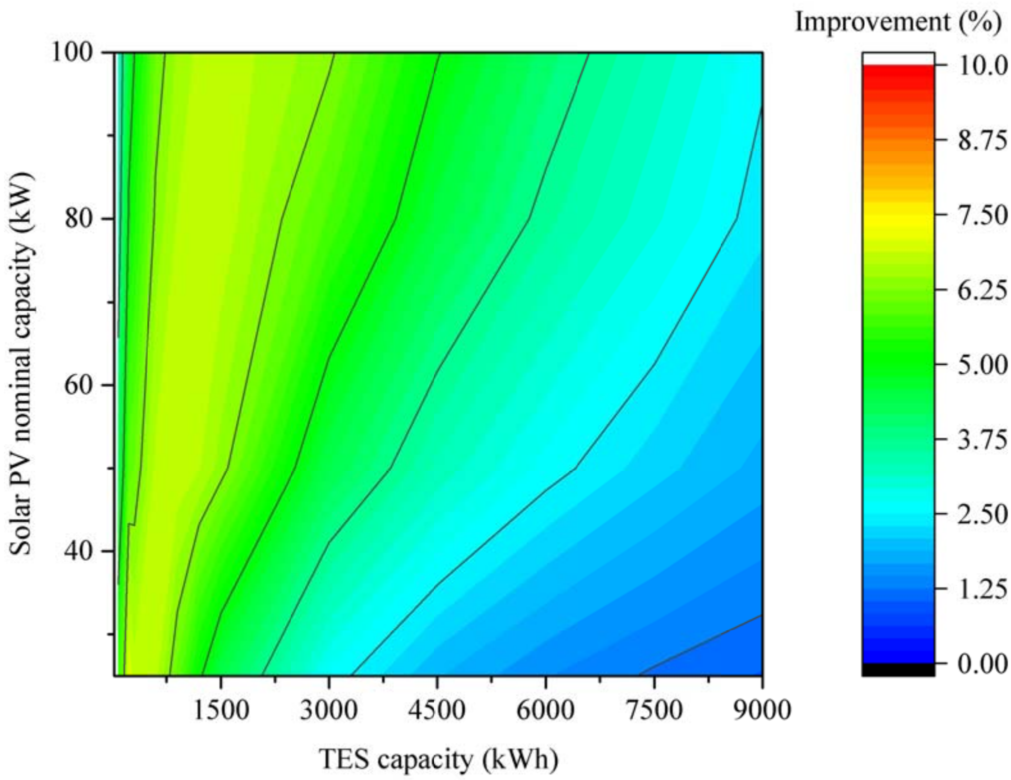

Figure 11. Annual electricity saving improvement by coupling cold TES and solar PV technologies in

percentage, Nebraska (Dfa).

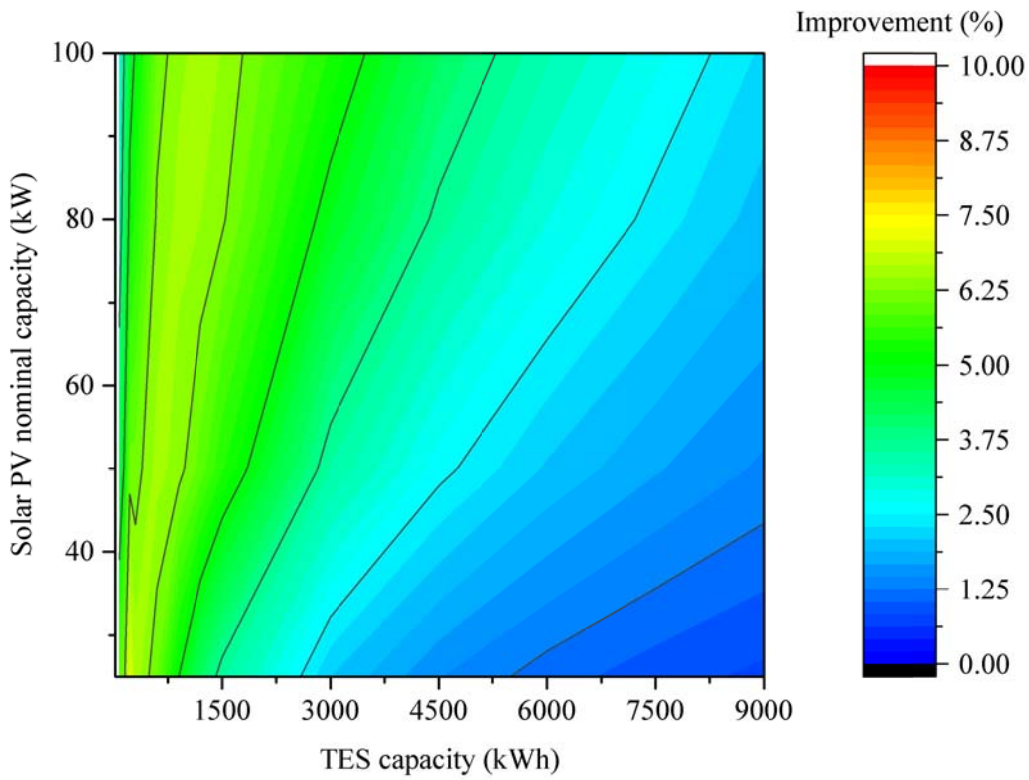

Figure 12. Annual electricity saving improvement by coupling cold TES and solar PV technologies in percentage, Syracuse (Dfb).

3.5. The impact of heat loss on final economic savings

In the previous results, the storage heat losses were not considered. The aim of this section is to show the impact of standby heat losses of the thermal storage tank by different ratios and their influence on the final annual economic benefits. The results of different heat loss levels on the final annual electricity cost savings ratios are presented in Figure 13 for the case of PV 50 kW and under weather condition of Denver. Generally, it can be seen that heat losses at different levels can negatively influence the total annual cost savings from 0.5% to about 4%. For TES capacities between 75 kWh and 1500 kWh these reductions are steeper, however, when TES with capacities higher than 1500 kWh is used, these negative influences are negligible and even less than 1%. Herein, only the influence of thermal storage heat losses in Denver are presented since the heat loss trends under climate conditions of Nebraska and Syracuse are very similar to these results.

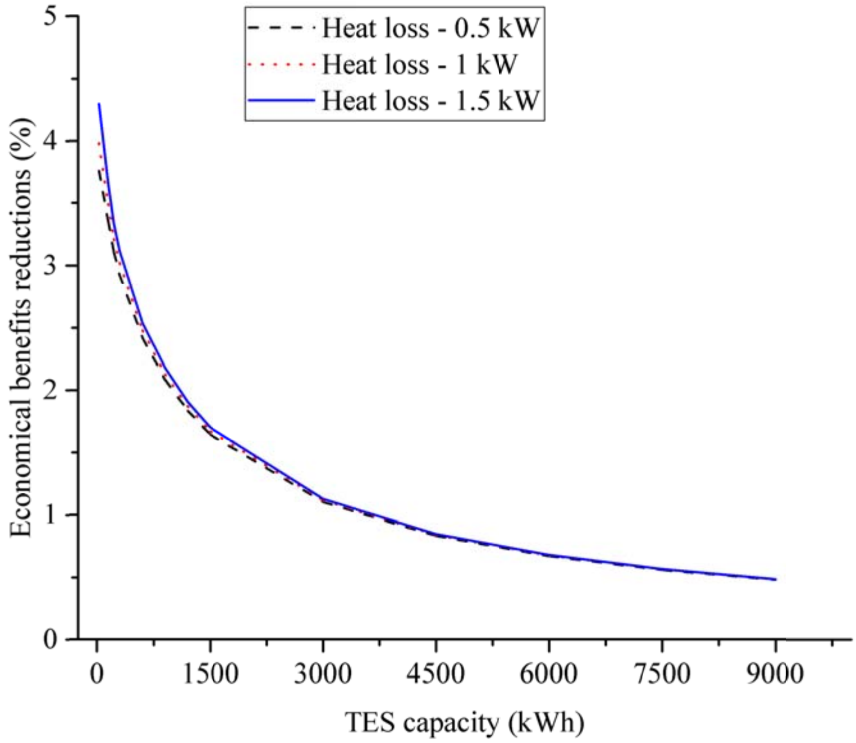

Figure 13. Impact of heat loss on the annual cost savings in case of PV 50 kW and TES, Denver (BSk).

4. Conclusions

- In the current paper, an optimization-based time-of-use DSM combined with low temperature TES and off-grid solar PV technologies is used to shift on-peak electricity demand of an industrial consumer under climate zones with high, medium, and low solar irradiance variability.
- 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.
- Savings attributed to the integration of cold 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 radiation is not achieved; excess electric power is demanded from the grid by cost of considerable charges.
- Solar PV without storage can reduce the energy term but not significantly the power term of the energy bill.
- 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.

- The implementation of cold TES not only can shift the on-peak load but also can improve the performance of the off-grid solar PV system under variable PV generation conditions.
- The proposed method can be readily used in practice. This research was related to the use of TES and solar PV for peak load shifting in a dairy factory; however, the results should be applicable also to beverage and food processing factories, cold-storage facilities, supermarkets, and any industrial processes with significant cooling demand.

5. Acknowledgments

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