STRATEGIES TO REDUCE GRID INTEGRATION COSTS OF SOLAR ELECTRIC PLANTS IN THE AUSTRALIAN NATIONAL ELECTRICITY MARKET

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Abstract

Many sites of high solar insolation in Australia are located far from major load centres, and it is likely that the siting of future solar power plants in Australia will necessitate extensive transmission infrastructure. The unique generation profile of solar electric plants limits the utilisation of dedicated transmission lines rated to the peak output of a plant. If a plant is oversized for available transmission, the revenue implications of curtailing peak output may not be significant. With Transmission Network Service Providers (TNSPs) and generators functioning as separate entities in the National Electricity Market (NEM), the pathway for efficient investment in transmission is not straightforward. TNSPs may be reluctant to extend the network at the scale required for long-term development of generation in a region. Moreover, solar plants can be constructed more quickly than transmission infrastructure, giving rise to the possibility of early plants being operational ahead of transmission capacity.

This paper explores the impact of transmission constraint on the financial performance of three types of large-scale solar power plant operating in Cobar, New South Wales in 2009: a fixed photovoltaic (PV) plant, a dual-axis tracking PV plant, and a concentrating solar thermal (CST) plant with varying levels of thermal storage. For plants with lower capacity factors (eg. fixed PV), significant constraints on transmission capacity has been found to have a minimal effect on total generation and revenue. The impact of transmission constraint is more profound for higher capacity factor plants of the tracking PV and CST types. The implication of this work is that it can be an effective strategy to oversize solar electric plants relative to available transmission and to construct plants incrementally as a means of mitigating the risks associated with transmission investment in the NEM.

Keywords: solar power, energy storage, transmission constraint, investment

1 Introduction

Some of the best sites in Australia for high solar insolation are located inland and far from the load centres along the eastern seaboard. It is likely that the siting of future solar power plants in Australia will require extensive transmission infrastructure to bring their power to the Australian National Electricity Market (NEM). Limited transmission in high insolation areas has two implications for future plants: the cost of bringing transmission capacity to the plant, and the merit of utilising what limited transmission capacity is available.

Depending on their design, solar electric plants routinely approach rated output each day around solar noon, subject to clear sky conditions. Plants may generate power at the rated output for a small number of hours (see Figure 1), utilising available transmission poorly. A key question, given the low utilisation, is what are the implications of operating solar power plants with reduced transmission capacity? The main concern for plant operators will be the financial losses associated with not being able to get all available power to market.

This paper explores the potential impact of transmission constraint on the financial performance of large-scale solar power plants in the NEM. Three cases will be considered: a utility-scale fixed

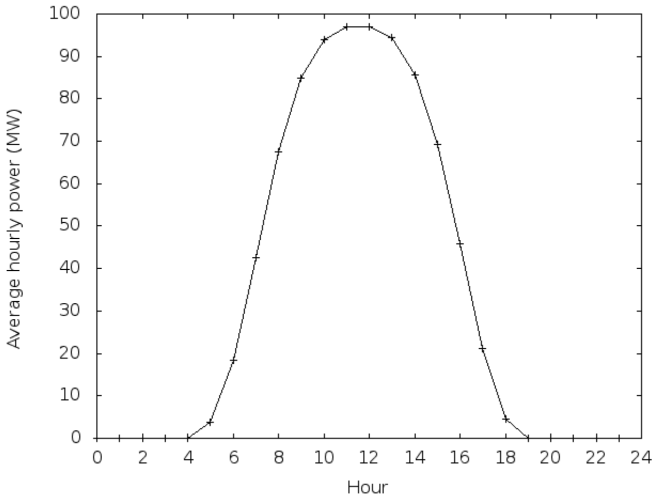

Figure 1: Typical power curve for a fixed 100 MW PV system in clear sky conditions

photovoltaic (PV) plant, a dual-axis tracking PV plant, and a concentrating solar thermal (CST) plant with varying amounts of thermal energy storage (TES). We first briefly outline the structure and operation of the NEM, which is necessary to appreciate the issues facing generators and Transmission Network Service Providers (TNSPs) in the context of renewable electricity expansion. The paper then outlines the methodology and results of modelling transmission constraint on the three types of solar electric plants operating in Cobar, New South Wales, Australia, a high insolation inland location, using historical weather data and NEM spot prices from 2009. By quantifying the constraint impacts, we conclude with recommendations for how future plants could be integrated into the transmission network with insufficient transmission capacity.

2 NEM background

The NEM is the largest interconnected power system in the world, spanning 5,000 km from Far North Queensland to South Australia [1]. The NEM is comprised of five regions, one region for each of New South Wales, Queensland, South Australia, Victoria and Tasmania. The regions have been progressively interconnected to widen the NEM balancing area and improve market efficiency. However, the regions are still somewhat autonomous and have relatively weak interconnection [2].

The NEM uses a *shallow connection cost model* governing how costs are assigned when a generator requests connection to the transmission network. In this model, generators pay for assets required to connect to the most suitable transmission connection point, and the cost of connection is borne by the generator. Hence, it is important to minimise these costs, which are not necessarily faced by an incumbent generator.

The National Electricity Rules specify a regulatory test that describes the circumstances under which a transmission network must be reinforced by the TNSPs. If the regulatory test does not support reinforcement, a generator may still self-fund an increase in transmission capacity. However, an open access policy permits other generators to connect to the network and benefit from any reinforcement. The open access policy introduces a barrier to generators funding their own network reinforcement.

Generators, TNSPs, Distribution Network Service Providers (DNSPs) and retailers are market participants in the NEM and operate under varying degrees of government regulation. With TNSPs and generators functioning as separate entities, the pathway for efficient investment in transmission is not straightforward. TNSPs may be reluctant to extend the network at the scale required for long-term development of generation in a region. Constructing a transmission network extension at an appropriate scale may be more economically efficient in the long run, but introduces a risk to the TNSP that the forecast generation does not materialise. Similarly, generation projects are unlikely to proceed without guaranteed available transmission. The problem is exacerbated by the large disparity in the time taken to construct smaller scale renewable energy plants (2–3 years) and new transmission infrastructure (up to 10 years) [3].

A recent change to the National Electricity Rules aims to overcome the scenario described above by improving the public availability of information to market participants [4]. By allowing participants to better coordinate network extensions, the risk of network duplication or stranded assets can be minimised. This minimal approach to regulation provides no guarantee that the transmission network will be extended to connect a distant generator.

Experience in other more densely populated countries suggests that the expansion of transmission networks can be controversial, often requiring right-of-way through areas of conservation or heritage value, or raising community opposition to visual impact. Yeleti and Fu [5] report that transmission line construction can be slow due to rights to land and planning approval. Georgilakis [6] identifies inadequate transmission planning and unclear planning objectives as a significant barrier to the wider deployment of wind energy in the United States.

3 Transmission line sizing

Conventional power plants typically connect to the grid via a transmission line sized to the rated capacity of the plant. High capacity factor units, such as coal-fired plants, run at rated output much of the time and therefore require transmission capacity to transfer all of this power. Peaking plants with lower capacity factor generate power during periods of high demand and higher prices and, similarly, require transmission capacity equal to the rated output of the plant to get power to market. Some types of renewable electricity plants, notably wind and solar, have a less predictable output profile and it is not necessarily economic to size the transmission line to the rated capacity of the plant if the duration of rated output is short. For these periods the plant output can be curtailed [7, 8].

Renewable electricity has a very low marginal cost of generation and it is legitimate to consider situations where excess energy is discarded. The literature suggests that this is not a new idea. Cavallo [8] first presents the idea of oversizing wind farms with respect to available transmission to increase the capacity factor. More recently, Wiser and Bolinger [9] reports that 17 per cent of potential wind energy in the Electric Reliability Council of Texas (ERCOT) grid was spilled in 2009.

Boerema and MacGill [7] found that, in some circumstances, it can be economically advantageous to oversize wind farms with respect to available transmission capacity in the South Australian region of the NEM. The financial impact is minimised because high wind periods, when constrained transmission curtails wind farm output, were correlated with low spot prices in South Australia. Pattanariyankool and Lave [10] develop a method to find the optimal transmission line capacity for a distant wind farm as a fraction of the wind farm rating. Like Boerema and MacGill [7], they find that the optimal transmission capacity is less than the rated output. Given 79 per cent available transmission capacity, 97 per cent of total energy can be delivered.

Considerable prior work has examined the value of energy storage for CST plants. The primary role of storage in CST plants to date has been to reduce fluctuations in power output and improve the financial performance of the plant through energy arbitrage. Denholm and Sioshansi [11] examines the benefits of siting energy storage with wind farms to increase the capacity factor and transmission line utilisation, versus siting the storage elsewhere in the grid where it may potentially have greater value. Compressed air energy storage (CAES) is promoted as a means to deploy wind farms in areas of constrained transmission [8]. Wittmann et al. [12, 13] has considered the role of energy storage in operating CST plants in Spain, where plant operators are fined for deviating from day-ahead forecasts. Storage can be used to minimise the costs associated with such deviations. Other work on CST deployment has considered a variety of optimisation techniques to specify the size of the power block, solar field and thermal energy storage subsystems in CST plants [14, 15].

4 Transmission constraint modelling

In this section, we outline the methodology and results of a study into the revenue implications of transmission constraint for three different solar power plants. The hourly generation of three solar electric plant types has been modelled using System Advisor Model (SAM) version 2010.11.9. To simulate the effect of constrained transmission on plant revenue, the transmission capacity is applied as a ceiling to hourly generation. Any excess energy is discarded. Transmission capacity is therefore modelled at a constant level, which is not representative of real transmission networks where the constraint is often managed dynamically according to weather conditions and other potential factors. However, this simple approach allows us to gain indicative figures for the impact of a constraint that is applied every hour of the year. The modelled plant types are:

- a non-tracking PV plant (tilted to latitude angle);
- a dual-axis tracking PV plant; and
- an air-cooled parabolic trough CST plant (for four cases of storage: none, 2, 4, and 6 full-load hours).

Each simulated plant was assigned a nameplate capacity of 100 MW_e and sited in Cobar (31.5°S, 145.8°E), approximately 600 km northwest of Sydney. Cobar is currently connected to the NEM via a 66kV transmission line, insufficiently rated for the plants considered in this study. The choice of Cobar illustrates the anticipated issues with transmission availability in areas of high solar resource.

A weather data file compatible with SAM was generated for Cobar using 2009 Bureau of Meteorology data and a software utility written by the authors. Global horizontal irradiation and direct normal irradiation data for Cobar in 2009 were obtained from hourly estimates of surface irradiance derived from satellite imagery, also provided by the Bureau of Meteorology. Other meteorological variables such as dry bulb temperature, wet bulb temperature, relative humidity, wind speed and wind direction were obtained from Cobar weather records. As a verification step, the simulation results for a typical meteorological year in Cobar were compared with the 2009 weather data and found to be in general agreement.

To evaluate the potential revenue impact of transmission constraint, acknowledging the limitations of past price data, 2009 Regional Reference Price (RRP) data for the New South Wales region were collected [16]. Pairs of half-hourly RRP values were averaged to produce hourly prices. The annual revenue for the plant is calculated using the dot product of the hourly energy and RRP time series. Baseline results were calculated for unconstrained transmission. The simulation was then repeated for transmission capacities of 90 MW down to 50 MW in 10 MW increments.

4.1 PV systems (fixed and tracking)

We first consider two types of PV systems: fixed and dual-axis tracking. Assuming no storage is available, any power generated above the capacity of the transmission line must be curtailed. On a clear day, a fixed PV system has a typical generation profile similar to Figure 1. The period that the system produces power near its rated capacity is short and predictable. It is straightforward to predict the maximum power output of a PV system at any time of the day through clear sky models. On many days, power output does not reach the rated capacity of a fixed PV system due to cloud cover or seasonal decline in irradiance. In Figure 2 and the inset figure, the power duration curve for the fixed PV system illustrates how infrequently the system generates near peak rated output.

Electricity generation for a range of constraint levels is shown for a fixed system (Table 1) and a dual-axis tracking system (Table 2). With transmission capacity limited to 60 MW, total annual electricity generation from a fixed system is 92.5% of the unconstrained generation. This result is comparable to the other results cited earlier [10].

If the PV plant is curtailed during times of high prices, then the percentage revenue loss may be substantially greater than the loss in energy terms. Annual revenue is calculated using the dot product

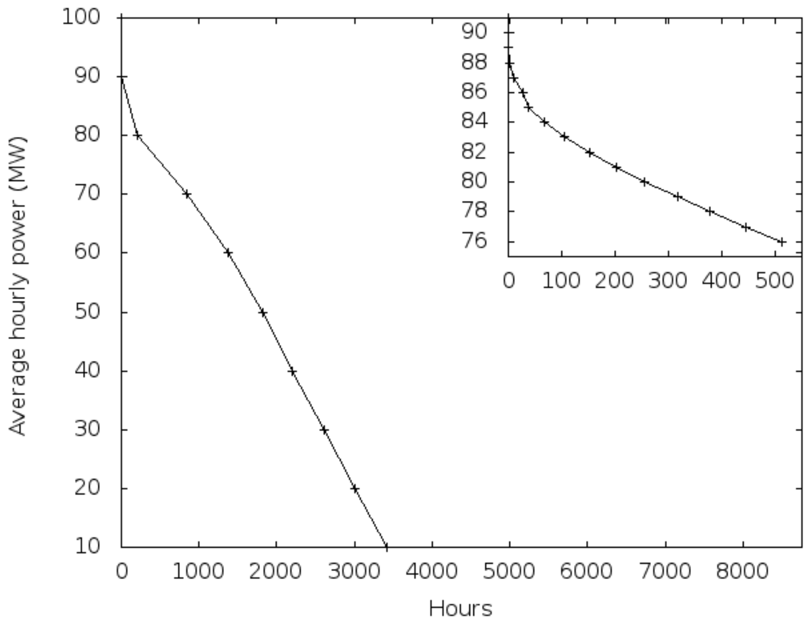

Figure 2: Power duration curve for fixed Cobar PV system in 2009

Transmission limit (MW)	Energy yield (GWh)	Energy fraction	Revenue fraction
100	178.31	1.000	1.000
90	178.31	1.000	1.000
80	178.17	0.999	0.999
70	174.74	0.980	0.976
60	164.99	0.925	0.931
50	148.93	0.835	0.821

Table 1: 2009 generation for fixed PV system

Transmission limit (MW)	Energy yield (GWh)	Energy fraction	Revenue fraction
100	251.70	1.00	1.00
90	251.70	1.00	1.00
80	242.71	0.96	0.97
70	223.58	0.89	0.89
60	198.07	0.79	0.79
50	168.98	0.67	0.67

Table 2: 2009 generation for dual-axis tracking PV system

of 8,760 hourly power and RRP values for the year. The resulting revenue fractions for each level of transmission constraint are listed in Table 1 (fixed) and Table 2 (tracking). The finding is that the revenue fraction is not markedly different to the energy fraction. This can be explained by considering a single day analytically. If the daily energy is segmented into hourly energy values e_i with a constant energy price p, then the daily revenue r is:

$$r = p \cdot \sum_{i=1}^{24} e_i$$

If transmission constraint reduces daily energy generation by some fraction f_e, then revenue is scaled by the same factor. Hence, when the energy price is constant, $f_r = f_e$. When the energy price is higher during constraint events, the revenue loss will be greater than energy loss and $f_r < f_e$. Conversely, when the energy price is lower during constraint events, $f_r > f_e$. The empirical results for the two types of PV systems suggest that the spot market prices are not significantly higher, or consistently higher, during constraint events. Short periods of very high prices during constraint events do not impact significantly on annual revenue.

4.2 Concentrating solar thermal systems

The simulation was repeated for an air-cooled parabolic trough CST system with various levels of storage. For the no storage case, a solar multiple of 1.0 was used, whereas for 2, 4, and 6 full-load hours of storage, a multiple of 2.5 was used. The basic dispatch model in SAM was used for this simulation; energy is dispatched whenever it is available. Future work could consider more sophisticated dispatch schedules. In the NEM context, it is likely that plant operators would utilise solar forecasts and day-ahead price data to operate the storage.

The reduction in annual electricity generation and annual revenue due to various levels of transmission constraint is shown for the system with 4 full-load hours of storage in Table 3. Figure 3 summarises the results for all cases. The main observations that can be made about these results are:

- the CST plant with no storage has an energy fraction curve more similar to the tracking PV case than to the other CST cases, as the plant produces power at rated output less often; and
- although increased storage will increase the capacity factor of the CST plants, it also produces a modest decrease in the amount of spilled energy, due to increased power that can be delivered under the transmission constraint late in the day.

Transmission limit (MW)	Energy yield (GWh)	Energy fraction	Revenue fraction
100	334.84	1.00	1.00
90	309.17	0.92	0.92
80	280.05	0.84	0.83
70	247.86	0.74	0.73
60	214.44	0.64	0.63
50	180.52	0.54	0.53

Table 3: 2009 generation for CST system with 2.5 solar multiple and 4 hours storage

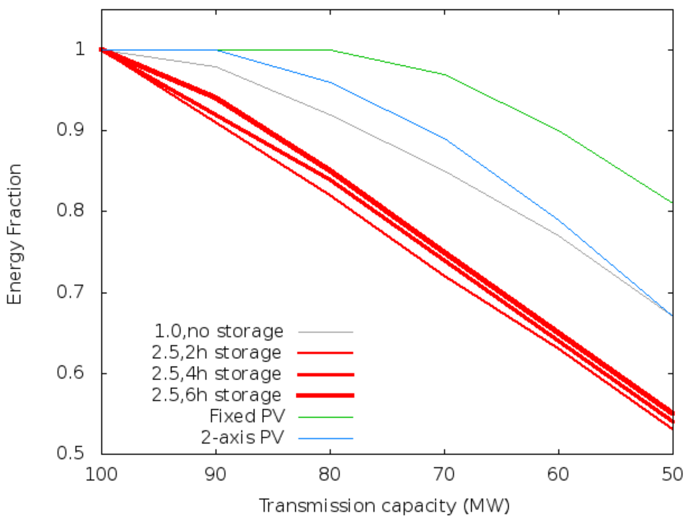

Figure 3: Energy production due to constrained transmission on CST and PV systems

As a CST plant gains greater amounts of storage, it begins to assume a more conventional generation profile: more hours of the day are spent at rated output. With an increasing capacity factor, these plants require transmission matching the rated output of the power block. The physical trough plant model used by SAM aims to run the power block at full power for high efficiency operation. Hence, when there is inadequate solar radiation and stored thermal energy is available, the plant runs as close to rated output as possible. Constrained transmission will have a significant impact on the annual energy yield in this case.

5 Conclusion

Integrating large-scale solar electric plants into the Australian NEM, either of the CST or PV type, carries some risk at present due to the separated roles of transmission networks and generators in the NEM, and a minimal approach to regulating network extensions. It is plausible that the earliest large-scale solar plants to be built in Australia could operate in an environment of constrained transmission, or construct private wires to connect to a suitable transmission network node. In the case of private wires, the capacity of the transmission line can be limited to reduce costs.

The modular nature of CST and PV technologies alike permits a plant to be initially constructed in locations where transmission capacity is inadequate. The scalability of solar PV technology allows an incremental approach to plant construction. If additional plants were to subsequently cluster in an area of high insolation, the transmission network extensions are likely to proceed. The first plant can then expand to utilise additional transmission capacity.

Although not as scalable as PV, CST plants can also benefit from such an approach. An early CST project could initially use a smaller power block, with a view to increasing this as transmission availability becomes more certain. Existing CST plants in Europe have demonstrated technical feasibility at small scale. Smaller plants could be progressively built in greater number in response to investment risk. Another possible response to the lack of available transmission for large-scale plants is to construct smaller plants closer to loads, and connect them into the network at sub-transmission level.

This work indicates that an effective strategy to mitigate the risks associated with the connection of large-scale solar generators in the NEM is to oversize solar electric plants relative to available transmission, particularly for plants with lower capacity factors. Even if transmission planning can proceed in a timely fashion, solar plants can be constructed more quickly than transmission infrastructure. It is likely that early plants will be operational before transmission network extensions are complete.

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References

[1] Australian Energy Market Operator. About AEMO, 2010. URL `http://www.aemo.com.au/corporate/aboutaemo.html#nem`. Last accessed 28 March 2011.

[2] Mark Diesendorf. Submission on National Transmission Network Development Plan, March 2010. URL `http://www.aemo.com.au/planning/0419-0008.pdf`. Last accessed 28 March 2011.

[3] Andrew Mills, Ryan Wiser, and Kevin Porter. The Cost of Transmission for Wind Energy: A Review of Transmission Planning Studies. Technical Report LBNL-1471E, Ernest Orlando Lawrence Berkeley National Laboratory, February 2009.

[4] Australian Energy Market Commission. National Electricity Amendment (Scale Efficient Network Extensions) rule 2011 no. 7, 2011. URL `http://www.aemc.gov.au/Electricity/Rule-changes/Completed/Scale-Efficient-Network-Extensions.html`. Last accessed 25 July 2011.

[5] S. Yeleti and Yong Fu. Impacts of energy storage on the future power system. In *North American Power Symposium (NAPS), 2010*, pages 1 – 7, September 2010.

[6] Pavlos S. Georgilakis. Technical challenges associated with the integration of wind power into power systems. *Renewable and Sustainable Energy Reviews*, 12(3):852 – 863, 2008.

[7] Nicholas Boerema and Iain MacGill. The economics of transmission constraints on wind farms – some evidence from South Australia. In *Solar 2010: proceedings of the annual conference of the Australian Solar Energy Society*, 2010.

[8] Alfred J. Cavallo. High-Capacity Factor Wind Energy Systems. *Journal of Solar Energy Engineering*, 117(2):137–143, 1995.

[9] Ryan Wiser and Mark Bolinger. 2009 Wind Technologies Market Report. Technical Report LBNL-3716E, Lawrence Berkeley National Laboratory, August 2010.

[10] Sompop Pattanariyankool and Lester B. Lave. Optimizing transmission from distant wind farms. *Energy Policy*, 38(6):2806 – 2815, 2010.

[11] Paul Denholm and Ramteen Sioshansi. The value of compressed air energy storage with wind in transmission-constrained electric power systems. *Energy Policy*, 37(8):3149 – 3158, 2009.

[12] M. Wittmann, H. Breitkreuz, M. Schroedter-Homscheidt, and M. Eck. Case Studies on the Use of Solar Irradiance Forecast for Optimized Operation Strategies of Solar Thermal Power Plants. *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, 1(1):18 –27, March 2008.

[13] Michael Wittmann, Markus Eck, Robert Pitz-Paal, and Hans Mller-Steinhagen. Methodology for optimized operation strategies of solar thermal power plants with integrated heat storage. *Solar Energy*, 85(4):653 – 659, 2011.

[14] Yabei Zhang, Steven J. Smith, G. Page Kyle, and Paul W. Stackhouse Jr. Modeling the potential for thermal concentrating solar power technologies. *Energy Policy*, 38(12):7884 – 7897, 2010.

[15] J.M. Cabello, J.M. Cejudo, M. Luque, F. Ruiz, K. Deb, and R. Tewari. Optimization of the size of a solar thermal electricity plant by means of genetic algorithms. *Renewable Energy*, 36(11): 3146 – 3153, 2011.

[16] Australian Energy Market Operator. AEMO price & demand data sets, 2011. URL `http://www.aemo.com.au/data/price_demand.html`. Last accessed 19 April 2011.