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Solar tower-biomass hybrid plants – maximizing plant performance

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Abstract

Concentrating solar power (CSP)-biomass hybrids plants are becoming increasingly interesting as a low cost option to provide dispatchable renewable energy since the first reference plant commenced operation late 2012, 22.5MWe Termosolar Borges in Spain. The development of such project is a complex task with not only one but two energy sources required to make the project successful. The availability of several studies but only one reference plant worldwide is proof of that.

This paper investigates the hybridisation of a biomass power plant with a molten salt solar tower system. The benefit of this combination is a high cycle efficiency as both the steam generators can provide steam at 525°C and 120bar to the steam turbine. A case study approach is used to provide technical, economic and environmental benefits of a 30MWe CSP-biomass plant with 3h thermal storage in Griffith, New South Wales. At this site such a plant could provide annually 160,300MWh of electricity with an annual average electricity price of AU$155/MWh. Compared to a standalone CSP plant with 15h of thermal storage the hybrid plant investment is 43% lower, providing a possibility to fast-track CSP implementation in countries where CSP is struggling to enter the market due to low wholesale electricity prices, such as Australia.

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1. Introduction

CSP-biomass hybrid plants are a well-accepted option to decrease the investment and levelised cost of electricity of CSP plants while increasing power dispatchability. The first reference plant in Spain [1] proves the concept and is likely to enable further installation in high direct normal irradiance (DNI) locations where biomass is also available, such as Australia, India, Greece or Spain.

Several CSP-biomass concepts have been investigated in the past but only the 22.5MWe Termosolar Borges project in northern Spain was built [1]. This shows that the development of such projects is complicated as in addition to all regular project development considerations, such as land availability and network access, not only one but two energy resources have to be abundant in this particular location. While this is a challenge modern geospatial modeling software can help to identify the best sites and allows project developers to not only get a good understanding of the energy resources but also land use, water availability, network access etc.

This paper is based on preliminary geospatial work for CSP-biomass hybrid plants in Australia and outlines the benefits of this concept in a case study in Griffith, New South Wales. The paper provides a technical, economic and environmental analysis for this site and while not all the results are fully transferrable to other sites the concept could be deployed in several regions in Australia and overseas.

2. Current CSP-biomass hybrid concepts

Some early efforts to combine CSP with biomass or waste materials were discussed briefly in the 1980's with dish systems [2]. However, due to technical and financial issues no plants were built. It took another 25 years before construction of the first commercial CSP-biomass hybrid plant commenced near Lleida, ca. 150km west of Barcelona in Spain, see Figure 1. The 22.5MWe Termosolar Borges plant came online late 2012 [1], is located further north than any other CSP project in Spain and uses the mature parabolic trough technology with thermal oil [3]. Several other studies investigated the hybridisation of parabolic trough plants with biomass [4–6] but no other project has commenced construction yet.

Alternatively, Fresnel has been investigated for hybridisation with biomass and waste materials [7–9]. The benefit of using Fresnel would be steam temperatures of up to 500°C [10] and subsequently higher conversion efficiencies. However, no reference plants exist yet.

In addition to live turbine steam other CSP-biomass concepts included the use of CSP for air and feedwater heating as well as external steam superheating from an energy from waste plant [9]. However, none of the concepts considers CSP steam temperatures >430°C which limits the cycle efficiency.

Figure 1: First CSP-biomass plant under construction near Lleida, Spain (left) and biomass fuel (right)

3. Solar tower-biomass hybrid plants

Solar tower systems with direct steam generation and molten salts have the potential to provide steam parameters identical to a biomass plant, >500°C and >100bar, and are according to a recent CSP hybrid assessment the most suitable for hybridisation with biomass [11]. Without thermal storage a direct steam generation would be most favorable while a thermal storage concept would favor a molten salt system. In addition to solar towers with molten salts and DSG systems using a volumetric air receiver are being investigated [12]. However, due to the limited reference situation and the higher complexity of such systems they are more complicated to finance.

In addition to the cost sharing opportunities of hybrid plants in general, such as joint use of steam turbine and condenser, solar tower biomass hybrid plants have the potential to use the required stack to support the receiver. This concept has been investigated for integrated solar combined cycle plants [13] and is also suitable for solar tower-biomass hybrids.

To have a significant solar share in a CSP-biomass hybrid both steam generators have to be able to provide high temperature/pressure steam to the turbine rather than using CSP for feedwater heating or reheat steam (steam reheating is not common in smaller power plants). A CSP-biomass hybrid example is shown in Figure 3.

4. Case study

The case study is based on a CSP-biomass hybrid plant with a total capacity of 30MWe, 15MWe biomass and 15MWe CSP. The CSP component will be modeled as a molten salt and direct steam generation solar tower. Biomass and the aforementioned solar tower references exist for steam temperatures of 525°C at 120bar which provides financiers with investment certainty. Technical reliability is highly important to secure project finance and turn projects into actual power plant installations.

4.1. Methods

Thermoflex version 23.0.1[†] was used for the techno-economic assessment. The software is widely used in academia and industry to model actual solar tower, parabolic trough and Fresnel plants. The software's cost database is used to identify the investment for the different power plant components. With biomass boilers not being a standard Thermoflex component the authors' industry expertise was used to ensure equipment cost accuracy. With an assumed plant commissioning in 2016 the solar field investment is lowered by 10% to reflect 2015 pricing based on a reasonable learning curve [14].

The economic assumptions are a plant lifetime of 30 years, commissioning in 2016, 65% debt finance, a debt interest rate of 8%, a 7% discount rate and an internal rates of return on investment of 11%. The modeling includes capital and operational costs as well as escalation rates for inflation, fuel, electricity and water prices. The investment shown are the owners total project cost consisting of the engineering, procurement and construction price and 9% owner's soft cost covering permits, project management, legal and finance aspects of a power plant project. Network connection is also included. Payback times and net present values derive from the total project cost.

From the different CSP technologies available a solar tower was selected as according to a recent multi-criteria assessment for CSP hybrid plants [11] it is the preferred technology for >500°C hybrid systems. Without thermal storage a direct steam generation tower scores best but due to the integration of 3h thermal storage a molten salt system is preferred as its thermal storage is proven and commercially available from a variety of suppliers.

A water tube boiler with a vibrating grate is selected for the biomass boiler as this is the dominant technology for straw. References exist up to 540°C [15] which matches the CSP parameter well and allows high efficiency power generation.

[†] www.thermoflow.com

The technology selection for a hybrid plant is crucial to obtain finance. This assessment requires the CSP and biomass components to have at least 15MWe reference plants in operation. Both technologies fulfill this criterion with commercial plants in operation, e.g. 20MWe Gemasolar solar tower [16] and 25MWe Sanguesa straw fired power plant [15].

4.2. Site

Griffith in central New South Wales is chosen for the case study as it is a region with strong agriculture and horticulture industries and a DNI of 2,150kWh/m^2/year [17]. From a DNI perspective Griffith is significantly better than Lleida in Spain, 1,800kWh/m^2/year [18], where the first CSP biomass plant commenced operation recently.

A recent study [19] indicates sufficient stubble in this region to provide the 86,000t required annually to fuel a 15MWe biomass plant continuously. The maximum biomass potential in the Mildura region is even higher but the annual biomass yield varies and a conservative approach is important to ensure continuous biomass supply.

The Tharbogang substation near Griffith would require little upgrades to accommodate the output of a 30MWe power plant. The CSP-biomass hybrid plant could follow the daily demand well by providing base-load as well as peak capacity during the day and evening, see Figure 2. This optimises revenue by covering the high price periods.

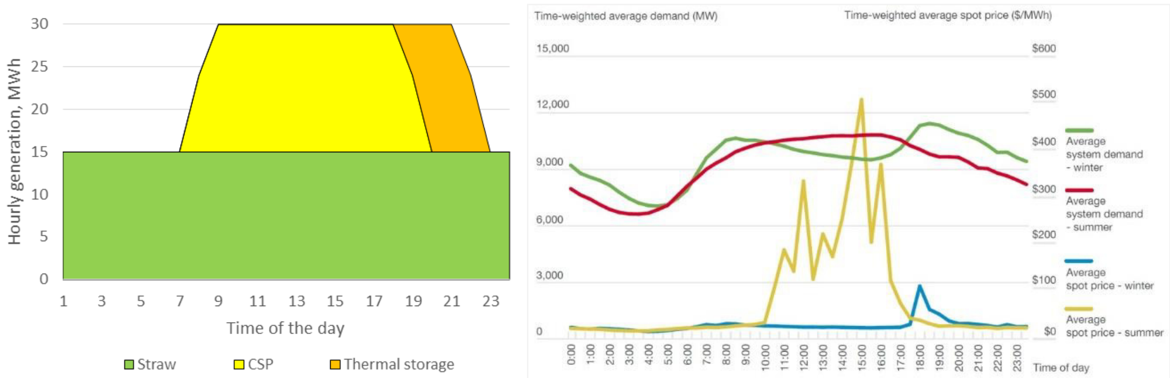

Figure 2: Ideal CSP-biomass generation profile for a 30MWe plant (left) and NSW average weekdays system demand and spot price year ending 2010 (right) [20]

4.3. Technical analysis

Figure 3 shows the process diagram of the proposed hybrid plant with its main components, such as furnace and boiler heating surfaces (1-8), flue gas cleaning (14), stack (18), solar tower with 3h thermal storage (34), molten salt/steam heat exchanger (35-37), steam turbine (19-21, 53, 57), air-cooled condenser (22), feedwater heating system (25-26, 30, 52, 61), and auxiliary equipment.

At full load each steam generator provides 59t/h of steam at 525°C and 120bar to the joint steam turbine generating a net output of 30MWe. Due to the high steam parameters and feedwater heating the plant reaches a net cycle efficiency of 33.4% at full load and 30.2% with only the biomass boiler in operation, see Table 1.

The annual plant output was modeled for the years 2006-10 and the CSP component reached an average annual capacity factor of 29.1% resulting in an average plant output of 160,300MWh. During this period the annual DNI changed resulting in the lowest annual generation in 2010 and highest in 2006, see Table 1. In winter the DNI output decreases significantly while the biomass output increases slightly due to lower ambient temperatures. However, the biomass increase cannot offset the CSP shortfall.

To operate the biomass plant for 8,000h/year a continuous straw supply of 10.74t/h is required. The onsite storage capacity for straw bales is 4 days of full-load operation with the remaining material being stored on the fields where it was harvested. Baling is essential to avoid the material degrading during outdoor storage.

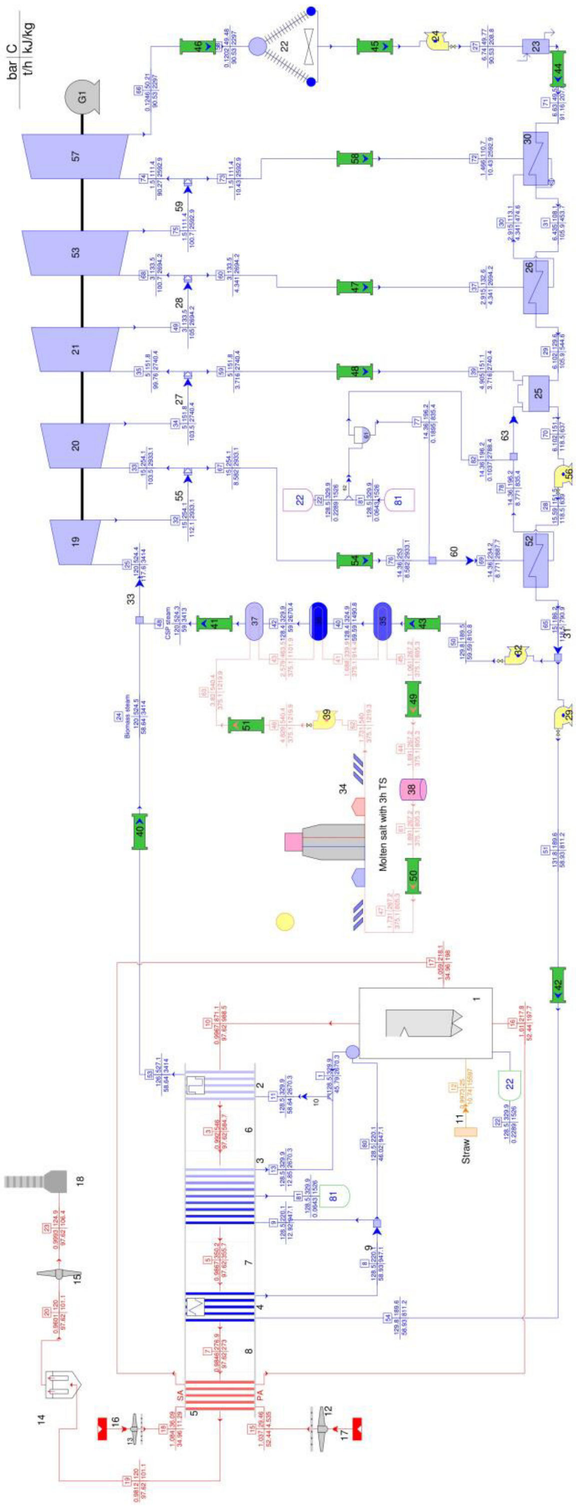

Figure 3: Process diagram for 30MWe solar tower-biomass hybrid plant in Griffith

Table 1: Technical data summary

Total plant capacity	30	MWe
CSP contribution to steam turbine capacity	15	MWe
Biomass contribution to steam turbine capacity	15	MWe
CSP contribution to annual generation (2006-10)	38,300	MWh
Biomass contribution to annual generation (2006-10)	122,000	MWh
Total annual average generation (2006-10)	160,300	MWh
Minimum annual generation (2010)	154,100	MWh
Maximum annual generation (2006)	164,400	MWh
Peak electric plant efficiency (gross)	36.1	%
Net electric plant efficiency	33.4	%
Parasitic losses	7.5	%
Net electric plant efficiency biomass only	30.2	%
Annual straw consumption at 15.6MJ/kg	86,000	t
Plant footprint	74	ha

4.4. Economic analysis

The economic data for the 30MWe CSP-biomass hybrid at Griffith are shown in Table 2. It should be noted that the grid connection, AU$17m, is a significant addition to the plant investment and adds AU$10/MWh to the electricity price. To meet industry typical internal rates of return (IRR) of around 11% an annual average electricity price of AU$155/MWh is required assuming a biomass price of AU$100/t.

The low specific investment for the biomass components, AU$4.2m/MWe, reduces the higher CSP specific investment, AU$7mMWe, to an average of AU$5.6m/MWe while increasing the plant's capacity factor.

Generating the same annual electricity output as the CSP-biomass hybrid would require 26MWe CSP standalone plant with 15h thermal storage (solar multiple of 2.8 and 70% capacity factor). In 2015 such a plant would have a total invest of AU$292m incl. network connection or AU$11.2/MWe. Comparing this with the CSP hybrid results in a 43% cost reduction. The CSP standalone plant would require an annual average electricity price of AU$205/MWh to achieve same IRR.

Table 2: Economic data summary

Plant investment	151	AU$m
Network connection charge	17	AU$m
Specific investment	5.6	AU$m/MWe
Specific CSP investment	7.0	AU$m/MWe
CSP percentage of investment	62	%
Biomass percentage of investment	38	%
Biomass price	100	AU$/t
Net present value	103.7	AU$m
Internal rate of return	10.9	%
Payback	9.5	years
Required annual electricity price	155.0	AU$/MWh

The proposed power station would create 30 positions for plant operators and engineers. Based on literature [21] the additional employment from a biomass power plant can be 10 times higher than the direct employment, e.g. fuel harvesting and logistics. With the Griffith proposal being half CSP and half biomass a factor of 5 has to be assumed for the maximum additional indirect/induced employment. This is still significant for a rural region.

A benefit worth mentioning is the opportunity for local farmers to diversify their businesses as they currently receive annually varying revenues for their crops. A power station would stabilize their revenue stream by making use of a product that is currently considered waste and is, at an expense, burnt in the field.

4.5. Environmental analysis

Both CSP and the biomass are renewable energies which can offset the use of fossils fuels elsewhere in the electricity network. Based on future annual electricity demand and CO_2 emissions trajectories [22] the average annual carbon intensity of Australia's electricity mix between 2016-45 could be 604kg CO_2/MWh. This value seems high but the emissions intensity is expected to stay above 500kg CO_2/MWh until around 2038. Based on this assumption the CSP-biomass hybrid plant could abate up to 2.2 million tonnes CO_2 over its 30 year lifetime. It has to be mentioned that long-term future electricity and CO_2 emissions trajectories contain a high degree of uncertainty, which can be observed currently by a falling rather than increasing electricity demand in Australia.

In addition to avoided CO_2 emissions the use of straw in a power station has further benefits as it can avoid straw burning in the field with its associated particle emissions and subsequent public health impact. The ash collected from the power station could be brought back to the field as it still contains valuable compounds, such as potassium.

4.6. Plant layout and architecture

As the plant stack and receiving tower climbs approximately 70m above the surrounding planar river valley landscape and the conspicuous reflective mirrored heliostats occupy a significant area (72ha), the plant will serve as a significant landmark for the region. Thoughtful consideration to its architecture is essential. Therefore, for the purposes of this study, devising design concepts for the plant was proposed as an assignment for masters students enrolled in subject Advanced Environmental Design at University Technology Sydney (UTS) during the 2013 fall semester. Master student Kinneth Galang developed the preliminary conceptual scheme described below.

For maximum solar power generation, 1,480 heliostats are evenly placed around the central stack in an elliptical shape measuring approximately 1km x 0.9km located on a flat plot of land to the southwest of the intersection of Harward Road and Kidman Way. Walter Burley Griffin used the circle several times in designing Griffith's masterplan and these circles are still prominently evident in city road network today, a continuation of the circular layout was initially considered for the field of heliostats. However as the elliptical layout increases optical efficiency, this variation was determined the superior solution. One road bisects the ellipse to provide a secure main entrance to the central plant. The road then encircles the central plant providing serviceable access to its six main components: fuel storage, the boiler, thermal storage, flue gas cleaning, condenser and the steam turbine, see Figure 4. Of these, the combined stack/receiving tower is the most visible rising above the surrounding buildings and area with a height of 70m, see Figure 5. The fuel storage with its area of approximately 3,100m^2 occupies the most space. While several different configurations of the various components were considered, keeping the stack on the central axis and then clustering the other elements nearby so that distances between the processes could be kept minimal resulted in the most satisfactory solution.

In deference to the agrarian nature of the surroundings, metal siding typical of agricultural buildings was considered most appropriate cladding for the operations. The variation of the building's overall form and detailing of this metal cladding however seek to create a dynamic more consistent with electricity generation. In deference to the local regenerative fuel sources, strawbale infill walls were considered a possibility as a secondary construction system in the more public and visible spaces. The plant complex would include a small public lobby to showcase and explain the technologies being used at the plant. This showroom would be housed next to the main office rooms for the plant and located at the end of the central corridor. In keeping with the circular vocabulary used in the public areas of Griffin, and circular landscaped pool would surround this circular portion of the plant, with the water serving the dual purpose of being the required fire reserve.

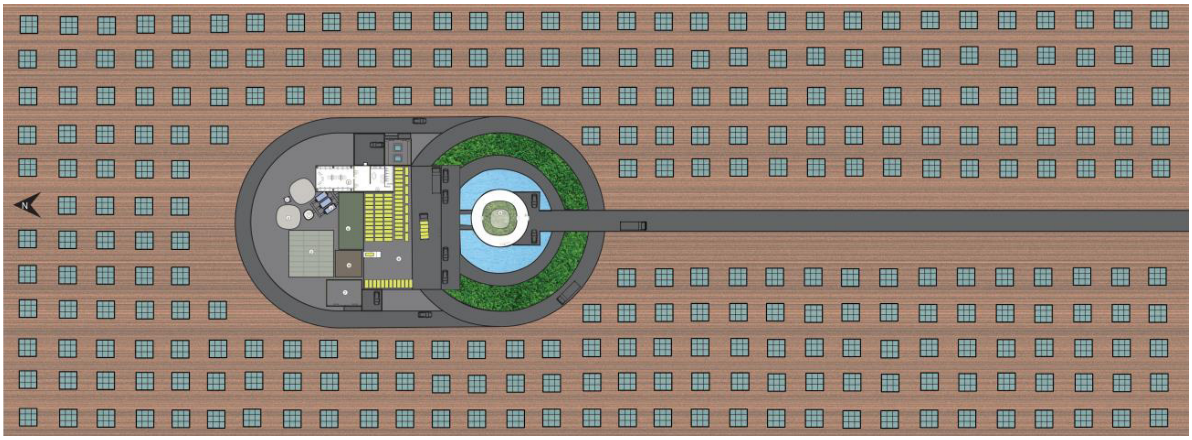

Figure 4: Plan view of the CSP-biomass hybrid plant (heliostat arrangement only schematic)

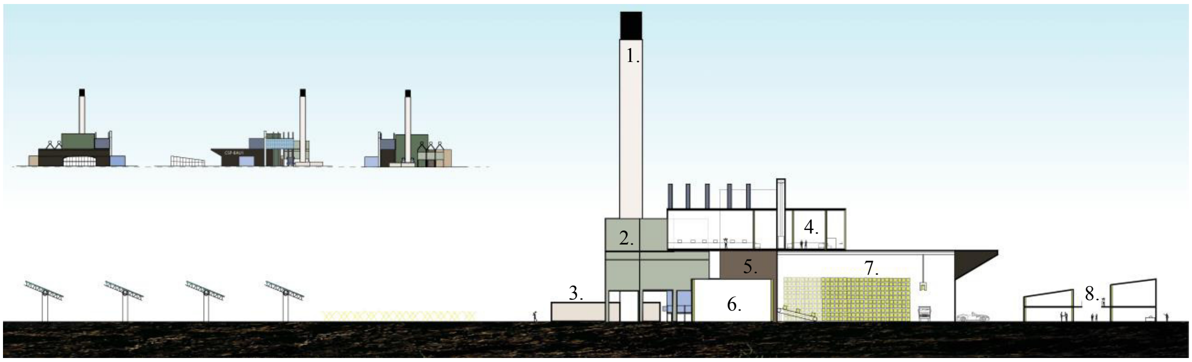

Figure 5: Cross section view of the CSP-biomass hybrid plant; 1. Stack/solar tower, 2. Condenser, 3. Molten salt tanks, 4. Offices, 5. Biomass boiler, 6. Building for auxiliary equipment, 7. Fuel storage, 8. Reception

4.7. Molten salt biomass heater alternative

With 3h thermal storage integrated in the CSP hybrid plant the option of a biomass fired molten salt heater rather than a steam boiler is worth investigating as such a plant configuration could optimise electricity dispatchability with pricing. Currently, there are no references for biomass fired molten salt heaters but significant industry expertise is available for biomass and waste fired thermal oil heaters, which could be used for the design of a molten salt unit, such as fluid circulation, drainability and solidification. To simplify molten salt draining a heater design with vertically arranged heating surfaces, as in the Energy from Waste plant Bamberg in Germany [23], would be ideal. The technical risk of a molten salt heater would be slightly higher compared to a conventional steam boiler but the benefit of shifting electricity output to higher price periods, such as morning peak, makes the concept interesting. A biomass fired molten salt heater would have a lower investment than a steam boiler due to features such as lower working fluid pressure and no drum. However, the molten salt/steam heat exchanger would have to be designed for the total plant capacity and not only the CSP flow which is likely to offset the heater savings.

Typically, electricity prices are lower during the night than the day with peaks in the morning and evening. The evening peak could be covered with CSP charging the thermal storage but the morning period could not. However, with a molten salt biomass heater the plant could operate the steam turbine at minimum load, 7.5MWe, during low electricity price times at night, simultaneously charge the thermal storage and dispatch 30MWe as soon as electricity prices recover in the morning. The biomass fired molten salt unit could also charge the thermal storage during lower DNI winter days to ensure appropriate thermal storage levels to cover the evening peak.

Figure 6 provides an example based on the New South Wales wholesale electricity prices for the 23/07/2012 and the plant's operational strategy to maximize revenue. By diverting thermal energy from biomass to the thermal storage during the 0-5AM low electricity price period and only operating the plant at minimum 7.5MWe load the thermal storage could be charged to 91%. With electricity prices increasing significantly after 5:30AM the thermal storage can be discharged until CSP is able to provide its 15MWe share at 9:30AM. In addition to CSP charging the thermal storage to 48% during the day a biomass fired molten salt heater could further charge the thermal storage from 2-3:30PM to 100%, which allows longer electricity dispatch during the economically attractive evening times. Having the plant online earlier at full load for the morning peak and longer for the evening peak increases the daily revenue by 6.1% compared to a biomass fired steam boiler operating continuously at full load.

With electricity prices fluctuating during the year the economic benefits of a biomass fired molten salt heater are lower at other times. On the 23/01/2013 the New South Wales electricity price was stable at a low level and a molten salt biomass concept could have only capitalized on the small price differences during the night and early morning by charging the TS from 02-4:30AM to 50% and dispatching at slightly higher prices from 5-7:30AM, see Figure 7. The small electricity price differences result in a daily revenue increase of only 0.3%.

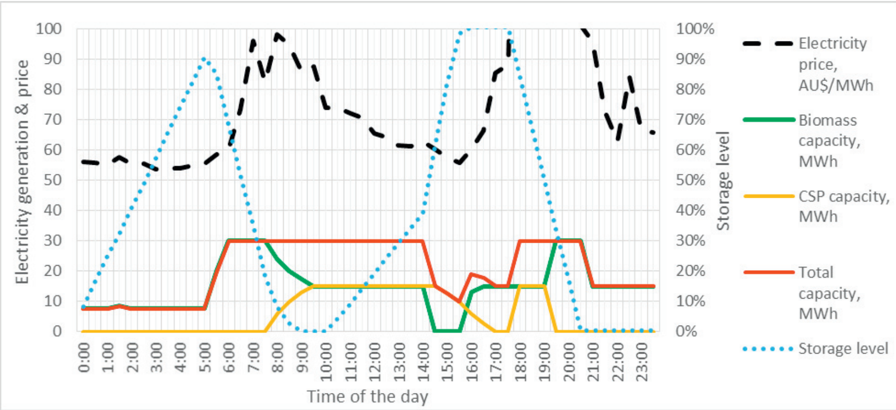

Figure 6: Example of daily electricity generation with molten salt biomass heater in winter (23/07/2012); Peak electricity price at 6:30PM was AU$291.66/MWh

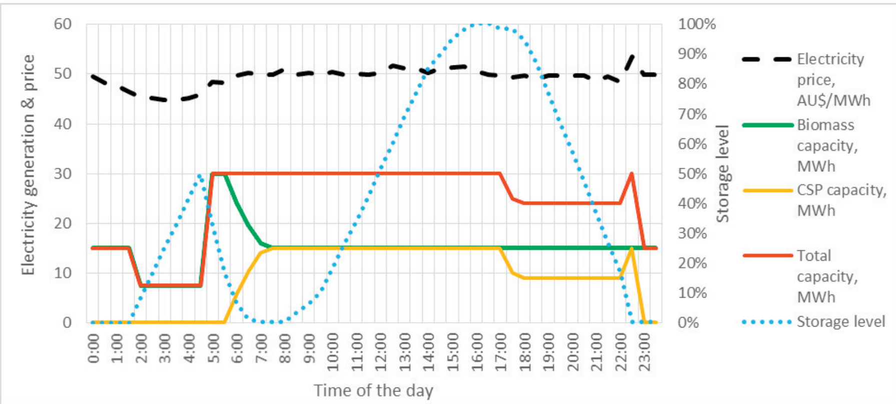

Figure 7: Example of daily electricity generation with molten salt biomass heater in summer (23/01/2013)

5. Conclusion

The combination of a biomass and solar tower energy system is beneficial to maximise the cycle efficiency with proven technologies, which financiers can see operating successfully elsewhere in the world. By combining these two energy sources in Griffith, New South Wales, a power plant could provide lower cost, AU$155/MWh, dispatchable renewable electricity, base-load with additional capacity during the day and evening, as well as additional benefits by avoiding the burning agricultural residues in the field.

Reducing the investment by 43% with a CSP-biomass hybrid plant, compared to standalone CSP, has the potential to fast-track CSP implementation in Australia and familiarize financiers and operators with the different CSP technologies available.

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