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

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## HIGHLIGHTS

- Constraint integer programming was used for optimization of electricity tariffs.
- Demand side management was used with PV and TES for peak electric load shifting.
- Higher demand can be reduced by low temperature TES compared with solar PV system.
- Coupling TES and solar PV technologies can improve the overall system performance.

## ARTICLE INFO

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## 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.

## 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 (Fig. 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.

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

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**Nomenclature**

| | |
|---|---|
| $\Delta t$ | 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 [°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 | acquired |
| d | day |
| e | energy |
| h | hour |
| i | period i (1, …, 6) |
| m | month |
| p | power |
| y | year |

[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 ppm 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].

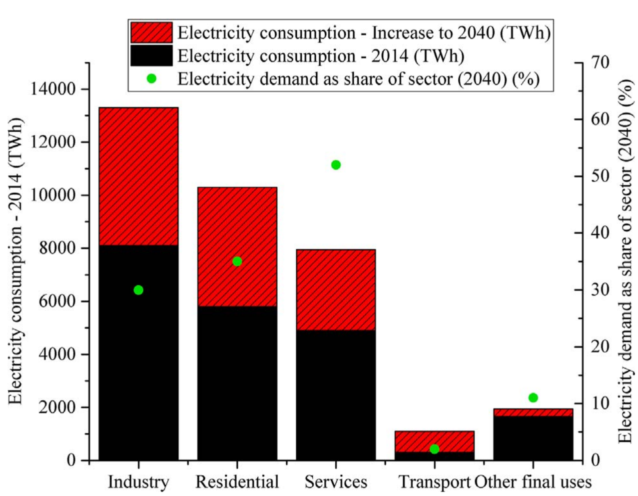


**Fig. 1.** Growth in global electricity demand by sector and electricity's share of sector demand in New Policies Scenario, adopted from [1].

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 [12].

Solar PV is fast becoming a key technology in global energy market [13]. 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 [14].

Demand side management (DSM) is a proactive way to increase the energy efficiency among customers in the long-term [15], and can reduce both the electricity peak power demand (kW) and the electricity consumption (kWh) [16,17]. 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. [18].

In order to avoid grid constraints, time-of-use distribution network tariff structure has been adopted by some countries such as Spain to