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Analysis and Simulation of CSP and Hybridized Systems

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Augmenting a Concentrated Solar Power (CSP) Plant With a Solar PV Plant

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Abstract. The search for enhanced dispatchability at decreased prices has led to a surge in research on hybrid renewable energy systems. This paper explores the integration of Photovoltaic (PV) technology with Concentrating Solar Power (CSP) plants to enhance energy generation and economic feasibility, focusing on optimising the size of PV augmentation for existing CSP facilities. The study considers CSP plants with both Time-of-Day (ToD) and single tariffs, employing modelling techniques to assess the synergies between these two technologies. The cost of PV technology has significantly reduced, making it a cost-effective choice for electricity generation compared to CSP. CSP-PV augmentation promises to reduce online and offline auxiliary consumption, resulting in enhanced energy generation and a subsequent reduction in energy production costs. This study aims to explore the advantages of combining solar PV with a CSP system and determine the ideal PV size to maximise return, building upon previous studies to assess the technological and economic potential of integrating solar PV with CSP, focusing on South Africa. It utilises a rigorous analysis, combining the System Advisory Model and PVSyst modelling tool within an MS Excel framework. This economic assessment and sizing exercise aims to maximise profits while adhering to the limitations imposed by the power purchase agreement of a 100 MW CSP facility. The optimal size is 15 MWp for the ToD tariff and 16 MWp for the flat tariff. This highlights the potential for CSP-PV augmentation to improve energy dispatchability and financial viability, making it a compelling solution for existing CSP plants.

Keywords: CSP-PV Hybrid, PV Augmentation, Time-of-Day Tariff

1. Introduction

As the need for renewable energy grows worldwide, the variable nature of this technology has led to a greater demand for solutions that can supply energy during periods of low or no resources, such as at night or on cloudy days when solar power plants have no irradiance. Energy storage options are required to enhance the dispatchability of variable renewable power.

The cost of generating energy through Solar Photovoltaic (PV) plants is decreasing compared to Concentrating Solar Plants (CSP) due to reduced PV module prices. Therefore, PV is now the preferred choice for renewable energy technologies, with an average global Levelized Cost of Energy (LCOE) of 0.049 USD per kilowatt-hour [1]. However, CSP has a built-in storage capability called Thermal Energy Storage (TES), which is unavailable to PV and other technologies. CSP can store energy for up to 16 hours. In contrast, PV requires battery energy storage, which can be expensive for larger systems and is limited to a storage capacity of around 4 hours [2].

Solar intermittency has led to research into hybrid systems that utilise the benefits of both technologies, incorporating the low cost of solar PV but the significant storage capabilities of CSP to allow more energy to be dispatched at night. The hybridisation can decrease the LCOE and Levelized Cost of Storage compared to single-technology projects. Techno-economic analyses on hybrid systems have been conducted for various popular CSP locations such as Spain, South Africa, and Morocco. A study by Hassani et al. concluded that a CSP-PV hybrid plant in Morocco could lower the CSP plant's LCOE while reaching a capacity factor of 90% [3].

Hybrid systems can include PV & battery systems, PV & TES systems, or an integrated CSP, TES and PV system [4]. There have been various studies conducted on the integration of CSP and PV systems, such as the paper by JK Riffelman et al. on Hybrid CSP-PV plants with integrated thermal storage, which looks at various scenarios, such as using PV during the day and using the CSP solely to charge the TES for dispatch at night, or supplying CSP auxiliary loads with PV [5]. A study by Goel et al. develops a bespoke model to assess the annual yield of a hybrid system involving a CSP and PV retrofit system [6]. In this paper, we investigate the techno-economic potential of a hybrid approach where an existing CSP & TES plant has been augmented with solar PV in a South African context, building on the paper previously published by SJ Bode et al. on retrofitting operating CSP plants with PV to power auxiliary loads [7].

2. CSP Plants in South Africa

South Africa, especially in its Northern Cape province, has exceptional conditions for a CSP plant due to its high levels of solar irradiation (specifically the Direct Normal Irradiation – DNI). There are currently six operational CSP plants and one under construction in South Africa, with the first one being commissioned in 2015 as part of the country's Renewable Energy Independent Power Producer Procurement Program (REIPPPP) [8], [9]. The South African Department of Energy created the REIPPPP to assist it in achieving renewable energy targets. It is a competitive tender program facilitating private sector investment in grid-connected renewable energy generation. Independent Power Producers are invited to submit bids for the supply of this energy to the grid with fixed Power Purchase Agreements (PPAs). These projects cannot exceed the stipulated Maximum Export Capacity (MEC) but do not have a contractual limit on energy exported [8]. The PPA limits the sale of electricity to the grid to power from the turbine generator only. South Africa's electricity public utility, Eskom, controls and distributes electric power. All renewable power plants that form part of the REIPPPP sell electricity to Eskom, and any energy purchased from the grid is bought according to Eskom's time-of-use (ToU) tariff structure.

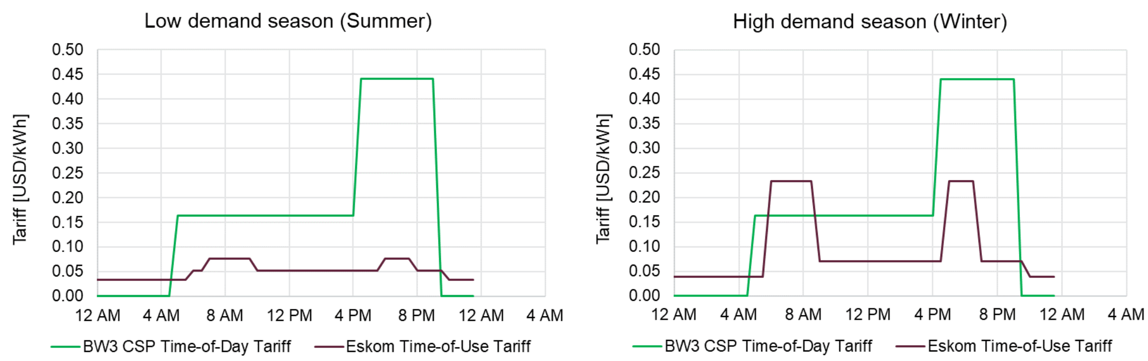

***Figure 1**. Weekday Eskom Time-of-Use and CSP Time-of-Day tariffs*

Rounds 1 and 2 CSP projects sold energy using a single flat tariff. However, in bid windows BW3 and BW3.5 of the REIPPPP, the intent was to leverage the energy storage capabilities of CSP plants by incorporating a varying tariff depending on time-of-use, also known as a time-of-day (ToD) tariff, where there is increased revenue during the evening peak periods. CSP plants built in this round have a 270% generation tariff premium for electricity exported to the grid during peak hours of the day, between 4:30 p.m. and 9:30 p.m. The average weighted ToD tariff for BW3 is $0.18 (ZAR3.42), which has been brought forward to present-day figures for this analysis [8]. The graphs in Figure 1 show the ToD tariff for a CSP plant built in bid window 3 (BW3) and Eskom's weekday ToU tariff for the low and high-demand season in 2022 [10].

3. CSP-PV Augmentation

A CSP plant's auxiliary loads, also known as parasitic loads, uses about 12% of the plant's power generation in summer and between 16% and 24% in winter [11]. The augmentation of a CSP plant with PV can increase its generating capability significantly while reducing its energy cost by replacing the CSP's auxiliary load consumption with PV-generated electricity. The reduction in auxiliary load is especially applicable in cases where the CSP has a PPA specifying the plant's MEC, whereby only generation from CSP can be exported to the grid. The PV plant can supply the CSP's online and offline consumption. Online consumption includes any loads associated with the operation of the plant during production hours, such as air pumps or air-cooled condensers, which comprise most of the auxiliary loads. Offline consumption is supplied from the grid during non-production hours and ramp-up periods. A smaller portion of the auxiliary loads supply standby loads such as heaters, circulation systems, control systems, and lighting. By supplying online consumption with PV instead of CSP, the auxiliary load can be redirected to the turbine or to thermal storage (TES) for dispatch during hours of peak load demand, which usually correspond with higher energy tariffs or night-time consumption. Supplying offline consumption can offset energy bought from the grid, increasing savings. Because PV's energy cost is lower than CSP's, augmentation could improve the financial return of the CSP project.

The principle of augmentation involves using PV input to supply auxiliary loads directly, reducing the amount of energy from the CSP turbine that is self-consumed. With augmentation, any extra solar thermal energy initially used by internal auxiliary systems can now be redirected to the turbine to compensate for low production. Alternatively, this excess energy can also be redirected to the TES. Ultimately, PV augmentation allows the system to be more flexible, enabling more energy to be exported to the grid and increasing revenue.

4. Modelling

4.1 Methodology

This study considered the impact of augmenting an existing BW3 CSP plant with PV to supply its auxiliary power. System Advisory Model (SAM, version 2022.11.21), developed and published by NREL, was used to model a theoretical existing 100MWe parabolic trough CSP plant for a location in the Northern Cape province of South Africa, with a 5-hour storage capacity. PVSyst, an industry-standard software package, was used to model the single-axis tracking PV plant augmentation at various capacities. Both simulations used the same weather dataset for Upington in the Northern Cape, taken from Climate.OneBuilding.Org [12]. The simulations output hourly data for various parameters, namely electricity generated by both PV and CSP, auxiliary load consumption, thermal storage stage of charge, field optical focus fraction, and power conversion efficiency of the CSP. The peak tariff hours have been adjusted to 5:00 p.m. – 10:00 p.m. to accommodate hourly data in this study.

The remainder of the system modelling was completed in Microsoft Excel, where the interaction between the two plants was analysed. The analysis integrated the hourly output data from both software packages in the Excel model, which could be tailored for various constraints and cases. For projects under Bid Window 3, the PPA prohibits power export from the PV plant and only permits export from the CSP plant turbine. The model handles these complexities to ensure that the PPA conditions are met whilst allowing the PV plant to offset the auxiliary loads of the CSP. It maximises the energy sent to the turbine and thermal energy storage. Figure 2 shows the process flow diagram of the CSP plant with PV augmentation. This approach allows for maximum dispatch of the CSP plant during peak ToD tariff hours. This methodology, shown in the modelling approach in Figure 3, can be generalised to study the interaction between other plants at other locations or under different constraints.

The model assessed the techno-economic potential of the augmentation by calculating cost savings due to the PV supply of offline consumption and revenue from the increased generation for the first year of the project. These figures are then estimated over the remaining years of the CSP plant's PPA, assumed to be 15 years. The assessment considers the performance degradation of both plants and inflation effects. The Net Present Value (NPV) is then calculated, which is used alongside the percentage increase in CSP turbine generation to optimise a PV plant size for augmentation.

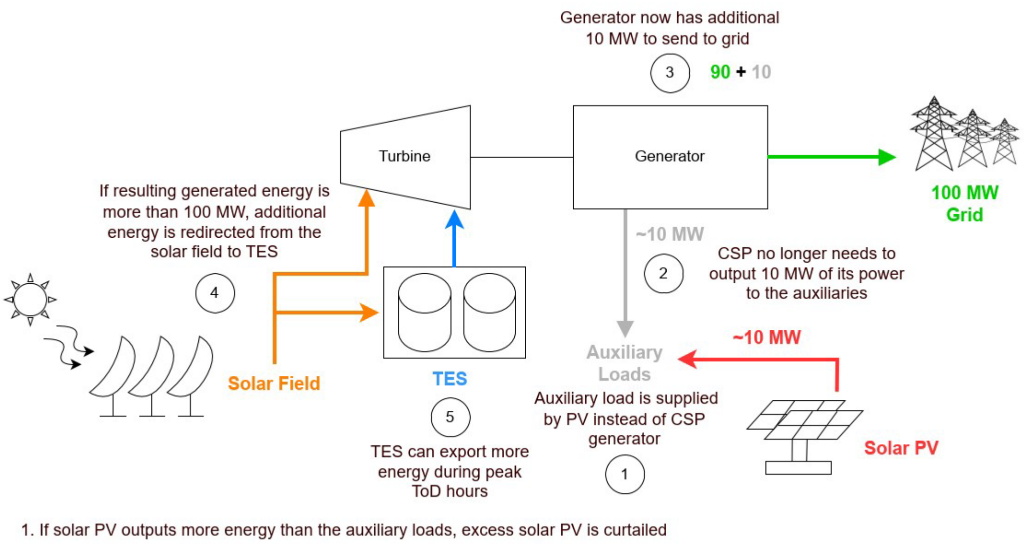

***Figure 2**. CSP-PV Augmentation system diagram with process flow*

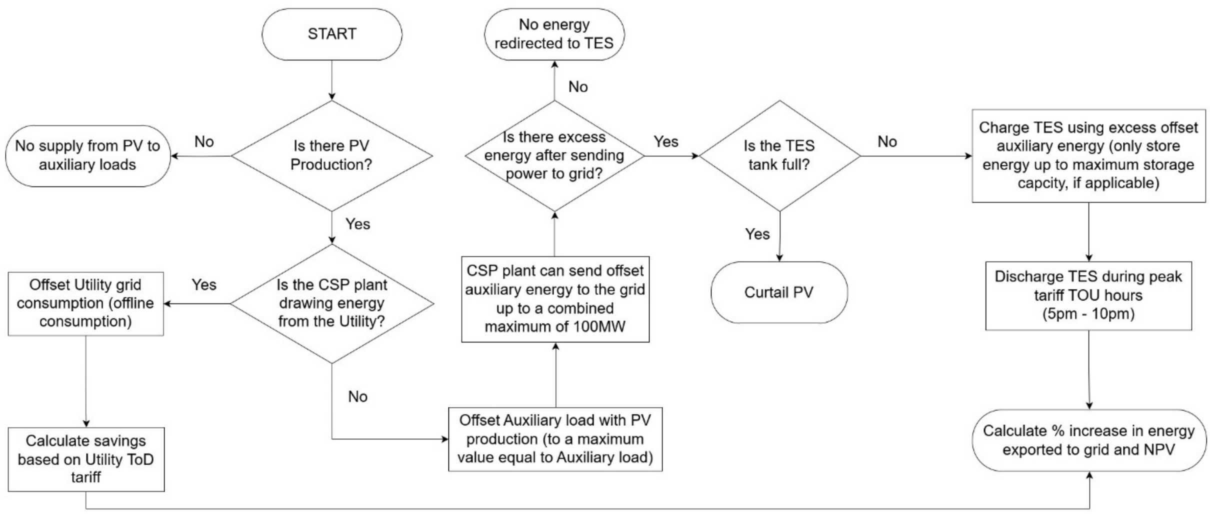

***Figure 3**. CSP-PV Augmentation modelling approach to supply auxiliary loads*

The Excel model had to consider the complexities of a CSP plant and TES system, such as electrical to thermal energy conversion factors and ensuring that the storage does not exceed its maximum capacity. It is assumed that the energy from PV gets converted to thermal energy with 100% efficiency, as all losses have been accounted for until the PV energy injection point. Additionally, any energy from the PV plant above the CSP auxiliary load is curtailed, as no energy can be exported from the PV plant to the grid. Charging of TES can only result from excess CSP generation to ensure compliance with the PPA. Three cases were investigated in this study:

1. Base case (ToD): using the standard ToD tariff structures for a BW3 project, brought forward to present-day figures
2. Sensitivity analysis: varying the standard ToD tariff to analyse the effect on the PV size optimisation result
3. Flat tariff case: using a flat tariff, which equals the ToD tariff averaged over 24 hours.

4.2 Model assumptions

Table 1 shows the financial assumptions used to calculate the cost of building, operating, and maintaining the PV plant. The cost of constructing and maintaining the theoretical CSP plant is not applicable as it already exists independent of the PV augmentation; however, the tariffs at which the energy is sold are included in the table. The cost savings due to the supply of offline auxiliary consumption are calculated using the 2022 “Megaflex” ToU tariffs charged by Eskom, shown in Table 2 and Figure 1.

Table 1. *Economic assumptions used in financial models to calculate savings and NPV*

Parameter	Value	Unit	Reference
PV CAPEX	876	USD/kWp	[1]
OPEX	7.70	USD/kWp	[1]
USD to ZAR conversion	18	ZAR/USD	-
Discount Rate*	11.5%	%	-
Lifetime	15	Years	-
Inflation*	6%	%	[13]
Annual Utility ToD Tariff Increase*	18%	%	[14]
Peak PPA Tariff	0.44 (7.92585)	USD/kWh (ZAR/kWh)	[8]
Standard PPA Tariff	0.163 (2.9355)	USD/kWh (ZAR/kWh)	[8]
Off-peak PPA Tariff	0 (0)	USD/kWh (ZAR/kWh)	[8]
Flat PPA Tariff	0.173 (3.11897)	USD/kWh (ZAR/kWh)	[8]
Annual PPA Tariff Increase*	6%	%	[13]

* All nominal rates

Table 2. *Eskom 2022 Megaflex tariffs used to calculate offline-consumption savings [10]*

TOU	High Season (Jun–Aug) USD/kWh (ZAR/kWh)	Low Season (Sept–May) USD/kWh (ZAR/kWh)
Peak	0.23291 (4.19)	0.07597 (1.37)
Standard	0.07054 (1.27)	0.05228 (0.94)
Off-peak	0.03833 (0.69)	0.03318 (0.60)

The PV plant was modelled based on a 1 MWp installed capacity plant with single-axis tracking, and the energy output was scaled from 2 to 30 MW to analyse the effect that various sizes have on the auxiliary supply. The CSP plant was modelled in SAM.

Table 3. *SAM design parameters for a 100 MWe parabolic trough CSP*

Parameter	Value	Unit	Parameter	Value	Unit
Solar Multiple	2		Cycle thermal efficiency	0.356	
Field Aperture [15]	869,000	m^2	Cycle thermal power	314.61	MWt
Total Aperture reflective area	871,168	m^2	Grid interconnection limit	100,000	kWac
Design turbine gross output	112	MWe	Hours of storage at the design point	5	hours
Estimated net output	100.8	MWe	TES thermal capacity	1,573.03	MWt-hr

The values in Table 3 were chosen to simulate a CSP parabolic trough plant with a storage duration of 5 hours to match the peak tariff dispatch period. The field aperture, turbine output, and grid interconnection were chosen and set for a typical 100MWe plant. Standard default values were used for the cycle thermal efficiency, cycle power, and the TES parameters.

5. Results

5.1 Simulation Outputs

Table 4 shows the annual output parameters of the CSP plant from SAM and the PV plant from PVsyst.

Table 4. *Outputs for 100MWe parabolic trough CSP plant and 1MWp single-axis tracking PV plant*

Parameter	Value
CSP Gross Annual Energy Output	371,812 MWh
CSP Annual Online Auxiliary Consumption	36,520 MWh
CSP Annual Offline Auxiliary Consumption	16,322 MWh
CSP Net Annual Energy Output	318,970 MWh
1MWp PV plant Net Annual Energy Output	2,591 MWh

The auxiliary load reaches a maximum of 10.34 MW throughout the year, with the offline night-time consumption being 3.32 MW. The total annual auxiliary consumption is 14% of the annual generation of the CSP plant.

5.2 Optimisation Results

The size of the PV plant augmentation was optimised based on the cost of generating the solar PV and the increased revenue returns experienced by the CSP plant, which is dependent on the ToD tariff in the base case. The CSP plant's increased energy, revenue, and offline consumption savings were calculated for each PV size ranging from 2 to 30 MW, which was then used to calculate the NPV.

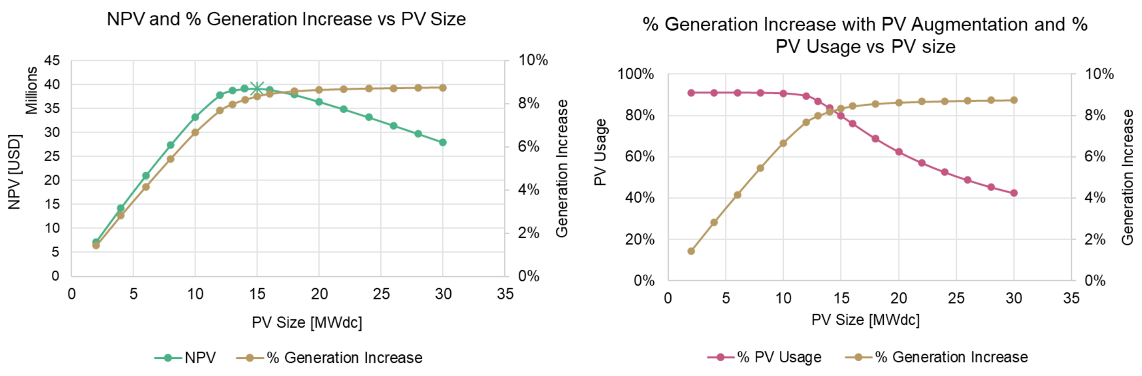

***Figure 4**. Graphs showing NPV, % Generation Increase, and PV Usage for various PV sizes*

The resulting optimal size for this case is 15 MWp, which translates to around 12.5 MWac if a DC/AC ratio of 1.2 is assumed. The 15 MWp size maximises revenue, or NPV, with an internal rate of return of 51.3%. The CSP plant increased its generation by 8.3%, which translates to an increase in revenue of USD 7.87 million in year one of the augmentation project. The generation increase of the CSP is maximised at around 8.8% for PV sizes above 20 MWp, which is the upper limit for auxiliary load supply through PV. However, the percentage of PV usage for sizes above 12 MWp starts to decrease significantly to below 80% as any energy generated above the auxiliary load is curtailed.

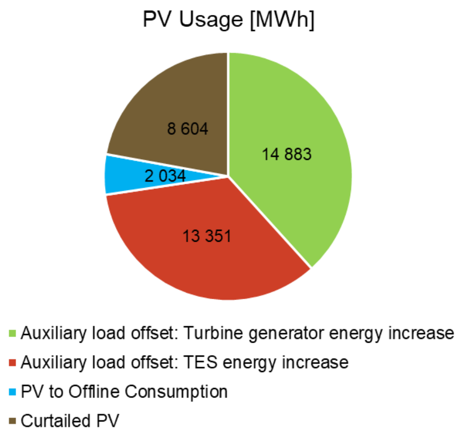

***Figure 5**. Usage for 15 MWp PV plant to offset auxiliaries and supply offline consumption*

With a 15 MWp PV augmentation system, 57.28% of the auxiliary load gets supplied by solar PV, with the offset energy being split between the turbine generator, TES, and offline energy consumption, as seen in Figure 5.

After optimising the base case, a sensitivity analysis explored how the tariff impacts the resulting PV system size. The standard tariff, set initially at ZAR2.9355, was increased and decreased by ZAR1 and ZAR0.5, and the NPV was calculated for various PV sizes. Based on the NPV curves in Figure 6, raising the standard tariff by ZAR1 led to an optimal PV size of 16 MWp. Alternatively, reducing the tariff by ZAR0.5 and ZAR1 resulted in PV sizes of 12 MWp and 13 MWp, respectively. Whilst the results show that the optimal PV size to maximise project returns does depend on the tariff, it is relatively insensitive.

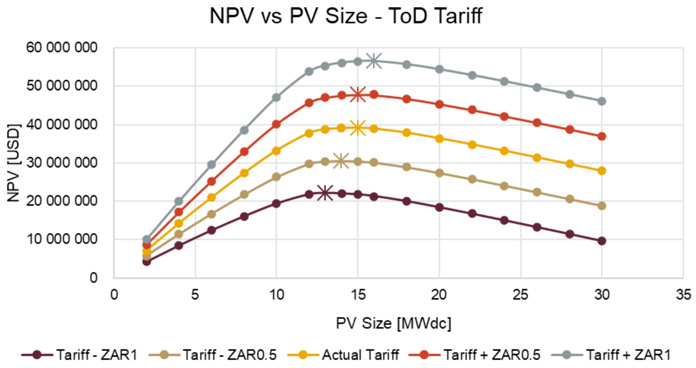

***Figure 6**. PV optimisation with varying ToD tariff*

The optimal PV size and return on the project are also dependent on the tariff structure. A flat tariff structure has an optimal PV size of 16 MWp or 13.33 MWac The graphs in Figure 6 illustrate how the optimal PV size changes by 1 MWp with a ZAR1 difference in the flat tariff.

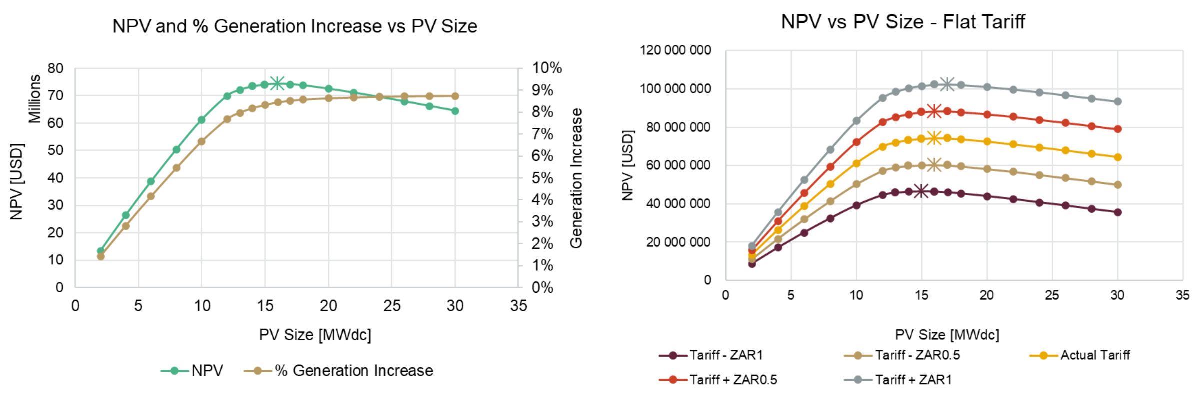

***Figure 7**. PV optimisation with varying Flat Tariff*

6. Conclusion

Integrating PV technology with CSP plants presents an innovative solution to address the growing global demand for renewable energy while enhancing dispatchability and reducing costs. Solar PV technology has become increasingly cost-effective, offering a lower LCOE than CSP. This research has focused on optimising the PV augmentation size for existing CSP plants operating under Time-of-Day (ToD) and Flat tariffs. By employing advanced modelling techniques, this study has shed light on the potential benefits of hybridising CSP and PV systems and identified the optimal PV plant size that maximises economic returns for both tariff cases.

The augmentation of CSP plants with PV significantly increases energy generation and financial returns. By supplying over half of online and offline auxiliary consumption with PV-generated electricity, CSP plants can optimise dispatch during peak load periods, increasing revenue. Additionally, the cost savings from reduced auxiliary consumption further improve the financial viability of CSP projects. The results have revealed an optimal PV plant size of 15 MWp for a 100MWe CSP plant using a ToD tariff, which maximises revenue return and increases CSP plant generation by 8.3%. The case where a flat tariff (no ToD) is considered results in an optimal PV size of 16 MWp and increases plant generation by 8.4%. These results translate to significant financial gains, demonstrating the practical benefits of CSP-PV augmentation. This research underscores the potential of augmenting CSP plants with solar PV, providing a use-case for their integration in South Africa's existing CSP plants and potentially in other regions with similar conditions.

Data availability statement

No data from this paper has been published, and all data used in the study is publicly available.

Author contributions

Investigation and writing by Ayesha Jacobs. Writing, review, and editing by Craig McGregor.

Competing interests

The authors declare that they have no competing interests.

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