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Energy and Ancillary Services Value of CSP with Thermal Energy Storage in the Australian National Electricity Market

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***Abstract*— The dispatchability of concentrated solar power (CSP) with thermal energy storage (TES) offers the ability to provide ancillary services (AS) such as spinning reserve and frequency regulation. In this paper, the energy and ancillary services value of CSP-TES in the Australian national electricity market (NEM) is estimated using production cost simulation (PCS) of the NEM system by the PLEXOS software. This study also compares the energy benefits of a CSP plant with TES estimated from the PCS of the NEM using a generator short run marginal cost (SRMC) based stack model and that obtained from the PCS using a generator bids based stack model. The latter model is more realistic as it uses actual generator bids data in the market and our results show that the energy benefits of a CSP with TES in the NEM estimated from the latter model is significantly higher than that estimated from the former model.**

***Index Terms*--Energy storage, Power system economics, Solar power generation.**

I. Introduction

With growing interest in renewable energy coupled with falling cost of electricity generation from renewable based power generation technologies such as solar PV and wind, it is expected that more and more variable renewable generation will be added to the Australian grid. However, a high dispatched fraction of variable renewable generation challenges the power system considerably due to the greater variability and uncertainty associated with output from these plants. This fluctuation in power output results in the need for greater flexibility on the grid, from other controllable generation. CSP with TES is a promising renewable energy generation option that can provide additional flexibility to the grid. However, there are no studies on valuing operational benefits of CSP with TES providing ancillary services in the NEM. Estimating the operational benefits that CSP with TES can provide to the NEM is vital to fairly valuing this technology compared to other variable renewable energy generation technologies.

A number of studies estimate the operational benefits of CSP with TES in the US grids [1-11] using different methods. Details of methods of estimating different benefits that a CSP-TES can provide to the grid including the value of energy and ancillary services can be found in [1]. The operational benefits of CSP-TES in the US grids have been estimated using the PLEXOS PCS model based on generators' SRMC in [2-4]. Some other studies have developed mixed-integer programming models to estimate the operational benefit and capacity value of CSP-TES using price taker approach (using historical prices)[5],[6]. Moreover, the value of CSP-TES in providing ancillary services and serving as a source of firm capacity is also investigated in the US grid [1], [7-9]. However, to our knowledge, our previous study [12] is the only study available in estimating operational benefits of CSP with TES in the Australian grid which also focused on estimating operational benefits only in terms of energy value, and neglected the ancillary service benefits. Since the CSP with TES has the potential to provide various ancillary services required in the NEM, our previous study may have underestimated the true operational benefits of CSP with TES in the NEM. Therefore, in this study we estimate operational benefits that a CSP-TES can provide to the NEM in terms of both energy and ancillary services. Furthermore, existing studies on estimating operational benefits of CSP with TES using the PCS of the system are based on the short run marginal cost (SRMC) of the generators in the system. However, in the NEM and most of other electricity markets, generators bid their plants in at their cost plus a mark up (as appropriate to cover both operation and capital cost of the plants) which is significantly higher than the SRMC of the plants. Because of this reason the operational benefits estimated by SRMC based PCS could significantly underestimate its value. As such, it is more appropriate to estimate the operational benefits of CSP with TES by carrying out PCS of the system using generator bids. In this context, this study also estimates the energy value of a CSP plant with TES in the NEM by PCS of the NEM system using a generator bid based stack model and compares the results with that obtained from PCS of the NEM system using a generator cost (SRMC) based stack model.

This paper is organized as follows: Section II presents the methodology used in this paper to estimate the operational value of the CSP-TES in terms of energy and ancillary services. Section III includes data and assumptions of the work. Section IV provides results and discussion followed by the conclusions in Section V.

II. Methodology

The energy value of a CSP-TES plant reflects the avoided variable fuel and operational cost of the rest of the power plants in the system with the inclusion of CSP-TES plant. Therefore, ideally, an estimation of energy value of CSP-TES in an electricity market should be based on the difference in the cost of the production cost simulation of the generation fleet in the system both with and without the CSP-TES plant. We use a PCS model for this purpose. The PCS model co-optimizes the need for energy and operation reserves subject to the various constraints and finds the least-cost mix of generators in each time interval. The flow chart of the methodology is presented in Fig.1. As the figure shows, the methodology involves two main steps, that is, calculation of total production cost of the system for (a) without the CSP-TES plant (hereafter "base case") and (b) with the CSP-TES plant (hereafter "CSP-TES case"). The difference in total production cost of the base case and CSP-TES case is the energy value or operational benefits that the CSP-TES plant provides to the system. In the first step, we determine the total production cost of the system for the base case (TC1) by carrying out PCS of the system as it is available in its current state by considering cost, technical, and energy inflow data of all generators in the system. In the second step, in order to determine the total production cost of the system for the CSP-TES case (TC2), we carry out the PCS of the system by adding the CSP-TES plant in the system assuming that the CSP-TES plant supplies its energy to the system free of charge. In other words, as shown in Fig.1, we add the CSP-TES plant in the system by considering only CSP-TES plant's technical and energy inflow data assuming that the plant provides energy to the system free of charge. As shown in Fig.1, the total energy value or operational benefits of the CSP-TES in the NEM would be the savings in total production cost (ΔTC) with the inclusion of CSP-TES plant in the power system. That is:

$$\Delta TC = TC1 - TC2$$

The per-unit operational benefits of the CSP-TES can be calculated by dividing the total operational benefits of plant by its total energy generation during the planning period.

In the present study, we estimate the operational benefits of a CSP plant for four different scenarios:

(i) The CSP power plant has no TES and provides only energy to the system (here after "CSP energy only" scenario). In this scenario, the energy value of the CSP plant is estimated following the methodology given in Fig.1, by the PCS of the NEM system without CSP plant (hereafter "base case" scenario) and the NEM system with CSP but without TES and no reserve provisions.

(ii) The CSP power plant is equipped with a TES and provides only energy to the system (hereafter "CSP-TES energy only" scenario). In this scenario energy value is calculated by the PCS of the base case and the NEM system with CSP-TES with no reserve provisions.

(iii) The CSP power plant is equipped with TES and provides both energy and ancillary services to the system (hereafter "CSP-TES energy and AS" scenario). In this scenario, the operating value (energy and ancillary services value) of the CSP plant with TES is estimated by the PCS of the base case and the NEM system with CSP plant with TES providing reserves.

(iv) In three scenarios discussed above, the PCS of each case was carried out using a generator cost based stack model. In this scenario, we estimate the energy value of a CSP plant with TES using generator bids data (hereafter "generator bids data" scenario). This scenario is same as the "CSP-TES only energy" scenario except the PCS of the system is carried out using a generator bids based stack model instead of a generator cost based stack model. In this scenario, it is assumed that the CSP-TES plant bids into the market at zero price.

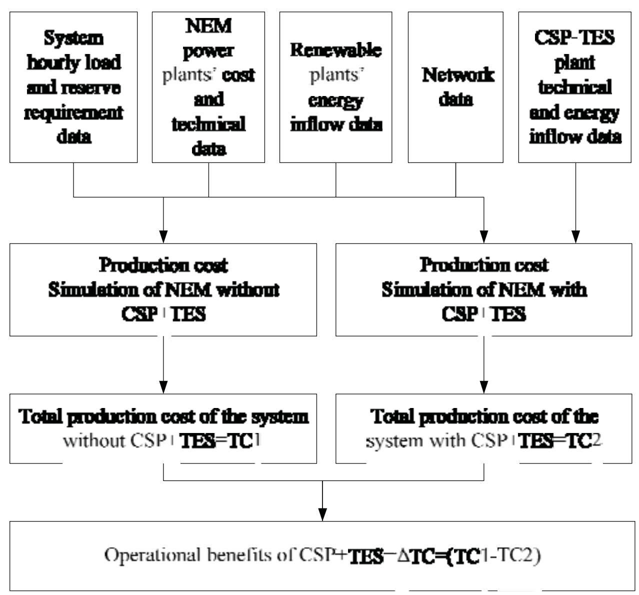

Figure 1. Methodology of estimating operational benefit of CSP-TES in NEM

The production cost simulation model PLEXOS [13] is used in this study to simulate the NEM system. The PLEXOS is a detailed production cost simulation model that can simulate the production cost of large system on 1 hour or sub-hourly simulation intervals by taking into account unit by unit commitments and operational constraints of generators and transmission lines. The main reason we selected PLEXOS for this study over other available models is that the Australian energy market operator (AEMO) uses the PLEXOS for development of their national transmission network development plan (NTNDP) and has recently released a PLEXOS NEM data set and hence we could use this publicly available data for the study.

We implement the CSP with TES plant as a reservoir type hydro power plant in the PLEXOS as described in [4]. To summarize, CSP-TES plant consists of solar collector and receiver, thermal storage, and power block. The solar energy is received by solar receiver and collector to produce thermal energy to heat the fluid through the tubes [14]. The correlated weather and sun radiation data of the location of the plant to the year of simulation are required to model the CSP generated energy. The SAM (system advisor model) [15] simulation tool is used to simulate the CSP generated electricity as the input to the PLEXOS. The ramp rates data and sizing parameters of CSP-TES including storage capacity, SM, and power block size are used to model the CSP-TES plant in the PLEXOS.

III. Data and Assumptions

In this study we estimate the energy value of a CSP-TES plant in the NEM system. The Australian NEM is a wholesale electricity market across the five interconnected states including Queensland, New South Wales, Victoria, South Australia and Tasmania excluding Western Australia and Northern Territory. The NEM system's total existing installed capacity is 48,116 MW which mainly consists of 51% coal, 22% gas, 17% hydro, and 8% wind power plants[16]. The NEM system works as a "pool", or spot market, where power supply and demand is matched instantaneously in real time through a centrally coordinated dispatch process [17].

The NEM system data used in this work is based on the AEMO's PLEXOS data set of the 2015 national transmission network development planning (NTNDP) model. The 2015 NTNDP PLEXOS model of the NEM includes the hourly regional demand traces of all states and data of all registered generators located on a common regional node (including fuel costs, O&M costs, heat rates, and minimum stable levels). In this model the inter-regional transmission lines are modelled only, ignoring intra-regional congestion [18]. The NTNDP PLEXOS model was provided for long term (LT plan) network capacity expansion planning. In order to simulate the short term operation of the system for one year in hourly basis, short term schedule (ST) supported by medium term (MT) schedule is added to the 2015 NTNDP model.

The regulation up and down and spinning up and down services are considered as operational reserve in this work. Ten percent load risk is set for the spinning up and down reserve. For regulation, we used historical data of lower regulation and raise regulation available in the AEMO website [19]. In order to estimate the energy value of CSP-TES using the generators bid based stack model, the required generator bids data (i.e., price and quantity offers of each generator) is extracted from historical generator bids data of the AEMO.

In this work, the energy benefits of a CSP-TES plant of 850 MW located in Longreach Queensland in the NEM system is estimated. The TES capacity is considered as 850 MW with eight hours of storage capacity. The solar multiple (SM) of two is considered for this study. The CSP-TES plant ramp rates are set to 10% of rated capacity per minute as in [8] and minimum generation point is set at 20% of the rated capacity of the power block.

IV. Results and Discussion

For determining the operational value of the CSP plant with TES located in Longreach, PCS exercises were carried out for the NEM system for the different scenarios described in the methodology section. The results are presented in two parts A (generators' SRMC based model) and B (generators' bid based model). The planning horizon for part A is one year starting from July first 2015 and for part B is one week starting June first 2016. PCS were carried out in the present study using the PLEXOS software and Xpress-MP solver.

A. *Energy value of CSP-TES using generator SRMC*

As can be seen from the Table I, the PCM simulation exercise of the NEM shows that the total annual generation cost of the NEM system is $3,192,968,963 compared to $3,130,482,859 when the CSP plant is added to the system. Therefore, the total avoided generation cost of the CSP plant is $62,486,104 and the corresponding per unit energy value of CSP plant is $36.4/MWh. Similarly, when the CSP plant with TES is included in the system, the per unit energy value of the plant would increase to $38.1/MWh, while if CSP plant with TES provides both energy and ancillary services to the NEM system, the combined per unit energy and ancillary services value of the plant would be $46.0/MWh.

TABLE I. Energy and operation reserve value of CSP-TES

Scenario	Total generation cost ($)	Avoided generation cost ($)	Value ($/MWh)
Base case	3,192,968,963	-	-
CSP energy only	3,130,482,859	62,486,104	36.4
CSP-TES energy only	3,126,589,582	66,379,381	38.1
CSP-TES energy and ancillary services	3,112,599,574	80,369,389	46.0

As the operational value of the CSP plant reflects the avoided variable fuel and operational cost of the rest of the power plants in the system with the inclusion of CSP plant, the reason for increasing operational value of CSP with the inclusion of TES can be explained from the generation mix of the displaced energy. Fig.2 shows the generation mix of displaced energy in the NEM system for CSP, CSP-TES energy only and CSP-TES energy and ancillary services scenarios. As can be seen from the Fig.2, CSP plant with no TES mainly displaces cheaper coal generation in the system with negligible amount of expensive gas, while in the CSP-TES energy scenario, the part of coal generation displacement is substituted by gas. In the CSP-TES energy and AS scenario, gas generation displacement is significantly higher than that of other two scenarios. Due to this reason CSP-TES plant providing both energy and AS to the system gives significantly higher benefits compared to other scenarios. It is interesting to note that the inclusion of CSP-TES increased hydro generation in all three scenarios. The reason for increasing hydro generation is that the low cost solar energy is used for pumping water back in hydro power plants, such as the Wivenhoe pumped hydro plant in Queensland.

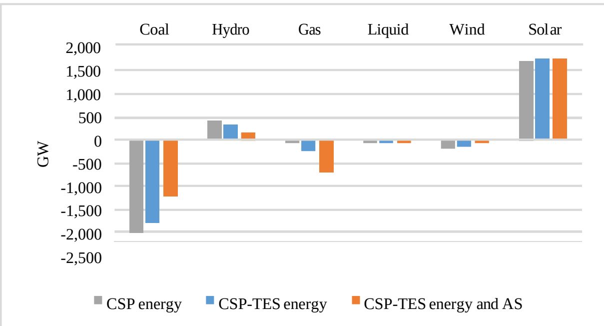

Figure 2. Annual generation replacement in the presence of CSP-TES

Fig. 3 shows how CSP with TES would displace more gas compared to the CSP only case using generation profile of the plant for three days. As can be seen from the Fig.3, When CSP plant is equipped with TES it will shift its generation to high demand hours replacing expensive gas from the system.

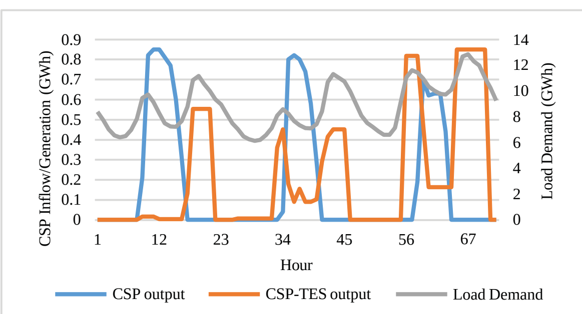

Figure 3. CSP simulated operation for three days starting July 1 2015

B. *Energy value of CSP-TES using generator bids*

In the previous section we estimated operational vlaue of a CSP plant with TES using the PCS of the sytem and generator cost data. As described in the introduciton section, the NEM is a bid-based energy market and hence it would be more appropraite to estimate the energy benefits of CSP with TES using a PCS of the sytem based on a generator bids based stack model. In this part of the work the energy value of the CSP-TES in the NEM for a period of one week is estimated using gnerator bids data and results are compared with that obtained from the PCS of the system based on generator cost data to see how the real market data change the operational benefit of the CSP-TES. The bids data of the NEM are extracted form AEMO website for one week starting June first 2016. Table II shows the energy value of CSP-TES estimated using genertor cost data and bids data. As can be seen from the Table II, the energy value of the CSP-TES estimated using the generator bids data is twice that obtained using the generator cost data. This shows that estiamtes of energy vlaue of CSP plants with TES using PCS of the sytem using the generator cost data could significantly underestimate its value in the real market.

TABLE II. Operational value (energy only) of various sizes of CSP-TES

Scenario	Case	Total generation cost ($)	Avoided generation cost ($)	Energy value ($/MWh)
SRMC	Base case	60,087,185	-	-
	CSP-TES	59,316,452	770,733	37
Bid data	Base case	110,102,100	-	-
	CSP-TES	108,582,187	1,519,913	74

Fig.4 shows the generation mix of the NEM for the one week period obtained from PCS of the sytem with and without the CSP-TES using grerator cost and bids data. As the figure shows, in the generator cost based scenario, coal dominates the generation mix with negligibale amount of gas generation while in the grerator bids based scenario, although the coal takes largest share in the gneration mix, gas generation also has a significant contribution in the generation mix. Furthermore, liquid fuel generation has also increased in the grerator bids based scenario. Since the gas and liquid fuel generation account for significant share in the generation mix in the real market, inclusion of CSP-TES plant in the system would replace more exapensive gas and liquid fuel genration in the sytem and hence CSP-TES plant in the real market would give higher operational benefits of $74/MWh compared to that estimated using the SRMC of gnerators (which is $34/MWh) .

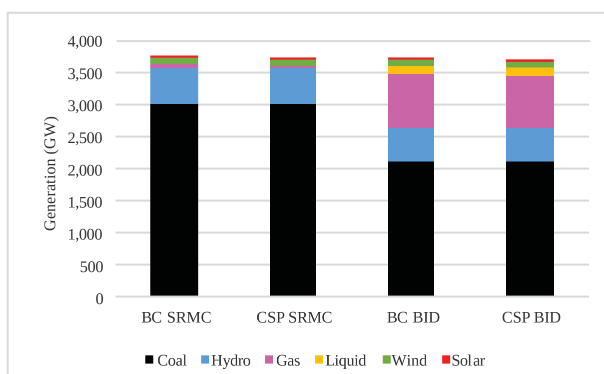

Figure 4. NEM generation mix for one week period starting June first 2016 using SRMC and bid data

Fig.5 shows the generation replacement for generator cost based and bids based scenarios. Our results show that in the generator bids based csae, coal and hydro generation diplacement due to the CSP-TES plant has reduced by amount of 12,776 MW and 5,202 MW respectively compared to generator cost (SRMC) based case, while the gas dispalment has increased by 282 MW. It is interesting to note here that in the generator cost based scenario, the inclusion of CSP-TES plant in the system would increase the hydro generation in the system, while in bids based scenario hydro generation has reduced with the inclusion of the CSP-TES plant. This is due to the fact that in bids based case hydro plant offer prices are set to well above its SRMC.

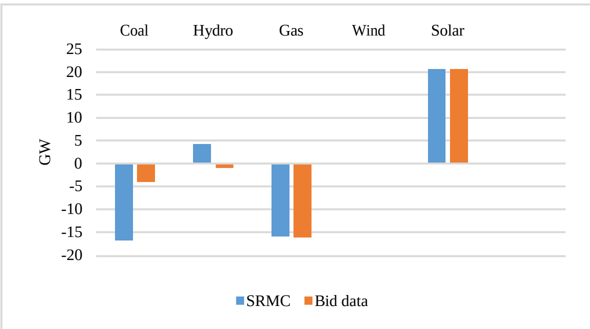

Figure 5. NEM generation replacement for one week period starting June first 2016 using SRMC and bid data

V. Conclusion

In this study we estimated the operational benefits that a CSP with TES can provide to the NEM in terms of both energy and ancillary services. The results showed that the CSP-TES value increases when providing operational reserve for the network. The reason is that the high cost generators required for the provision of operational reserve can be replaced by CSP-TES generation which reduces the total generation cost. Further, this study estimated the energy value of a CSP plant with TES in the NEM by simulating the NEM system using a generator bids based stack model and compared the results with those obtained from simulating the NEM system using generator cost (SRMC) based stack model. The results of a one-week simulation show that in real electricity market, the energy value of CSP-TES is significantly higher than that estimated using the PCS of the system using a generator SRMC based stack model, the approach used in the existing studies. Based on the promising results of this study, the authors intend to carry out in a future study on estimation of operational benefit of CSP-TES including operation reserves provision for longer period (one year) using a bid based stack model.

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