Applied Energy 317 (2022) 119154

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Enhancing solar energy generation and usage: Orbiting solar reflectors as alternative to energy storage

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HIGHLIGHTS

- Orbiting solar reflector (OSR) gives an option to deliver clean energy from space.
- OSR can enhance energy generation and market participation of solar PV farms.
- OSR can be an alternative integration option to energy storage (ES) for solar PV.
- OSR gives better economic value to solar PV than ES whatever the market condition.

ABSTRACT

Despite the growth of the solar energy sector, its utilization for energy provision has remained largely limited to hours of daylight. Previous studies have considered the integration of energy storage (ES) with solar farms to charge up using solar energy during daytime and to discharge in other hours. Alternatively, recent advancement in space technology enabling the deployment of orbiting solar reflectors (OSRs) opens a new vista of possibilities for delivery of clean energy services in an environmentally friendly manner. OSRs can provide additional illumination from space to identified large-scale solar farms on the Earth at critical hours of the day thereby enhancing energy generation and extending production hours of the solar farms. This paper investigates enhancing the solar farm output using OSRs as an alternative to energy arbitrage using ES and examines the short-term (annual) profitability and long-term (lifetime) economic viability of investment in either OSR or ES as integration option for the solar PV farm. Studies investigate different cases regarding both technologies as integration options for the solar farm under different market conditions regarding hourly electricity price variation. The obtained results demonstrate that irrespective of the market conditions, the solar farm receives better economic value when integrated with OSR.

1. Introduction

1.1. Background and motivation

The provision of clean energy services is receiving significant attention from governments worldwide. In this regard, policies and action plans are being initiated by governments to achieve the decarbonization of electricity systems through the large-scale integration of renewable generation. As an example, the European Commission set out a target for renewable-based generation to provide at least 32% of the total energy requirement in the European Union (EU) by 2030 [1].

Owing to these policies, the global solar energy industry has grown significantly in the last decade. By the end of 2018, there had been a 31-fold capacity increase in the cumulative solar PV installation worldwide compared to 2008 [2]. Forecasts indicate that the cumulative global PV installation capacity by the end of 2023 will be about 1296 GW, i.e., 81-fold capacity increase as compared to 2008 [2]. Despite this growth in global PV capacity, electricity production using solar energy is limited as its energy production is concentrated in a few hours of the daylight with up to 80% of solar energy production occurring within 26% of hours of the year [3].

In order to overcome this limitation, studies have focused on the use of ES to facilitate high renewable energy generation including solar PV [4,5] and wind [6,7]. ES can charge up using the renewable energy in its time of production (daytime for solar energy) and discharge in other critical hours of the day thereby extending the functional time of energy generated using the renewable energy technologies.

Alternatively, OSRs can extend the functional hours of solar farms by providing additional illumination to these farms outside the daylight hours. OSRs are ultra-lightweight reflectors deployed in space to orbit around the Earth and reflect sunlight from space to specified locations on the Earth. The reflector's orientation in space is controlled to ensure that appropriate geometry to both the Sun and the specified ground target is maintained. OSR as a concept was first introduced in [8]. Several years later, authors in [9–11] investigated its application for

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https://doi.org/10.1016/j.apenergy.2022.119154
Received 7 December 2021; Received in revised form 7 April 2022; Accepted 15 April 2022
Available online 27 April 2022
0306-2619/

Nomenclature

Indices and Sets

$m \in M$	Index and set of months
$d \in D$	Index and set of days
$t \in T$	Index and set of hours
$T^{orb} \subseteqq T$	Subset of hours where OSRs provide additional illumination

Parameters

$P^{ref}_{t \in T^{orb}}$	Additional energy output due to OSRs (MWh)
C^{ref}	Maintenance cost paid for OSR in one year ($)
C^{ES}	Annual Cost of operating and maintenance for ES ($/MWh)
$\lambda_{m,d,t}$	Electricity prices in month m at day d and hour t ($/MWh)
$P^{D}_{m,d,t}$	Demand in month m at day d and hour t (MW)
$P^{Sol}_{m,d,t}$	Maximum solar output in month m at day d and hour t (MW)
P^{max}	Combined capacity of existing generation technologies
s^{max}	Power capacity of ES (MW)
E^{min}	Minimum energy limit of ES (MWh)
E^{max}	Energy capacity of ES (MWh)
E_0	Initial energy level of ES (MWh)
τ	Temporal resolution
N_T	Length of market horizon
η^c	Charging efficiency of ES

Variables

$p^{g}_{m,d,t}$	Power output from conventional generation in month m at day d and hour t (MW)
$p^{s}_{m,d,t}$	Solar power output in month m at day d and hour t (MW)
$s^{ch}_{m,d,t}$	Charging power of ES in month m at day d and hour t (MW)
$s^{dis}_{m,d,t}$	Discharging power of ES in month m at day d and hour t (MW)
$E_{m,d,t}$	Energy level of ES in month m at day d and hour t (MWh)

providing illumination. Krafft Ehricke in [12] explored different possible applications including night-time illumination, agricultural enhancement and terrestrial power generation. Studies have also analysed the use of orbiting solar reflectors in providing illumination to other planetary bodies such as the Moon [13,14] and for climate engineering of Mars [15,16].

In the late 1970s, a system of OSRs for terrestrial power generation was studied by the United States National Aeronautics and Space Agency (NASA) in a project called SOLARES. The SOLARES project aimed to continuously reflect solar energy to selected locations on the Earth using approximately eighty thousand reflectors to orbit the Earth. A preliminary technological assessment was presented in [17] and further studies on the SOLARES concept are presented in [18–20]. These studies concluded that the technology requirement for the SOLARES system was not available at the time, they however predicted the early 1990s for realization of this. In addition, the studies acknowledged that OSRs can reduce the need for ES and serve as an alternative to them. The limited economic analysis presented in these papers focused on estimating the levelized costs of delivering 1 kWh of energy using SOLARES as compared with other conventional technologies.

In the last decade, the use of OSRs for terrestrial solar energy generation has attracted renewed interest. Recent studies by Fraas et.al in [21,22] considered a constellation of satellites which was assumed capable of providing illumination for energy generation for one hour each at dawn and dusk to 40 different solar PV farms on the Earth. The economic analysis estimated the years of payback using calculated revenue values and different launch costs. However, the revenue calculations have been derived using an overestimation of energy delivered which omitted the diminishing effects of factors such as reflectivity, cloud cover, atmospheric absorption, and reflection among others. In addition, a constant electricity price of $100 per MWh in both dawn and dusk hours was used for all locations considered. As regards the costs, reflector procurement cost and annual maintenance cost were omitted from the analysis, only the launch cost for transporting the reflector to space was considered. Furthermore, the discount rate to represent the time value of money was not considered in the payback time calculation. Given the oversimplification of the assumptions, the estimated payback time presented by the authors was too optimistic.

A year-round solar energy provision using OSRs to 5 selected sites on the Earth was analysed in [23]. Although the paper's author included the launch cost, reflector procurement cost and annual maintenance cost in the cost calculation, the author overestimates the projected revenue by assuming a fixed electricity price of $120 per MWh (excessively high) for all hours of the day for the 30-year lifetime considered for the energy provision with OSR. The financial viability was calculated for different discount rates using the net present value (NPV) and NPV based payback period.

The assumption of a constant electricity price for all hours in these papers [21,23] disregards the temporal and daily variation in electricity prices. Moreover, these prices will also differ across the multiple locations where the intended farms are located.

In [24], a flower constellation comprising of two OSRs operating in an heliotropic orbit is proposed. This constellation provides illumination to enhance energy generation of three large sized solar PV farms located in equatorial region across three different continents. However, a detailed economic analysis of the work is not presented. A high-fidelity analytical model to calculate the total energy delivered to a stationary ground-target from a reflector in a circular orbit is presented in [14]. The developed model is used to calculate the solar energy delivery to fixed size locations on the Earth, Moon and Mars. In [25], the use of OSR for lunar surface illumination is explored. The study presents astrodynamics analysis of different architectural options for the OSR configuration.

Authors in [26], present an overview of the technical challenges with the development and deployment of OSR. The paper also discussed advantages of alternative business models for the operations of OSR for global delivery of energy services.

1.2. Paper contributions

This paper investigates the use of OSRs as an integration option to enhance the energy generation of a solar PV farm. The paper discusses OSR as an alternative to ES and presents a novel analysis of the distinctiveness of both OSRs and ES as alternative technologies that can integrate with solar PV. Although the works of Gilbreath et.al [18–20] acknowledge that OSRs can serve as an alternative to ES, the use of these two technologies as integration options for solar PV farms has not been compared with each other in the literature. However, there are existing studies which analyse ES as an integration option for solar farms to change the time of use of the solar energy generated.

Specifically, the paper's main contributions include:

- This paper develops optimisation models which maximises the profit earned by the solar PV farm when operating alone, when integrated with ES and when integrated with OSR technology. The developed models are applied under different market conditions which reflect the general characteristics of existing systems regarding the electricity prices.
- The considered market conditions in this paper make use of historical electricity prices which vary for each hour of the day and for each day of the year, thereby addressing some of the shortcomings in the works of [21,23] where a fixed price was used for all the hours of the year.
- This paper presents an economic analysis on OSRs as an integration option to enhance the energy generation and profitability of a solar PV farm operating in an electricity market. A technological assessment of orbiting solar reflector is out of the scope of this paper, however, interested readers can find an assessment of orbiting solar reflectors as a space technology for solar energy generation in [17].
- The short-term profitability and long-term economic viability of investment in either OSR or ES by a solar PV farm is analysed and compared with each other and with a base case where the solar PV farm operates on its own.

Table 1
Comparison between interactions of Orbiting Solar Reflectors (OSRs) and Energy Storage (ES) with solar PV farms.

	Orbiting Solar Reflectors (OSRs)	Energy Storage (ES)
Operational Differences:	OSRs provide additional illumination to solar farms to increase their energy output. This illumination can also be provided in hours where there is no daylight thereby extending the operational hour of solar farms.	For the ES, it can provide energy arbitrage within a day and across days by charging (buying energy) in the hours where the energy price is low and discharging (selling energy) in the hours where the energy price is higher thereby leading to a flatter energy demand profile. The ES can also provide various reserve and frequency regulation services for the energy system some of which are analysed in [27].
Electricity Market Participation:	OSRs are unable to directly participate in the electricity market, rather they provide additional illumination to solar PV farms to generate more energy and enhance their participation in the electricity market.	ES can directly participate in the electricity market. Merchant Owners can invest in ES facility to participate in market and maximise its profit. Numerous studies existing in literature such as [28,29] have analysed different operations and impacts of ES as a distinct electricity market participant.
Geographical Limitations:	OSRs can provide illumination to enhance the energy generation of multiple solar PV farms located in different electricity markets across the continents of the world	Specific ES facility can only participate in the electricity market(s) to which it is connected.

1.3. Paper structure

The rest of this paper is organized as follows. Section 2 presents the trade-off between OSRs and ES. The models are presented in section 3. Case studies and results are presented in section 4. Finally, section 5 discusses the conclusions from this work.

2. Trade-off between OSRs and ES as alternative integration options for solar PV farms

OSRs and ES are two technologies considered in this paper as integration options for the solar PV farm to enhance its profitability. Both technologies possess unique attributes which affect their individual operation and integration with the solar PV farm. Some of these differences are presented in Table 1.

3. Model formulation

The models used to represent the operation of the solar PV farm under different integration options are presented in this section. The underlying assumptions are discussed in the next subsection.

3.1. Assumptions

The different models incorporate some assumptions which are summarized below for clarity:

- The models express the optimization problem to maximize the profit earned over a yearly period by solar PV farms when integrated with alternative technologies.
- An energy-only market is considered with day-ahead horizon and hourly resolution.
- The electricity price is considered a parameter in this model. However, the electricity price varies for each hour within the day. It is assumed that the electricity price is not affected by the activity of either OSR or ES.
- Since electricity price is not affected by the activity of considered technologies, the capacity of all existing conventional generation technologies is represented using a single parameter for ease of modelling.
- The considered solar PV farm is assumed to have a capacity of 1,750 MW. The hourly solar electricity production profile is obtained from the PVGIS database [30]. To obtain the profile, northwest of India is the assumed location for the solar PV farm.
- The technical characteristic of ES is represented using charging efficiency, energy balance constraints as well as minimum and maximum energy and power limits.
- We assume that the ES provides intraday arbitrage i.e., it starts empty and returns to empty at the end of the day.
- For the integrated solar PV farm and ES case, the ES is charged using only energy generated by the solar PV farm.
- For the integrated solar PV farm and OSR case, the OSR provides additional illumination to the solar farm to generate additional energy at dawn and dusk. The calculation of the additional energy generated by the solar PV farm under the OSR case is adapted from the study presented in [14]. Energy calculation for this paper is presented in Appendix A.
- For ease of illustration, we assume that the OSR makes ideal overhead passes over the solar farm at dawn and dusk respectively following the approach in previous studies [21]. It should be noted that orbital dynamics will restrict the geometry of such passes in practice, so this is an optimistic assumption, although the specifics of

the pass geometry are a function of the orbit and the solar PV farm locations, which are not considered here.

- OSRs can provide illumination to multiple locations so we assume the considered OSR constellation is jointly owned by five solar PV farms including the examined solar PV farm, such that the examined solar farm is responsible for only 20% of the cost incurred by the operation of the OSR.

3.2. Model for the sole operation of solar PV farm

The solar PV farm functions to maximise its profit in the electricity market. The problem is formulated below:

$$Max\sum_{m,d,t}\left\{\lambda_{m,d,t}{}^{*}p^{s}_{m,d,t}\right\} \tag{1a}$$

subject to:

$$p^{g}_{m,d,t}+p^{s}_{m,d,t}=P^{D}_{m,d,t};\ \forall m,\forall d,\forall t \tag{1b}$$

$$0\le p^{g}_{m,d,t}\le P^{G};\ \ \forall m,\forall d,\forall t \tag{1c}$$

$$0\le p^{s}_{m,d,t}\le P^{Sol}_{m,d,t};\ \forall m,\forall d,\forall t \tag{1d}$$

The objective function (1a) maximizes the profit of the solar farm over the period of one year. Given that the hourly production cost of solar is assumed to be negligible, the operational profit is the same as the operational revenue earned. Constraint (1b) enforces the energy balance between the demand and supply. Constraint (1c) gives the lower and upper limits for other conventional generators, constraint (1d) presents the lower and upper limits of the solar energy dispatched in an hour.

3.3. Model for integrated solar PV farm and ES operation

In this model, the solar PV farm is integrated with an ES facility to charge and store solar energy generated during low price periods and sell same in the periods with higher electricity prices thereby enhancing the profit earned over the year. The problem is formulated below:

$$Max\sum_{m,d,t}\left\{\lambda_{m,d,t}p^{s}_{m,d,t}+\lambda_{m,d,t}\left(s^{dis}_{m,d,t}-s^{ch}_{m,d,t}\right)\right\}-C^{ES}E^{max} \tag{2a}$$

$$p^{g}_{m,d,t}+p^{s}_{m,d,t}+s^{dis}_{m,d,t}=P^{D}_{m,d,t};\forall m,\forall d,\forall t \tag{2b}$$

$$0\le p^{g}_{m,d,t}\le P^{G};\ \forall m,\forall d,\forall t \tag{2c}$$

$$0\le p^{s}_{m,d,t};\ \ \forall m,\forall d,\forall t \tag{2d}$$

$$p^{s}_{m,d,t}+s^{ch}_{m,d,t}\le P^{Sol}_{m,d,t};\ \forall m,\forall d,\forall t \tag{2e}$$

$$0\le s^{ch}_{m,d,t}\le s^{max};\ \forall m,\forall d,\forall t \tag{2f}$$

$$0\le s^{dis}_{m,d,t}\le s^{max};\forall m,\forall d,\forall t \tag{2g}$$

$$E^{min}\le E_{m,d,t}\le E^{max};\ \forall m,\forall d,\forall t \tag{2h}$$

$$E_{m,d,t}=E_{0}+\tau\eta^{c}s^{ch}_{m,d,t}-\tau s^{dis}_{m,d,t};\ \forall m,\forall d,\forall t=1 \tag{2i}$$

$$E_{m,d,t}=E_{m,d,t-1}+\tau\eta^{c}s^{ch}_{m,d,t}-\tau s^{dis}_{m,d,t};\ \forall m,\forall d,\forall t>1 \tag{2j}$$

$$E_{0}=E_{m,d,t};\ \forall m,\forall d,\forall t=N_{T} \tag{2k}$$

The model's objective function (2a) maximizes the overall profit which comprises of: i) The profit from the sale of the energy from solar PV farm, (first term), ii) the profit from the energy arbitrage of the ES facility (second term) calculated as the difference of the revenue earned from the sale of energy discharged from the ES and the price paid for energy charge by the ES, and iii) the fixed yearly operations and maintenance cost for the ES.

The system wide demand–supply market balance constraint is expressed by the constraint (2b). Constraint (2c) gives the lower and upper limits for other conventional generators, constraint (2d) presents the natural non-negative limits of the solar energy dispatched in an hour. The ES is charged directly from the solar farm, so the constraint (2e) limits the sum of hourly solar energy output traded in the market and the hourly ES charge to the hourly expected production of the Solar PV Farm.

The ES power capacity limits for the charging and discharging are defined by constraints (2f) and (2g). The energy limits of the ES are defined by constraint (2h). Although the assumption is that the ES can be fully discharged, the parameters representing the minimum discharge level has been included for completeness of the model.

The constraints (2i) and (2j) show the energy balance equation which connects the hourly value of energy stored (for first hour and other hours of the day) to its level of discharge or charge within the hour and the initial energy level or energy level in previous hour respectively. Constraint (2k) ensures that the energy arbitrage by the ES is intraday and the final energy level in the last hour of the day is the same as the initial energy level at the start of the day.

3.4. Model for integrated solar PV farms and OSRs

Next, the solar PV farm is integrated with OSRs which provides additional illumination to enhance energy generation at dawn and dusk. The problem is formulated below:

$$Max\sum_{m,d,t}\left\{\lambda_{m,d,t}p^{s}_{m,d,t}\right\}+\sum_{m,d,t\in T^{orb}}\left\{\lambda_{m,d,t}P^{ref}_{t}\right\}-C^{ref} \tag{3a}$$

subject to:

$$p^{g}_{m,d,t}+p^{s}_{m,d,t}+P^{ref}_{t\in T^{orb}}=P^{D}_{m,d,t};\ \forall m,\forall d,\forall t \tag{3b}$$

$$0\le p^{g}_{m,d,t}\le P^{G};\ \forall m,\forall d,\forall t \tag{3c}$$

$$0\le p^{s}_{m,d,t}\le P^{Sol}_{m,d,t};\forall m,\forall d,\forall t \tag{3d}$$

The objective function (3a) maximizes the overall profit over the period of one year which includes i) profit of the solar farm (first term), ii) the additional profit from energy generated due to the additional illumination by the OSR, and iii) the yearly operational and maintenance cost of the reflector. Constraint (3b) enforces the hourly demand–supply energy balance constraint and includes the additional energy provided by the reflector. Constraint (3c) gives the lower and upper limits for other conventional generators, constraint (3d) presents the lower and upper limits of the solar energy dispatched in an hour.

These models have been implemented and solved using CPLEX 20.1 solver on the AIMMS optimization software, (AIMMS version 4.77) [31].

4. Case studies

4.1. Input data

Case studies are examined considering a test system which reflects the general characteristics of existing electricity markets. The hourly power demand is taken from historical values of the India Energy

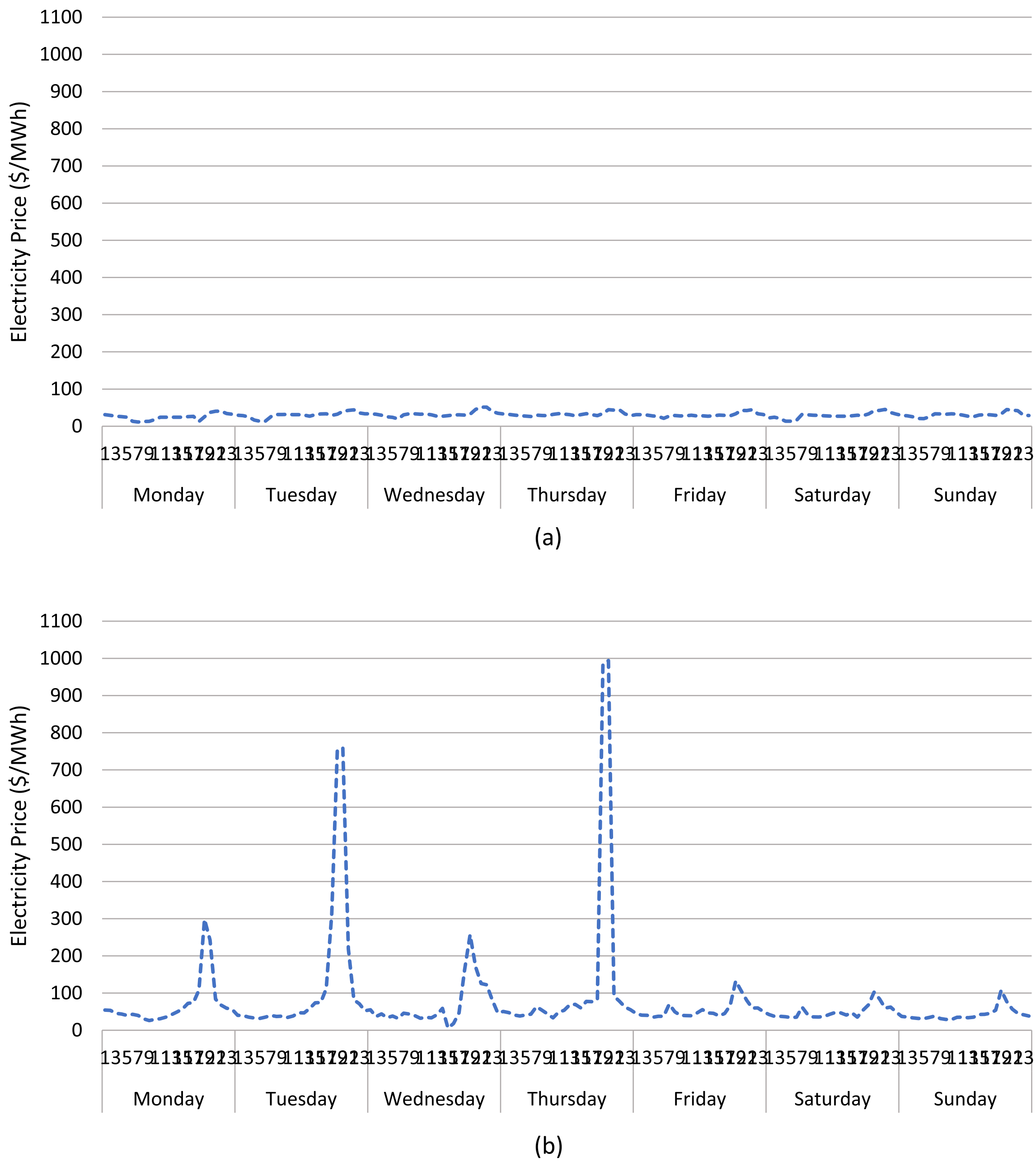

Fig. 1. Historical Electricity Prices for a week in August for a) IEX market, b) CAISO market.

Exchange (IEX) market [32]. Conventional generation technologies existing in the considered electricity market are assumed to have a combined capacity of 50 GW.

We assume that the energy capacity of the ES is the same as the total additional energy generated by the solar PV farm (in dawn and dusk hours of 6 am to 7 am and 6 pm to 7 pm respectively) due to illumination received from OSRs. The calculation of energy generated using a constellation of OSRs is presented in Appendix. The hourly production profile from the solar farm over the year has been obtained using the PVGIS software. The solar farm is assumed to have a nameplate capacity of 1,750 MW.

Three cases relating to the operations of the solar PV farm are examined:

i) **Base case**: The solar PV farm operates on its own.

ii) **Case 1**: Energy Storage (ES) facility is integrated to the solar PV farm, and they operate such that the ES is only charged from the energy output of solar PV farm.

iii) **Case 2**: Orbiting Solar Reflector (OSR) is integrated with the solar PV farm to provide additional energy output for the solar farm at critical dawn and dusk hours.

Table 2
Values for the technical parameters used in the case studies.

Parameters	Value
P^{ref}	100 MWh
η^{c}	0.9
E^{max}	200 MWh
s^{max}	50% E^{max}/1h

Table 3
Solar Output Curtailment.

	Market Condition 1			Market Condition 2		
	Base Case	Case 1	Case 2	Base Case	Case 1	Case 2
Solar Energy Curtailment (GWh)	–	–	–	250.36	225.45	250.36
Solar Energy Curtailment (%)	–	–	–	8.39%	7.56%	8.39%

In order to account for multiple credible operating conditions, these three cases are evaluated under two market conditions with distinct characteristics. The first market condition (MC1) is a market with relatively stable prices, prices vary slightly from the average prices. The second market condition (MC2) is a market with very high price variation across the hours of the day, prices can be very high in certain peak demand hours and prices can also be very low in certain off-peak demand hours of the day.

Real energy price data for the year 2020 which fit the above description has been obtained from two different markets. The hourly price data for the year 2020 in India Energy Exchange (IEX) market [32] ranges between 9.63 $/MWh and 80.67 $/MWh. This has been selected to represent MC1. The hourly price data for the year 2020 obtained from California ISO (CAISO) market [33] has a range between −11.07 $/MWh and 994.22 $/MWh. This has been selected to represent MC2. Historical price values for a typical week in August 2020 for both MC1 and MC2 are shown in Fig. 1. below.

Furthermore, using data obtained from [34], the ES in case 1 is considered to have a lifetime of 20 years, a capital cost of 385 $/kWh, operation and maintenance cost (C^{ES}) of 2.44 $/kWh per year. The ES has a storage duration of 2 h represented through a power to energy ratio of 50%. However, note that the ES can charge and discharge multiple times in a day.

For the OSR in case 2 to produce additional illumination sufficient to generate 100 MWh, a constellation of thirty 1-km diameter sized reflectors is considered. Each reflector has a 20-year lifetime, weighs approximately 7860 kg, and is placed in low Earth orbit. As used in [26], a procurement cost of 375 $/kg[1] and a recurring annual maintenance cost of 5.63 $/kg is considered for the reflector constellation. The launch costs of $1400 per kg (cost for the Falcon Heavy satellite [35]) is used in the long-term economic analysis.

Given that the reflector constellation can provide illumination to multiple sites, we assume that the constellation is equally owned by a consortium of 5 solar farms. Therefore, the examined solar farm only incurs 20% of the entire costs for installation and maintenance of the reflector constellation.

The values for other technical parameters used in these case studies are presented in Table 2.

4.2. Results

Our first discussion focuses on the solar PV output utilisation and curtailment in both market conditions. Table 3 presents the curtailment of energy generated by the solar PV farm for the three cases considered in both market conditions. For the three cases considered in MC1, energy production by the solar PV farm is fully utilised and there is no curtailment.

[1] Although varying procurement cost values have been used in literature for orbiting solar reflectors, the decision to use 375 $/kg as an estimate cost in this work has been informed by observed trends in the large-scale cost of essential reflector components.

Table 4
Operational Profit earned in one year under different cases in different market conditions in millions ($).

	Market Condition 1			Market Condition 2		
	Base Case	Case 1	Case 2	Base Case	Case 1	Case 2
Solar Farm Profit	104.87	104.83	104.87	67.12	66.06	67.12
ES Profit	0	0.84	0	0	4.18	0
OSR Profit	0	0	2.39	0	0	3.53
Total Profit	104.87	105.67	107.26	67.12	70.24	70.65

Table 5
NPV and IRR for cases considered under both Market Conditions.

	Market Condition 1		Market Condition 2	
	Case 1	Case 2	Case 1	Case 2
NPV (in millions)	-$66.96	-$53.92	-$38.11	-$39.73
IRR	−11.78%	−4.83%	−1.92%	−1.57%

However, in MC2, there is curtailment of the energy generated by the solar PV farm. This curtailment occurs especially in hours where the electricity price is negative. The level of solar energy curtailment reduces in case 1 where ES is integrated with the solar PV. The ES charges up using some of the solar energy that would have been curtailed. On the other hand, in case 2 where the OSR only provides additional illumination to increase solar generation in specific hours of the day, the curtailment of solar energy is the same as in the base case. This is because the OSRs do not influence the operation of solar PV farms in other hours of the day as discussed in Section 2.

Table 4 presents the different components of the yearly operational profit for each case considered. We start our analysis of the annual operational profit with market condition 1, where the prices are relatively stable within each day. While operating alone (base case), the solar PV farm earns a profit of $104.87 million. The integration of ES with solar PV (case 1) increases the overall profit by $0.80 million (0.77%) with respect to the base case. Although the use of solar energy to charge the ES reduces the profit earned by the trading of solar energy in the market, the ES earns a higher profit (in comparison to the profit reduction by solar PV) to achieve an increase in the overall profit. Specifically, the ES energy arbitrage operation results in higher energy sale during the high-priced hours of the day.

In case 2, the additional illumination by the OSR enhances the energy generated by the solar farm in the dawn/dusk hours but does not reduce the output from the solar energy farm in other hours. Therefore, the solar PV farm retains its profit from participating in the electricity market as in base case. Alongside this, the dawn and dusk increase in the solar energy output by the reflectors leads to additional profit which increases the overall profit of the system by $2.39 million (2.28%) compared to the base case. This surpasses the profit increase of $0.80 million (0.77%) in case 1.

Next, we analyse the results obtained in MC2 where the hourly market prices vary between very low (and negative) price values in some hours and very high price values in the certain hours of some days. When the solar farm operates solely (base case), a combination of the very low prices in some hours and curtailment of its energy output in other hours (see Table 3) lead to a lower profit (36% lower) for the solar farm in its profit than obtained in base case of MC1.

In case 1, the integration of ES with solar farm has a similar effect as observed in MC1, the profit from direct solar energy sale reduces compared to the base case while the overall profit increases due to the activity of ES. However, the profit increase is significantly higher under MC2 (4.65%) compared with the increase of 0.77% in MC1 since the price variation across the day enhances the profitability of ES arbitrage. Furthermore, in this study, the arbitrage of ES reduces the curtailment of solar PV output compared to the base case.

In case 2, integrating with OSR leads to an overall increase in the profit by 5.26% compared to the base case. Although this profit increase is higher than what is obtained in case 1, the relative difference in profit increase in MC2 (5.26% − 4.65% =0.61%) is lower than the relative difference in profit increase (2.28% − 0.77% = 1.51%) in MC1.

From a higher-level perspective, this result demonstrates that irrespective of the market conditions and potential market outcome, the solar PV farm realises a higher operational profit over the year when integrated with OSR than when integrated with ES.

Next, we proceed to carry out the long-term economic analysis (considering the capital costs and yearly revenue) on the ES and OSR.

4.3. The Long-Term economic analysis

In this section, we carry out analysis to evaluate the economic feasibility of investment in either ES or OSR as integration options for the solar PV farm. The net present value (NPV[2]) metric and the internal rate of return (IRR[3]) metric are calculated for both the ES and the OSR in the considered market conditions and discussed. The NPV is an aggregate of the discounted cash flow over the lifetime of a project. The respective discounted cash flow is obtained by applying a fixed discount rate to the cash flow for each year. A discount rate of 5% is used for this analysis.

In Table 5, the NPV and the IRR obtained for the considered scenarios is presented.

For market condition 1, in case 1, where the ES realises a very low yearly profit as discussed in section 4.2, the NPV is negative which indicates that this case is not economically feasible for the considered discount rate. The IRR also has a negative. A negative IRR means that the sum of the non-discounted expected revenue is less than the initial investment cost, therefore, such an investment always loses money.

In case 2, the NPV improves slightly, though it is still negative just as in case 1. The IRR likewise improves in this case but also still negative.

For market condition 2, the higher annual profit of the ES and OSR (in comparison to the profits in MC1 – see Table 4) enhances their long-term economic value. Consequently, both the NPV and IRR give higher values than the values obtained under MC1. However, these values are negative for both metrics. The negative values for NPV and IRR in case 1 and 2 shows that the long-term economic feasibility is not achieved for both ES and OSR.

In the next subsection, breakeven analysis is carried out on both ES and OSR to evaluate the impact of cost on the long-term economic viability.

4.3.1. Breakeven analysis for ES

Market trend has shown a reduction in the capital cost for ES over the years. Further analysis is carried out to examine the extent to which the cost of ES should reduce, to achieve financial viability (NPV of $0.00), of case 1 under both market conditions, given the average yearly net cash flow calculated earlier. Under MC1, an overall capital cost of $10.04 million (a reduction of 86.96%) is required. This translates to a capital cost of 50.21 $/kWh for the ES. To achieve a NPV of $0.00 under MC2, an overall capital cost of $38.89 million (a reduction of 49.49%) – which translates to a unit cost of $194.47 per kWh – is required.

From a high-level perspective, the significant difference in the cost to achieve zero NPV of ES in both market conditions reinforces the importance of specific market analysis to inform both technology adoption and investment strategy.

[2] The NPV is calculated by the formula: $NPV = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} - C_0$ where C_0 is cost of initial investment; R_t is annual net cash flow; i is discount rate; N is duration of the project in years; t is time of the cash flow.

[3] IRR is calculated through an iterative process with the use of Microsoft Excel program

Table 6
Launch Cost to breakeven for OSR ($/kg).

	MC1	MC2
Launch Cost to breakeven ($/kg)	256.70	557.62

4.3.2. Breakeven analysis for the OSR

The capital cost of the OSR comprises of two independent costs namely the procurement cost and the launch cost. The launch cost for transporting satellites into orbit is reducing in recent years. As of 2018, the SpaceX Falcon Heavy Launcher has a cost of approximately $1400 per kg [35]. SpaceX is currently testing its Starship launcher with a capability to transport more than 100 metric tonnes of payload to low Earth orbit (LEO) [36] – the orbit where OSRs are deployed – with an optimistic cost of $2 million for each launch [37]. This will imply a launch cost of approximately 20 $/kg.

The first analysis carried out is to determine the launch cost to achieve breakeven i.e., an NPV of $0.00 for the OSR in both market conditions. This breakeven analysis gives useful information to understand what the launch costs need to be for the project to be considered economically feasible.

Note that for this analysis, the revenue and other parameters are unchanged for both market conditions. As shown in Table 6, under MC1, the NPV is $0.00 when the launch cost is 256.70 $/kg. This is a reduction of 81.66% in launch cost. Under MC2, the NPV of $0.00 is achieved at a launch cost of 557.62 $/kg which represents a reduction of 60.17%. For MC1 and MC2, the launch cost to breakeven is higher than the optimistic SpaceX Starship launch cost of 20 $/kg. With these figures, the project will achieve economic feasibility even before the SpaceX Starship launch cost of 20 $/kg is realised.

There is also uncertainty in estimating the procurement cost for OSRs. For this reason, further analysis is carried out to determine the impact of both launch and procurement costs on the long-term economic feasibility of the project. For this analysis, the net present value for the two market conditions is calculated considering different launch costs for the OSR varying between 1400 $/kg to 20 $/kg. Furthermore, for each launch costs considered, a range of specific procurement costs in increasing values from 250 $/kg to 850 $/kg are also considered (250 $/kg, 375 $/kg, 500 $/kg, 675 $/kg, 850$/kg) for the OSR. The net present value (presented in Figs. 2 and 3 below) is calculated with the discount rate of 5% and reflector lifetime of 20 years used in the earlier sections of this paper. All other parameters have the same values as in previous sections.

Figs. 2 and 3 show the net present value for market conditions 1 and 2 respectively. For MC1 which has a lower annual profit, with a launch cost of 1400 $/kg, the NPV is negative for all procurement costs considered. A substantial reduction in the launch cost is essential to achieve a positive NPV for the lowest procurement cost considered. The NPV improves with further reduction in the launch costs. However, at higher procurement costs of 675$/kg and 850 $/kg, the NPV is negative at all launch cost values considered. This result shows that to achieve economic breakeven in this market condition, both launch costs and procurement cost should have values lower than the realisable values considered in this analysis.

For MC 2, due to the higher annual profit of the OSR, the NPV is higher than in MC1. However, similar to results obtained in MC1, a substantial reduction in the launch cost is required to achieve a positive NPV for a few of the procurement cost values considered. The NPV improves with further reduction in the launch costs, but in contrast to MC1, the NPV becomes positive and economic feasibility is achieved even at the highest procurement values considered.

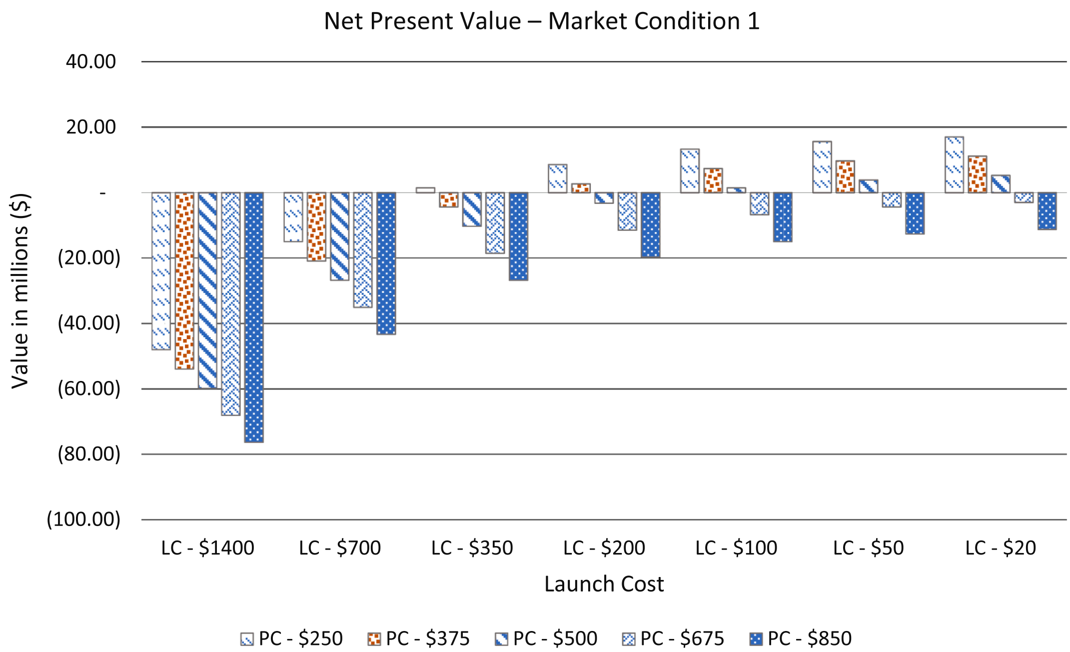

Fig. 2. Analysis of Net Present Value (5% discount rate) for different launch costs and procurement costs in Market Condition 1.

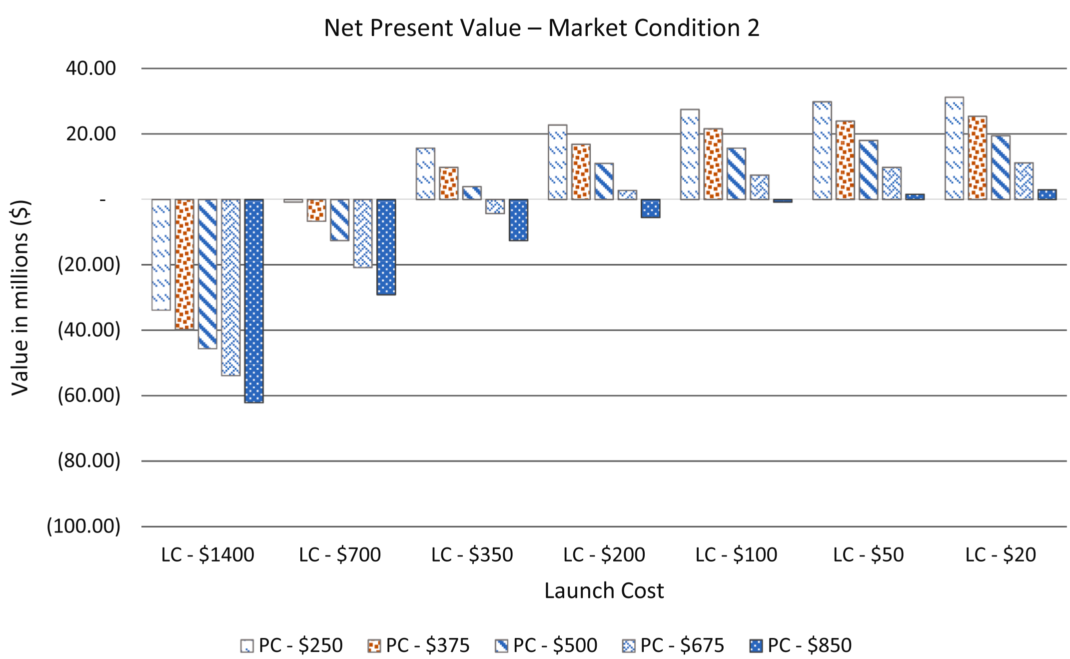

Fig. 3. Analysis of Net Present Value (5% discount rate) for different launch costs and procurement costs in Market Condition 2.

5. Conclusions

In the last decade, the global solar energy industry has grown significantly. However, solar energy generation is dependent on sunshine and is therefore limited to hours of daylight. Previous studies on enhancing solar energy generation have mainly focused on integrating energy storage to solar farms to charge up using solar energy during daytime and to discharge in other hours. Effectively, energy storage changes the time of use of the solar energy.

This paper discusses OSR as an alternative to ES in enhancing solar energy generation of a solar PV farm and analyses the impact of the considered alternative technologies on increasing the combined profit when integrated with the solar PV farm. The study investigated different cases regarding integration options available to the solar PV farm (solar PV farm operates on its own, solar PV farm is integrated with ES, solar PV farm is integrated with OSR) as well as different market conditions regarding the electricity prices (one market with relatively stable prices and another market with high price variations).

An important conclusion arising from the obtained results is that irrespective of the market conditions, the solar PV farm receives better economic value when integrated with OSR in comparison with ES. However, the magnitude of the relative difference in annual profit earned by the solar PV farm is dependent on the market condition. In MC2, the market with high price variations, this relative difference

(0.61%) is lower than those obtained (1.51%) in MC1, the market with relatively stable prices. Further analysis is carried out to determine the long-term economic feasibility for both ES and OSR. This analysis focuses on determining the costs to achieve economic breakeven for both technologies. For both OSR and ES to be considered economically feasible in the long-term, the launch cost for OSR must reduce by 81.66% and 60.17% in MC1 and MC2 respectively while the capital cost of the ES must reduce by 86.96% and 49.49% in MC1 and MC2 respectively. The overall capital cost for OSR is expected to reduce in the future with advancement in fabrication technologies for large space structures and falling launch costs through reusability of launch vehicles. Therefore, for the OSR, the analysis also involved calculating the NPV under different launch costs and a selected range of procurement costs.

Future work aims to enhance this study in two ways. The first one is to consider the impact of financial mechanisms and incentives such as support policy or subsidy on the deployment and utilization of OSR for solar energy generation. The second one is to analyse the economic feasibility of OSR and solar power satellite (SPS), an alternative technological concept to harness renewable energy from space.

CRediT authorship contribution statement

Temitayo Oderinwale: Conceptualization, Methodology, Software, Validation, Formal analysis. **Colin R. McInnes:** Resources, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 883730). CRM is also supported by the Royal Academy of Engineering under the Chair in Emerging Technologies scheme.

Appendix A:. Calculation of additional energy generated by solar PV farm from the orbiting reflector.

- The OSR has a diameter of 1 km, is in the sun-synchronous orbit at an altitude of 1000 km.
- Using calculation presented in [14] a 1 km-diameter reflector located at an orbit height of 1000 km will provide illumination that can generate up to 35 MWh of energy to the area covered by solar PV farm.
- The illumination from the OSR will cover an area of approximately 10 km in diameter on the Earth. We assume that the solar PV farm considered in this paper covers a land area which is approximately 10 km in diameter so the illumination from OSR is fully utilized.
- Solar PV farm is assumed to have a panel to area coverage ratio of 50% and a conversion ratio of 20%. Therefore, the additional solar energy generated due to illumination from one reflector is 35.2*0.50*0.20 = 3.52 MWh
- To achieve the 100 MWh considered in this work at least 29 reflectors are required. A constellation of 30 reflectors is considered in this paper.
- Cost to the solar farm (C^{ref}) is only 20% of the total cost.
- Annual Cost (C^{ref}) = 0.2*5.63*7860*30 = $265,510.80.

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