Hybrid concentrated solar biomass (HCSB) plants for supporting the clean energy transition in New South Wales, Australia

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Doctor of Philosophy in Sustainable Futures

under the supervision of
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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Ella Middelhoff declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, at the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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ABSTRACT

Replacing fossil fuels with renewable sources is the key strategy to limit global warming to below 1.5 °C and mitigate the more severe impacts of rising temperatures on the Earth's climate system. Today, positive developments in renewable energy technologies and significant investment from government and industry is driving the energy transition, which can be observed in many countries around the world. In Australia, the country where this research project was carried out, already around 7% of the energy and one quarter of the electricity produced is sourced from renewable sources. These developments demonstrate that the global and national energy transition are underway. However, an adequate supply of dispatchable[1] renewable electricity and renewable thermal energy (specifically for industrial applications) are just a few examples of the numerous challenges that the energy transition is facing and that will be (beside others) the focus of this doctoral research.

Addressing these challenges and achieving full decarbonisation requires a multidimensional strategy, which has spurred interest in novel renewable technologies, for example hybrid concentrated solar biomass (HCSB) plants. HCSB plants are not a radically new energy generation technology; rather, the technology integrates two mature renewable energy (RE) systems – concentrated solar and bioenergy. HCSB plants have been demonstrated in several locations worldwide, e.g., the 16.6 megawatt thermal (MW_{th}) *Aalborg CSP*[2] system in Brønderslev, Denmark. In Australia, the technology is not yet demonstrated, although the renewable resources – solar and biomass – are abundant and underutilised in the context of energy generation. This doctoral research project investigates the potential deployment of HCSB plants for supporting the energy transition in New South Wales (NSW), Australia's most populous state.

The specific focus of the doctoral project is the investigation of the **technical options**, **deployment potential** and the **benefits** of HCSB plant utilisation in NSW (Figure 1). Following a detailed review of the literature on the technical and commercial maturity of the different HCSB design options, this research is presented across four distinct research packages, investigating: i) biomass residue availability in Australia, ii) energy market integration of HCSB plants in NSW, iii) techno-economic feasibility of HCSB plants as an electricity generator in the Riverina-Murray region (case study), and iv) techno-economic feasibility of HCSB plants for cogeneration at a major beef abattoir in Casino, NSW (case study).

[1] Dispatchable generators provide flexible energy on demand utilising energy storage systems. In the future energy supply system dispatchable energy technologies will be particularly important to secure continuous supply in times of diminished solar and wind resources availability.
[2] https://www.aalborgcsp.com/projects/166mwth-csp-for-combined-heat-and-power-generation-denmark/.

Figure 1: Simplified research design of doctoral research project.

The most important findings of this thesis can be summarised as follows:

Technical Options

A variety of promising HCSB design options have been proposed. Based on a literature review, different HCSB systems were compared, and mature and ready-to-use options were identified. Maturity was graded using a numerical ranking system. It is assumed that systems with a high level of maturity can be deployed in NSW without having to wait for further research or development. A total of six different HCSB design options were identified, of which two design options were selected for detailed investigations in two case studies. In these two case studies i) Rankine cycle (RC) HCSB plants for small-to-medium (5 – 50 MW_e) electricity generation, and ii) organic Rankine cycle (ORC) HCSB plants for low-to-medium temperature (40 – 250 °C) cogeneration systems were investigated. For both options mature and efficient technology components were selected to be suitable for the case study design context. Performance was evaluated based on a thermodynamic model.

Deployment Potential

The siting and deployment potential of HCSB plants depends on the local availability of renewable resources, siting constrains (such as protected land), and the access to energy markets and consumers. A geographic information system (GIS)-model was developed to investigate the siting of HCSB plants in NSW. HCSB plants rely on two renewable resources: solar and bioenergy. For both feedstocks, the GIS-model considered high-resolution (at 5 x 5 km) resources maps. In a second step, ‘network opportunities’[3] were identified, defined as locations in proximity to the transmission infrastructure or industries that allow for economic and ready-to-use grid access. For each of these prospective sites, minimum resources thresholds for HCSB plant deployment as well as further siting constrains (e.g., protected land) were considered. In NSW, HCSB plants have a good siting potential and as grid connected systems, they could theoretically be installed at a capacity > 870 megawatt electric (MW_e) with a potential to abate more than 6 Mt carbon emissions (CO_2-e) per year.

[3] These are locations in the electricity network that offer economic and ready-to-use grid access.

Benefits

In two case studies, HCSB options were selected, designed, and investigated to address current challenges of the energy transition in NSW. In the first case study, RC HCSB plants were investigated as dispatchable renewable electricity generators that can help to stabilise the electricity supply in the grid. In the second case study, ORC HCSB plants supplied low-to-medium temperature (40 – 250 °C) process heat and electricity for industrial applications (here meat processing). The economic feasibility of both systems was evaluated. The estimated levelised cost of energy at AU$ 90 – 200 per megawatt hour (MWh)[4] for RC and ORC HCSB systems is comparable with other dispatchable renewable technologies, underlining their economic competitiveness. In addition, several other advantages of HCSB plant deployment are discussed, e.g., in regard to supporting bioenergy and concentrated solar power (CSP) industry development in Australia, as well as benefits of deployment for local communities.

In summary, the doctoral project has expanded the evidence base and outlined the advantages of HCSB plant deployment to support the local RE transition in NSW. The empirical contribution lies in the detailed investigation of two HCSB plant options for electricity and industrial cogeneration. HCSB plants are particularly interesting in the context of NSW because they combine the use of solar thermal and bioenergy and their supplying resources (solar thermal, biomass residues and waste). These resources are currently underutilised, however are expected to play an important role in future energy supply systems. The findings show that HCSB plants provide dispatchability services that are aligned with current NSW government climate and energy policy priorities. In NSW, these dispatchability services will become even more advantageous as larger amounts of RE is deployed and fossil fuelled stations are retired. The methodological approaches developed and tested in this thesis can inform future research and offer novel insights concerning the techno-economic feasibility of currently unused RE technologies in other jurisdictions.

[4] This equals US$ 61 – 136, using the conversion rate of July 2022.

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I would like to acknowledge the traditional owners of the land, the Gadigal people of Eora Nation on which the City Campus of the *University of Technology Sydney* (UTS) stands. I would like to pay my respect to the Elders past, present and emerging, and acknowledge them as traditional custodians of knowledge for this land.

Writing my thesis over the past three and a half years has been an extraordinary process. While impossible to recount all learning experiences and priceless insights that the process has brought me, on reflection, the one thing that really stands out, is the experience of personal growth. From writing the research proposals, through to my final thesis – it was not only the slowly accumulating word count; the ever-increasing collection of written pages and articles or the experience of turning ideas into actions, but my development and expansion both as an academic and as a person. Being exposed to so many new ideas and concepts has sharpened the lens through which I now see the world – and it is this shift in perspective, that I am most grateful for. My inner evolution, as well as the thesis itself, would have not been possible without the significant contribution from the people around me who guided me personally and academically; and who made this experience so meaningful and rich.

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List of Publications

This doctoral project produced four stand-alone journal articles (and research contribution to additional published journal and conference articles):

I. **E. Middelhoff**, B. Madden, M. Li, F. Ximenes, M. Lenzen, and N. Florin**,** "Bioenergy siting for low-carbon electricity supply in Australia," *Biomass & Bioenergy*, vol. 163, no. August 2022, p. 106496, doi: https://doi.org/10.1016/j.biombioe.2022.106496.
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III. **E. Middelhoff**, L. Andrade Furtado, J. H. Peterseim, B. Madden, F. Ximenes, and N. Florin, "Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia : Design and evaluation of techno-economic and environmental performance," *Energy Converstion and Management*, vol. 240, no. July 2021, p. 114244, doi: https://doi.org/10.1016/j.enconman.2021.114244.
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ABBREVIATIONS

ABS	Australian Bureau of Statistics	MW_e	Megawatt electric
AD	Anaerobic digestion	MWh	Megawatt hours
AREMI	Australian Renewable Energy Mapping Infrastructure	MW_{th}	Megawatt thermal
ARENA	Australian Renewable Energy Agency	n	Lifetime of plant
AU$	Australian Dollar	NASA	National Aeronautics and Space Administration
BoM	Australian Bureau of Meteorology	NCMC	Northern Co-operative Meat Company
C	Installed cost	NSW	New South Wales
CCGT	Combined cycle gas turbine	NT	Northern Territories
CO_2-e	Carbon emissions	O&M	Operation and maintenance
CRI	Commercial readiness index	ORC	Organic Rankine cycle
CSP	Concentrated solar power	PHES	Pumped hydro energy storages
CST	Concentrated solar thermal	PV	Photovoltaic
CRF	Capital recovery factor	RC	Rankine cycle
DPI	Department of Primary Industries	RE	Renewable energy
E	Generated electricity	REZ	Renewable energy zones
GIS	Geographic information system	SA2/4	Statistical area 2/4
HCC	Hybrid combined cycle	SA	South Australia
HCSB	Hybrid concentrated solar biomass	TRL	Technical readiness level
HRSG	Heat recovery steam generator	UTS	University of Technology Sydney
HTF	Heat transfer fluid	VIC	Victoria
ISCC	Integrated solar combined cycle	WA	Western Australia
ISF	Institute for Sustainable Futures	WACC	Weighted average cost of capital
LCoE	Levelised cost of electricity		

1. Introduction

This work stands in the context of the Australian clean energy transition, which is the long-term objective to achieve a sustainable energy supply system [1][5] by reducing Australia's dependency on fossil fuels for energy generation and achieving net-zero greenhouse gas emissions by 2050 [2]. This objective has become necessary as concentrations of greenhouse gases, mainly emitted from human energy generation[6], increase in the atmosphere. This is changing the Earth's climate system [3], with the rising temperatures provoking catastrophic tipping points [4], [5][7] and disruptions in the functionality of the Earth's ecological and meteorological systems [6]. Impacts of climate change can already be observed in many parts of the world. In Australia, climate change causes rising temperatures and reduced average precipitation followed by droughts and an increase of frequency, length, and intensity of bushfires [3]. For example, between 2019 and 2020, Australia experienced one of the worst bush fire seasons. The fires had strong impacts along the East coast of Australia and dense ash clouds darkened the sky over Sydney for several weeks, as shown in Figure 2. These events ensure that averting climate change and implementing the energy transition is one of the most important political objectives of our time. Because the energy transition needs to be achieved around the world, both locally and at the global scale, it is arguably the most challenging policy objective of our current times. International agreements are in place to monitor its compliance and success on a global level [7], [8], [9][8], however progress towards the goals set under these agreements has been slow.

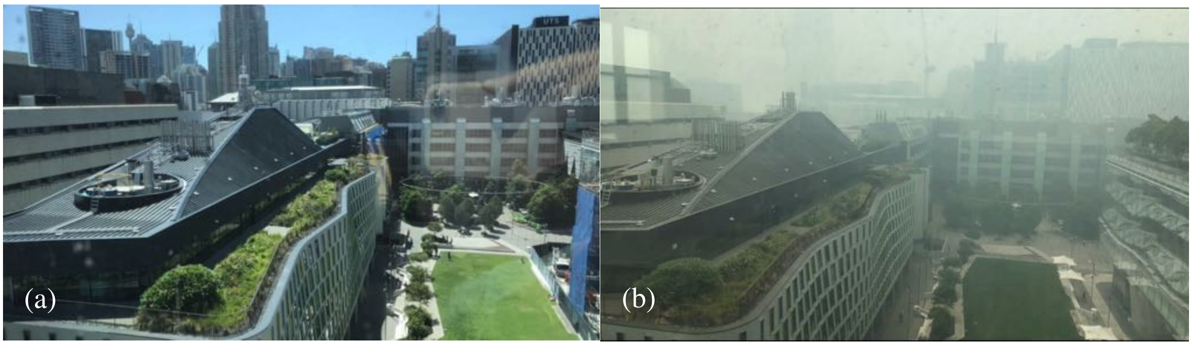

Figure 2: *University of Technology Sydney* (UTS) city campus in 2019: (a) regular day, and (b) during bush fires. Photos taken by author.

[5] 'Sustainable energy supply' is a vision of suppling clean, reliable, affordable and safe energy to human communities and industries '*that meets the need of the present without compromising the ability of futures generations to meet their own needs*' (direct citation United Nations [1], p. 15).
[6] According to the physical *law of energy conversion*, the term 'energy generation' is imprecise. In the context of this thesis, the term describes the generation of an economic asset (e.g. electricity or heat) and not the actual physical generation of energy.
[7] Ensuring future human well-being requires to '*calibrate the operations of the human systems so that it remains within safe parameters for a stable Earth system*' (direct citation Rockström [4], p. 1). Anthropogenic climate change caused by increasing greenhouse gas emissions in the Earth atmosphere is likely to overstep its planetary boundary of 350 to 450 ppm CO_{2-e} which will lead to irreversible changes [5].
[8] The *United Nations Framework Convention on Climate Change* (UNFCCC) [7], the *Kyoto Protocol* [8], and the *Paris Agreement* [9] were joined by Australia in 1994, 2008 and 2016 respectively.

The particular focus and contribution of this doctoral project is an understanding of the potential and benefits of a novel renewable energy (RE) technology in supporting the clean energy transition of New South Wales (NSW), Australia's most populous state. The technology is referred to as hybrid concentrated solar biomass (HCSB) plants. HCSB plants are not a radically new energy generation technology; rather the technology combines two mature renewable energies: concentrated solar thermal (CST)[9] (hereafter also referred to as 'solar thermal') and bioenergy. The technology has been demonstrated in several plants worldwide, e.g. the 22.5 megawatt electric (MW_e) *Termosolar Borges* plant in Lleida, Spain [10] and the 16.6 megawatt thermal (MW_{th}) *Aalborg CSP* plant in Brønderslev, Denmark [11]. As of 2022, the technology is under-developed in the context of energy generation in Australia.

The underlying premise of this research is that the deployment of novel energy generation technologies (in terms of installed capacity and number of installed systems) does not always reflect the actual benefits and advantages they offer. Some technologies have great potential to support the energy transition; however, their deployment is hampered by technical and non-technical barriers. This doctoral project builds on earlier work by Juergen H. Peterseim, who was the first one to investigate HCSB plants in Australia and highlighted the great deployment potential of HCSB plants in Australia owing to abundant and underutilised solar and biomass resources availability (e.g. [12]–[16]). It provides a novel contribution by offering an up-to-date insight about the deployment potential of HCSB plants in supporting the energy transition in NSW. Specifically, the doctoral project expanded the existing evidence base by, i) outlining the advantages of HCSB plant deployment by aligning the technology characteristics (e.g., dispatchability) with current NSW government climate and energy policy priorities, ii) elucidating technical design options and detailed economic considerations of two HCSB plant options for electricity and industrial cogeneration, iii) assessing resource availability on a new higher level of resolution for both solar and biomass resources (underlaying resources for HCSB plants) on the Australian continent, and iv) assessing HCSB plant siting potential in terms of locations, resources, market access, and benefits of HCSB deployment in the context of the energy transition in NSW [10].

[9] The two designations 'concentrated solar thermal – CST' and 'concentrated solar power – CSP' are referring to the same technology, which in the first case is supplying heat and in the second case is supplying electricity as energy product.
[10] In parallel to the doctoral project other deployment barriers (mainly focussing on social acceptance) are investigated in a larger research project embedded at the *Institute for Sustainable Futures* (ISF), at the *University of Technology Sydney* (UTS).

1.1. Structure of document

This thesis is organised as a 'thesis by compilation', following the *University of Technology Sydney* (UTS)'s 2019 thesis preparation and submission guidelines[11]. The structure of this thesis is summarised in Figure 3. It contains the following sections:

- Introduction (section 1, p. 17), providing an overview over the current success of the energy transition of NSW, and reasons for focussing on HCSB plants,
- Literature review (section 2, p. 28), providing an overview of the current state of the energy transition of NSW, and reasons for focussing on HCSB plants,
- Research design (section 3, p. 50), introducing the research questions and structure,
- Summary of the research findings and outcomes (section 4, p. 53),
- Discussion (section 5, p. 74), aiming to give an synthesis about HCSB plant deployment in NSW, and
- Conclusions (section 6, p. 92).

Section 4 (p. 53) as the summary of the research findings and outcomes only summarises the main outcomes of the four journal publications. The full published texts are provided as appendences (sections 8.A.1. p. 107, 8.A.2. p. 127, 8.A.3. 141, 8.A.4. 154).

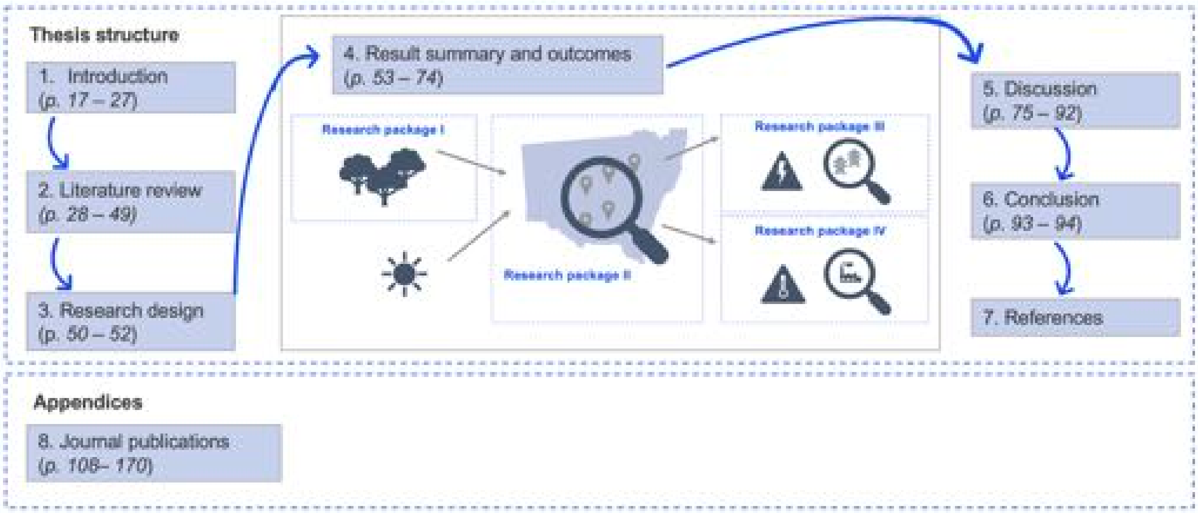

Figure 3: Structure of document.

[11] *University of Technology Sydney* (UTS), "Graduate research candidature management, thesis preparation and submission procedures", *version 1.6., Sydney, Australia*, 2019.

1.2. New South Wales (NSW)'s energy transition

This doctoral project aligns with the *NSW Climate Change Research Strategy 2018 – 2022* and was funded by the *NSW Climate Change Fund*. The project was instigated by the NSW *Department of Primary Industries* (NSW DPI) as part of the *Biomass for Bioenergy* project, which aims to explore options to increase the bioenergy share for energy generation in NSW. Against this background, this thesis aims not only to increase the technical and techno-economic understanding of HCSB plants, but also to examine benefits and advantages in the specific context of energy generation in NSW. Figure 4 shows a map of Australia and NSW. NSW is the south-eastern state of Australia (Figure 4b) with an area of over 801,000 km^2 and more than 8 million inhabitants [17]. The majority of NSW's population lives in the eastern coastal areas of the state including in the larger cities of Sydney and Newcastle, while the Western parts of the state are sparsely populated. This is illustrated in Figure 4b, which maps the *Australian Bureau of Statistics* (ABS) statistical area 4 (SA4) [18] regions in NSW, reflecting the population densities and labour markets[12] of NSW. In the context of NSW's energy transition, the NSW Government has formulated key objectives [19] that promote renewable, secure, safe and economical supply of energy to NSW's population and industries during and after the energy transition. Within the framework of this thesis, these objectives are taken into account to evaluate and discuss the deployment potential of HCSB plants in NSW.

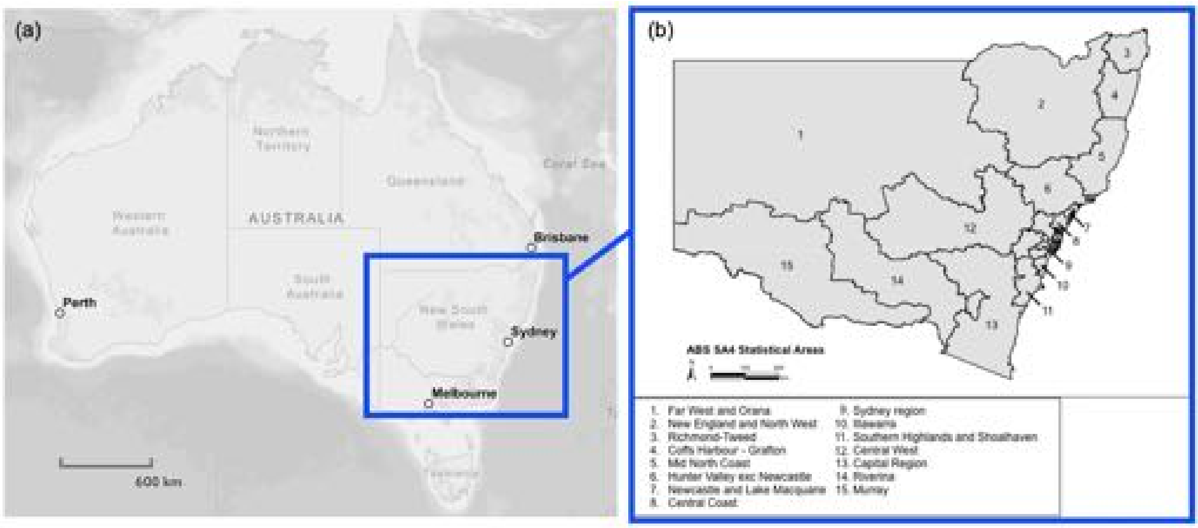

Figure 4: Maps of (a) the Australian continent, showing state boundaries (Source: *Australian Bureau of Statistics* (ABS) [17]) and (b) New South Wales (NSW) showing ABS Statistical Areas (SA) 4 regions.

The following sections provide an overview of the current success of the energy transition in NSW. There is not just one energy transition in NSW, but several for the different sectors, of transport,

[12] Statistical area 4 (SA4) regions are roughly equivalent to the suburb scale, consisting of populations between 300,000 - 500,000 people.

residential, commercial, industrial, and electricity generation. For the transport, residential, commercial and industrial (including agriculture, mining, manufacturing, construction, and waste and water) sectors also an energy transition of different energy vectors (electricity, heat and fuels) is needed. These sectors are shown in Figure 5[13]. NSW is Australia's most populous state and accounts for around 27% of the total energy consumption of the continent. At 47%, NSW's transport sector has the largest energy demand[14] followed by the industrial, residential and commercial sectors with around 32%, 11%, and 9% respectively. The different energy vectors are shown in Figure 6. While the transport sector mainly depends on fuels, the other three sectors demand a mix of electricity, heat and fuels.

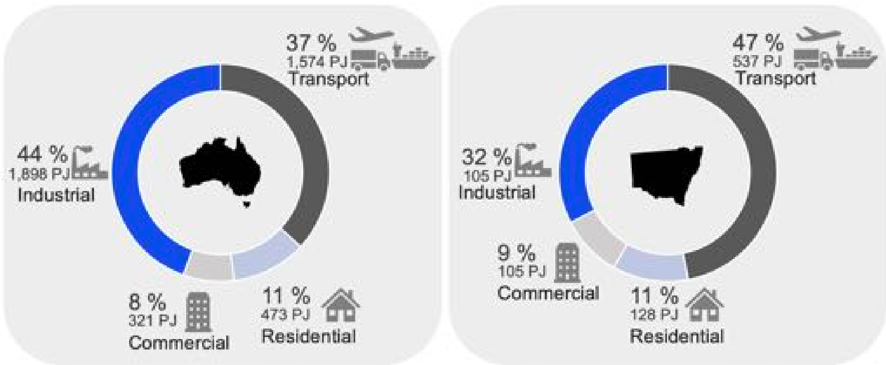

Figure 5: Energy consumption [PJ] by sector for Australia (left) [20] and New South Wales (NSW) (right) [21]. Figures do not consider energy conversion losses. Energy consumption for electricity generation is not included.

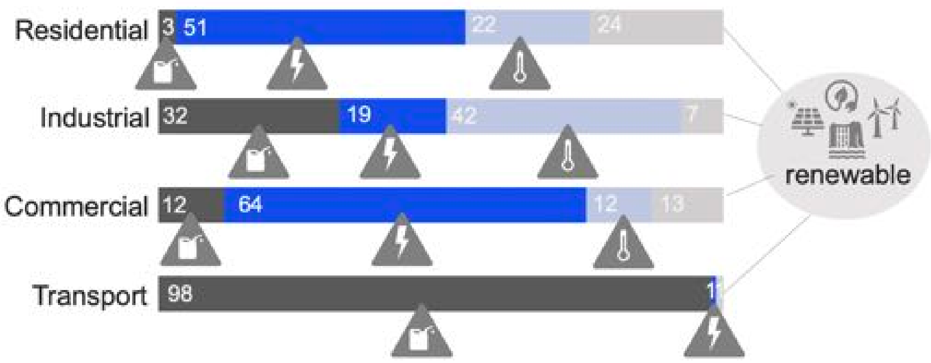

Figure 6: Energy type [%] consumption by sector in New South Wales (NSW) [21]. Figures do not consider energy conversion losses. Energy consumption for electricity generation is not included. Figures do not consider power plant heat and network and refinery losses from the transmission of electricity.

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[13] The Australian energy statistics are usually published in September of each year, and for this thesis the latest energy update that can be cited is for the year 2021 [20]. The report contains data for Australian energy consumption, production and trade from the financial year 2019/20, and for Australian electricity generation from the calendar year 2020. The energy statistics for New South Wales (NSW), which are published independently from the national report are summarized for the years 2018 – 2020.

[14] New South Wales (NSW) has large ports and is due to its geographical position between other Australian states of Queensland, South Australia (SA) and Victoria (VIC) in a prime trading and distribution position. This explains the high demand (compared to other Australian states) of refined products such as diesel and petrol which accounts for over 97% of the required energy in the transport sector.

In NSW, the total RE share[15] across the four sectors (not including electricity generation) is around 7% [21]. Figure 6 shows that the different sectors already deploy different amounts of RE: As of 2020, the transport, commercial, industrial, and residential sectors use 5, 13, 28, and 30 PJ of RE respectively. Industrial, commercial, transport, and residential sectors are facing unique challenges and developing independent approaches to transition.

The energy transition in the commercial and residential sectors are aiming to transform the type of energy that is required from fuel and thermal energy to electricity (electrification[16]). In this way, the energy demand can be supplied by rooftop solar photovoltaic (PV) or renewable grid electricity. Another action is the increase in energy efficiency[17] and thus a reduction in energy demand (which is e.g., supported by energy efficiency rating systems and standards for electric devices and houses [22].

The industrial sector is facing the challenge of renewable heat supply. Industrial heat demand often cannot be accounted for by electric devices and thus electrification is not always a solution [23]. The thermal energy demand of different industries is diverse. Some industries, like food processing and paper production, have a low-to-medium heat demand (40 – 250 °C), while other industries like steel and iron production have a demand for high temperature heat (> 800 °C) which is difficult to account for with existing common thermal renewable technologies [23]. Another harder-to-abate sector is heavy road fleet transportation, shipping and aviation [24] that could potentially be addressed with the development of hydrogen based transport systems [25]. For passenger vehicles the transition will likely be achieved with the deployment of electric vehicles [25].

Alongside the energy transition for the industrial, commercial, residential and transport sectors, the electricity sector is transitioning towards RE supply. About 37% of greenhouse gas emissions in NSW (and thereby an important target for a successful energy transition) is owing to large fossil fuel (gas and coal) electricity power stations. In 2021, the total electricity demand in NSW was around 68,000 GWh [26], of which about 21% was sourced from renewable sources. Figure 7 shows the share of different RE technologies for electricity generation. Solar PV and wind power plants are the largest renewable contributors to renewable electricity generation in NSW. Bioenergy generation accounts for 1,104 GWh of electricity generated from bagasse (sugar cane waste), landfill and other bioenergy

[15] Renewable energy (RE) figures quoted include biomass (including biofuels), solar and hydroelectricity.
[16] Electrification describes the process of exchanging non-electric technologies with electric technologies, an example is the transition from cars with internal combustion engine to electric cars and the use of solar hot water or heat pumps instead of domestic heating systems based on natural gas or oil.
[17] Energy efficiency is an important current trend. In the past 10 years, New South Wales (NSW)'s population and the gross state production grew 14% and 25% respectively [179], while the energy intensity per million Dollar and per capita decreased around 22%. This underlines that incentives to reduce the energy intensity and increase the energy efficiency is showing effect.

sources. Compared to the solar PV and wind power capacity, which increased drastically in the past five years, the bioenergy share has remained nearly unchanged.

A significant challenge in the increasingly renewable electricity grid is the balancing of electricity supply [19]. Traditionally, the energy supply in the electricity grid was easy to control because coal power stations provided a base load, while fast responding gas power stations and hydro dams produced additional electricity during peak hours (Figure 8). Today, solar PV and wind power stations (currently the cheapest electricity generators [27]) produce variable RE which is depending on the abundance of its supplying resources. This is leading to a supply problem in times without sun and wind, and the Australian Government is now supporting the deployment of RE technologies which are able to provide grid stability, system integration and flexibility [28]. Thus, the future electricity supply system will be formed by a mix of variable and dispatchable RE generation (Figure 8).

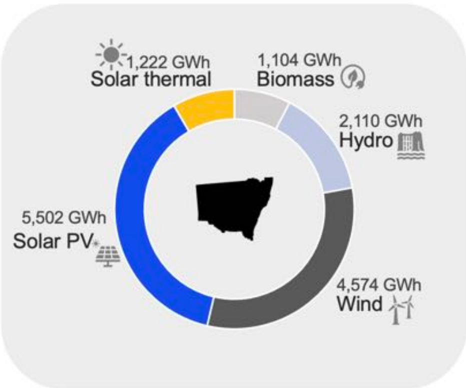


Figure 7: Renewable energy (RE) generation [GWh] by technology type in New South Wales (NSW) [29]. Figures do not consider power plant heat and network losses from the transmission of electricity.

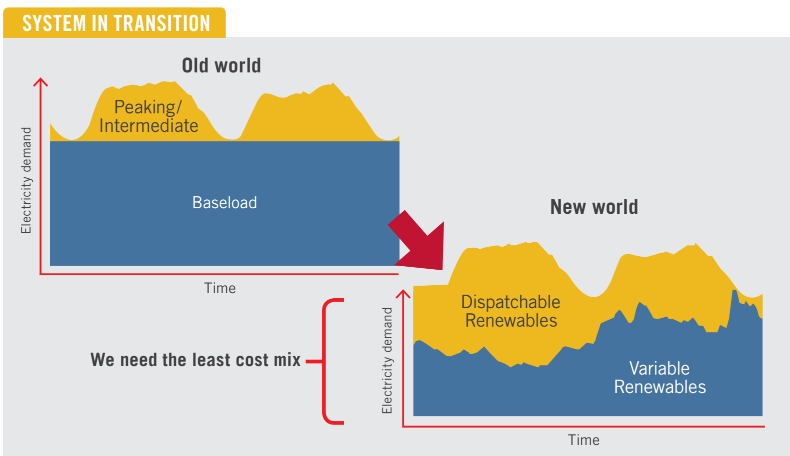


Figure 8: Energy transition of the electricity grid from fossil fuel to renewable supply. Source: Lovegrove et al. [30].

To sum up, the energy transition in NSW is underway, but still far removed from its goals of achieving 100% RE supply by 2050. Three significant current challenges are: i) the provision of thermal energy to industries with high heat demand, ii) the provision of dispatchable RE for continuous electricity supply in the grid, and iii) the energy transition of the transport sector. As part of this thesis the role of HCSB plants are evaluated to address the first two challenges for the energy transition in NSW.

1.3. Advantages of hybrid concentrated solar biomass (HCSB) plants

HCSB plants are 'direct' hybrid systems, in which the two supplying RE sources are:

- bioenergy (a range of biological materials, incl. waste, residues and forestry products, can be used in several technologies for the generation of electricity, thermal energy and biofuels, shown in Figure 9a), and
- CST (in this technology mirrors are used to concentrated solar irradiation onto a central receiver; absorbing the thermal energy it can be used for power generation in a steam cycle, shown in Figure 9b).

These two sources are combined for energy generation in the same system. The concept of direct hybridization is distinct from 'indirect' hybrid systems, in which two or more RE technologies are deployed at the same site (and use e.g. the same grid access) are however producing energy independently. All HCSB systems investigated in this thesis have at least one integrated solar thermal and bioenergy unit that are combined for energy generation, as shown in Figure 10. The primary energy product in HCSB plants is thermal energy that can be supplied as heat or can be transferred to a secondary energy products (e.g. electricity).

Figure 9: *Termosolar Borges* plant in Lleida, Spain: (a) bioenergy system and steam cycle, and (b) parabolic trough collector field. Source: *Power Technology* [31], and Crespo [32].

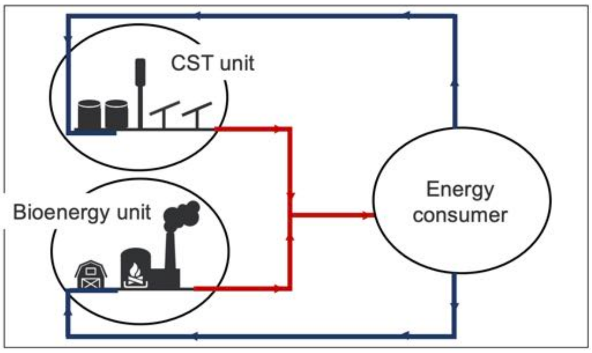


Figure 10: Schematic concept of hybrid concentrated solar biomass (HCSB) plant with concentrated solar thermal (CST) and bioenergy unit.

A key driver for the development and investigation of HCSB systems (beside their technical compatibility) is the striking spatial overlay of their two supplying resources – biomass and solar. Since biomass growth and thus the availability of biomass residues is heavily dependent on solar resources, it is not surprising that many areas of the world feature both: good biomass and solar resources. Figure 11 shows global areas with high solar resources (> 1,800 kWh/m^2/year) suitable for the deployment of hybridised concentrated solar power (CSP) plants [15]. Areas which are especially interesting for the deployment of HCSB plants are: Southern Europe, large parts of the United States of America and central America, central South America, the north-east of Brazil, eastern parts of China, India and central Asia, the Middle east, regions in central and South Africa, also the east coast of Australia.

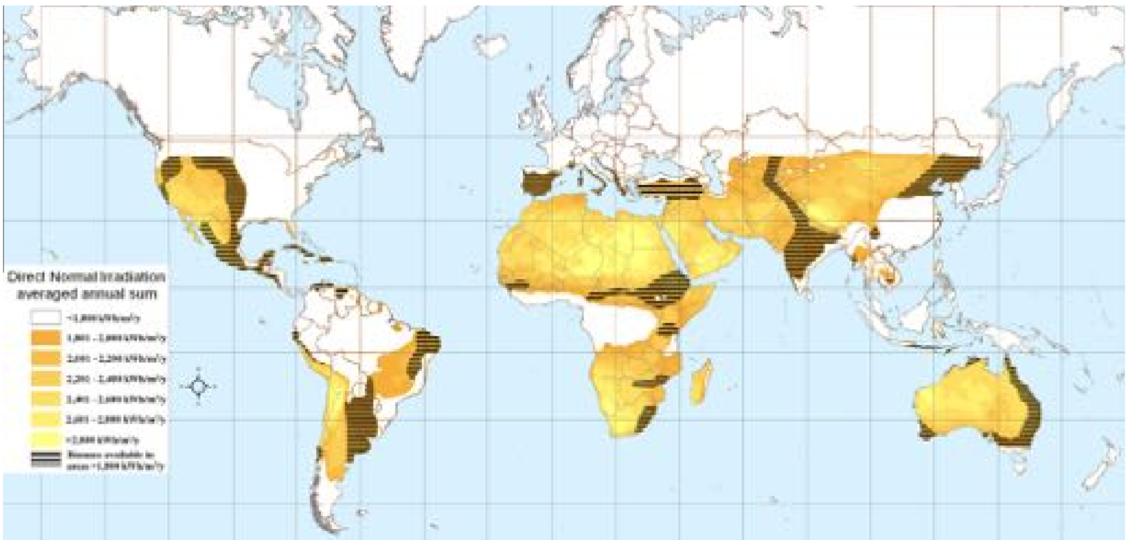
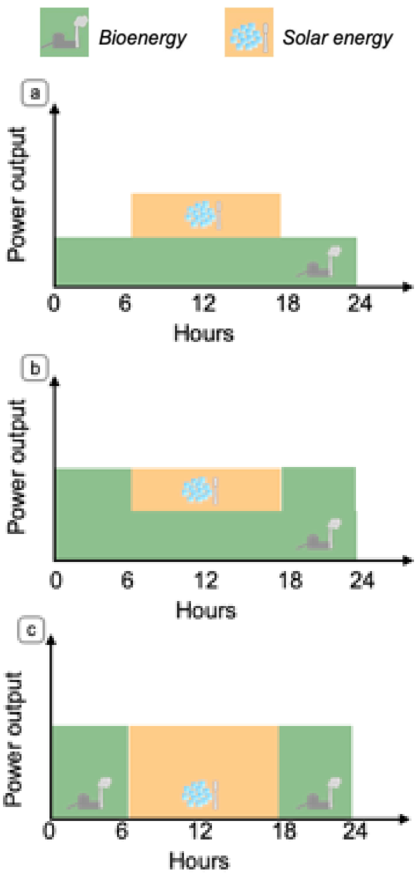


Figure 11: Potential regions for hybrid concentrated solar biomass (HCSB) plant deployment potential worldwide. Source: Peterseim et al. [15].

The hybridisation of solar thermal and bioenergy has several advantages compared to standalone systems. These advantages have been described in the context of existing HCSB plants and numerous academic and industrial research projects (e.g. [15], [33]) and can be summarised as follows:

(i) The opportunity to offset or boost energy generation from combustion technologies with CST and vice versa, offers increased flexibility in response to periods of diminished resources availability when reliant on single feedstocks or resources. As such solar thermal integration offers a solution to extended periods of biomass shortage, while still maintaining part of the energy production. Periods with biomass shortage [34] are not uncommon as biomass availability underlays inter- and intra- annual variations [35] (e.g. designated harvest periods of agricultural residues), which can be a risk to a bioenergy facility that depends on continuous resources supply. Similarly, the solar resources availability is characterised by strong variations (e.g. day-night cycles and passing clouds) and in HCSB plants these gaps in resources supply can be managed with bioenergy.

(ii) Freely available solar energy can substitute or supplement the use of biomass resources and thereby reduce raw material costs [36], [37]. The solar thermal unit in HCSB systems uses freely available solar resources for energy generation during the day, while the bioenergy unit uses biomass feedstock around the clock or in times of solar resource intermittencies (e.g. day-night cycles and changing weather conditions) [38]–[40]. The reduced biomass demand depends on the chosen operational modes for HCSB plants, which are compared in Figure 12. In particular, the 'fuel saving operation' (Figure 12b), and the 'complementary operation' (Figure 12c) reduce biomass feedstock demand compared to standalone bioenergy systems. Another option is the 'solar boost operation' (Figure 12a) which does not reduce the used amount of biomass feedstock but can increase the overall energy generation potential of the power station.



Solar boost operation: The HCSB plant reaches the steam turbine full-load capacity during the day, when solar thermal and bioenergy unit are generating steam together. During hours with insufficient solar resources (e.g. night) the bioenergy unit is generating steam alone and the steam turbine operates at half load (investigated by Peterseim et al. [33]).

☑ Increased power generation
☒ Oversized steam turbine

Fuel-saving operation: During the night, the bioenergy unit is designed to produce steam at full-load capacity of the steam turbine. During the day, steam generation from the bioenergy unit is ramped down, because the solar unit can account for part of the steam generation (investigated by Peterseim et al. [41]).

☑ Economic use of steam turbine
☒ Comparably smaller solar share

Complementary operation: The bioenergy and solar thermal unit can produce steam with the same steam parameters. The solar thermal unit is used for energy generation during the day, while the bioenergy unit is used in the other times (investigated by Wang et al. [42]).

☑ Independence of both energy generation units
☒ Inefficient biomass use for regular ramping periods

Figure 12: Operational strategies of hybrid concentrated solar biomass (HCSB) systems.

(iii) Solar energy can substitute or supplement the use of biomass resources and thereby reduce transport emissions [36]. During sustainable bioenergy generation, the emissions from biomass combustion are reintegrated during the next growth period, as illustrated in Figure 13. Emissions from biomass harvest, transport and processing (e.g. compressing, bailing, pelletising and briquetting) are additional and without compensation. Because of this, these additional emissions should be kept to a minimum by considering short transport distances and local bioenergy use. With the reduction of biomass feedstock use, HCSB plants produce lower overall carbon emissions (as tonnes carbon emissions (CO_2-e) per megawatt hour (MWh)).

(iv) Compared to standalone CSP plants which often use fossil fuels (like natural gas) as backup systems [43], an integrated bioenergy system can achieve near 100% renewable energy generation [10].

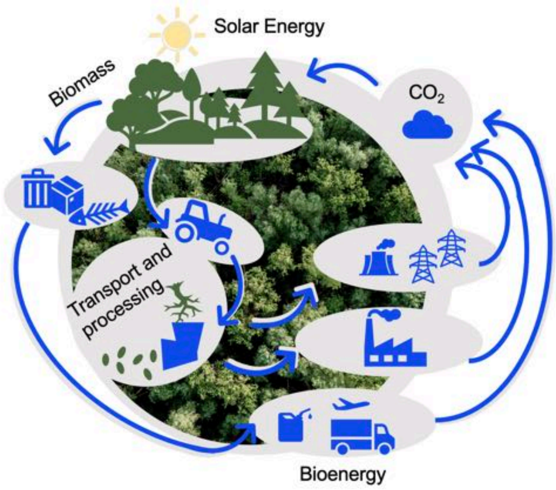


Figure 13: Cycle of sustainable bioenergy production.

This brief elaboration of advantages provides a clear basis for evaluating the hybrid technology in the context of energy generation. Throughout this thesis, these general benefits of the HCSB technology will be further described and expanded upon for the specific context of the energy transition in NSW.

2. Literature review: Design options and techno-commercial maturity of hybrid concentrated solar biomass (HCSB) systems

The content of this chapter was presented at the *Bioenergy STRONG Research Summit 2019* in Brisbane, Australia and with the reference:

Middelhoff, E., Florin, N., 2019, Technical option evaluation of hybrid solar biomass plants, *Bioenergy STRONG Research Summit 2019*, November 12th 2019, Brisbane, Australia, weblink: https://www.bioenergyaustralia.org.au/bioenergy-events/2019-strong-conference/.

Chapter summary: This chapter reviews technical design options of HCSB plants and rates their technical and commercial maturity. In HCSB plants, solar thermal systems (generating heat at temperature of up to 2,000 °C) are combined with combustion technologies of biomass, biofuels and waste materials for combined heat, fuel, and electricity generation[18]. Technical design options for HCSB systems are diverse, which can be explained by the fact that both bioenergy as well as CST systems are among the most varied RE generation technologies.

The maturity of these different HCSB systems is rated using the framework of technical readiness level (TRL) and commercial readiness index (CRI) to determine those that are best suited for deployment in NSW, answering the research questions:

- What are the different technical HCSB design options and what type of energy can be produced – electricity, fuel, or heat/cogeneration? (categorisation by energy product)
- What are the energy generation technologies commonly used by HCSB systems? (categorisation by energy technology)
- What is the technical and commercial maturity level of the different HCSB design options?
- Which HCSB design options qualify for commercial deployment in NSW/Australia (in the near future)?

As a first step, this literature review describes the development and commercial use of different stand-alone bioenergy and solar thermal systems, to than categorise different HCSB systems. Stand-alone bioenergy and solar thermal systems as well as HCSB systems are categorised by type of energy product (electricity, fuel, heat/cogeneration) and by energy generation technology[19]. As a second step, the technical and commercial maturity of the various systems is evaluated using the '*commercial readiness index for renewable energy sectors*' of the *Australian Renewable Energy Agency* (ARENA) [44].

[18] According to the physical law of *energy conversion*, the term 'energy generation' is imprecise. In the context of this chapter, the term describes the generation of an economic asset (e.g. electricity or heat) and not the actual physical generation of energy.
[19] Approach following Nathan et al. [38].

The chapter finds that HCSB systems for biofuel production are immature, but that there are three mature HCSB systems for electricity, heat or cogeneration (as shown in Table 1):

Table 1: Overview of three mature hybrid concentrated solar biomass (HCSB) systems: Energy generation type, bioenergy and concentrated solar collector types, example for existing plants, scale of operation [MW_e], as well as technical readiness level (TRL) and commercial readiness index (CRI).

HCSB system	Energy type	Biomass feedstock type	Concentrated solar collector	Existing plants	Scale of operation [MW_e]	TRL	CRI
Rankine cycle system	Electricity, cogeneration	Solid biomass, (biogas)	Parabolic trough, Linear Fresnel, Solar Tower	Termosolar Borges plant in Lleida, Spain [10]	~ 5 – 50	9	3
Organic Rankine cycle system	Cogeneration, (electricity)	Solid biomass, (biogas)	Parabolic trough, Linear Fresnel, (Solar Tower)	Aalborg CSP plant in Brønderslev, Denmark [45]	< 10	9	3
Micro-gas turbine	Electricity	Biogas	Solar Tower	AORA Solar tulip system, Israel [46]	< 1	9	1 – 2

The list of technically and commercially mature HCSB plants (Table 1) was used to select HCSB systems in the context of different case studies selected in the wider research project: RC HCSB plants were evaluated as grid connected electricity generator in the context of research chapter III (section 4.3., p. 63) and ORC HCSB plants were further evaluated in the context of industrial cogeneration in research chapter IV (section 4.4., p. 67) of this thesis.

2.1. Literature review introduction

During the past three decades, the idea of hybridising CST and bioenergy has received increasing academic and industrial attention. An important driver is their technical compatibility. Different to the indirect hybridisation of e.g. solar PV and bioenergy, which share the same location, infrastructure and e.g. grid connection, HCSB systems are directly integrated RE technologies [38]. HCSB plants refer to a broad class of solar thermal and bioenergy technologies that can be combined in different ways depending on a range of factors including resource availability and energy demand. There are various HCSB design options in which a CST unit is integrated i) to support biofuel generation, ii) to preheat or iii) to work in parallel with combustion technologies [13]. This review attempts to categorise the different technology design options according to technical and commercial maturity.

Earlier studies with a similar scope are compared in Table 2. While some of the previous reviews focussed solar thermal integration into bioenergy plants (e.g. [38], [47]), others focussed on solar thermal integration into fossil and other renewable technologies (e.g., [48]–[50]). Furthermore, previous reviews use different categorisation systems to group HCSB design options and some studies categorise HCSB systems according to the degree of energy generation synergy [49], while others group systems according to their CO_2-e abatement potential [48], [50]. The different earlier studies also chose different ways to evaluate HSCB options. Some studies focussed on the economic feasibility [13], [48], while others concentrate on the energy efficiency of different systems [49]. This review extends the former studies by assessing the maturity of HCSB plants. This review explicitly assesses the technical and commercial readiness of the various HCSB systems through a quantitative approach using a numbering system, with emphasis on the Australian context. By focussing on the technical and commercial maturity this study can be used to identify HCSB systems ready for immediate deployment without awaiting further research and development. Further, HCSB design options are categorised by energy output to understand applicability for integration with electricity generation and industrial systems.

Table 2: Overview of hybrid concentrated solar biomass (HCSB) plant reviews in the literature.

Hybrid concepts	Categorisation system	Energy efficiency	Maturity	Economic efficiency	References
CSP with coal, natural gas, biomass, wind and geothermal	Based on CO_2 [kg/MWh] emissions, grouping into high, medium and low-renewable hybrid	Considering peak net efficiency [%]	Description of the current state-of-art	Considering specific investment [m$/MW$_e$]	Pramanik & Ravikrishna, 2017 [48]
CSP with coal, natural gas, biofuels, geothermal, photovoltaic (PV) and wind	Based on type and level of synergy considering hybrid energy source, location, CSP technology and plant configuration	Considering peak net efficiency [%], also considering temperature and pressure in detail	Not considered	Not considered	Powell et al., 2017 [49]
CSP with different fuels (natural gas, coal, fuel oil, wheat straw, wood pellets and biogas)	Six Life Cycle Assessment including [CO_2/MWh] scenarios based on different fuel type	Not considered	Not considered	Energy payback time	Corona & Miguel, 2015 [50]
CSP with coal, natural gas, biomass and waste materials	Categorisation into light, medium and strong hybrids	Net cycle efficiency [%]	Considering operating plants	Considering specific investment [m$/MW$_e$]	Peterseim et al. 2014 [13]
CSP with biomass		Net cycle efficiency [%]	Not considered	Lowest specific investment [$/MW$_e$]	Peterseim et al. 2014 [33]
CSP and PV with biomass	Biomass gasification and combustion with different CSP options and PV	Peak energy conversion efficiency [%]	Description of technical challenges	Unspecific, describing investment into existing plants	Hussain, Norton & Duffy, 2015 [47]
CST with combustion technologies	By energy generation pathway: in Rankine cycle, via fuel or oxidant, in Brayton cycle and via chemical looping combustion	Net peak efficiency [%]	Considering development challenges	Not considered	Nathan et al., 2018 [38]

2.2. Technical and commercial readiness indicator

TRL were first defined by the *National Aeronautics and Space Administration* (NASA) [51] and have become a common tool in evaluating the status of technology development. The TRL range from 1 – 9, where technological concepts at TRL 1 – 3 exist as hypothetical idea, while concepts at TRL 3 – 6 are in the phase of research and development towards first non-commercial pilot plants. Technologies at TRL 6 – 9 are in the phase of final demonstration at industrially relevant scales towards commercial deployment. For the Australian context, ARENA adopted and extended the original concept of TRL with the '*commercial readiness index for renewable energy sectors*' [44]. This new framework provides a tool that quantitatively describes the CRI of RE technologies. Figure 14a shows how the CRI are aligned with TRL. CRI range from 1 – 6, where CRI 1 represents a pre-commercial concept. CRI 2 is a small-scale commercial pilot plant, while CRI 3 is used for commercial scale-ups. Technologies which are deployed commercially are classified within CRI 4 – 6.

In this literature review ARENA's TRL and CRI frameworks are used to classify the different HCSB systems, as well as standalone bioenergy and CST technologies. TRL and CRI were determined based on literature review and validated through targeted consultation with industry experts. A 'traffic light' key has been used to improve the visual communication as shown in Figure 14b. Technologies in green for technical and commercial levels are assumed to be ready for immediate deployment. As a first step the review chapter describes the development and commercial use of different standalone bioenergy and CST systems. The chapter then discusses the possibilities to integrate both technologies into hybrid systems to rate their maturity.

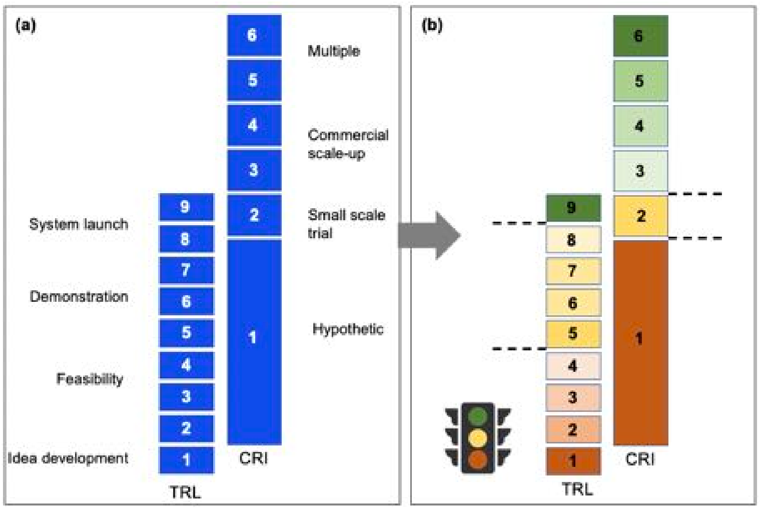


Figure 14: Technical Readiness Level (TRL) and Commercial Readiness Index (CRI). Adapted from the *Australian Renewable Energy Agency* (ARENA) [44].

2.3. (Standalone) bioenergy technologies

Biomass was not only the first type of energy resource used by human societies, bioenergy is also still the most commonly deployed RE type in third world countries today, where it is often used for cooking and space heating [52]. Broadly, the term 'biomass' refers to organic matter resources, for example short rotation crops, wood residues, other by-products from industries for example agricultural and waste residues from human activities. An overview of the most common biomass to bioenergy conversion processes is provided by Thrän et al. [53] and shown in Figure 15a. Three types of bioenergy can be differentiated: solid, gaseous and liquid biofuels. Each of the three bioenergy types can be produced through various pathways, including thermo-chemical (e.g. pyrolysis, and gasification), and bio-chemical (e.g. fermentation) methods. When biofuels are combusted they generate thermal energy.

Several thermal-to-power conversion pathways can use the thermal energy to generate electricity, including RC and ORC systems, gas and micro-gas turbines, gas engines and fuel cells.

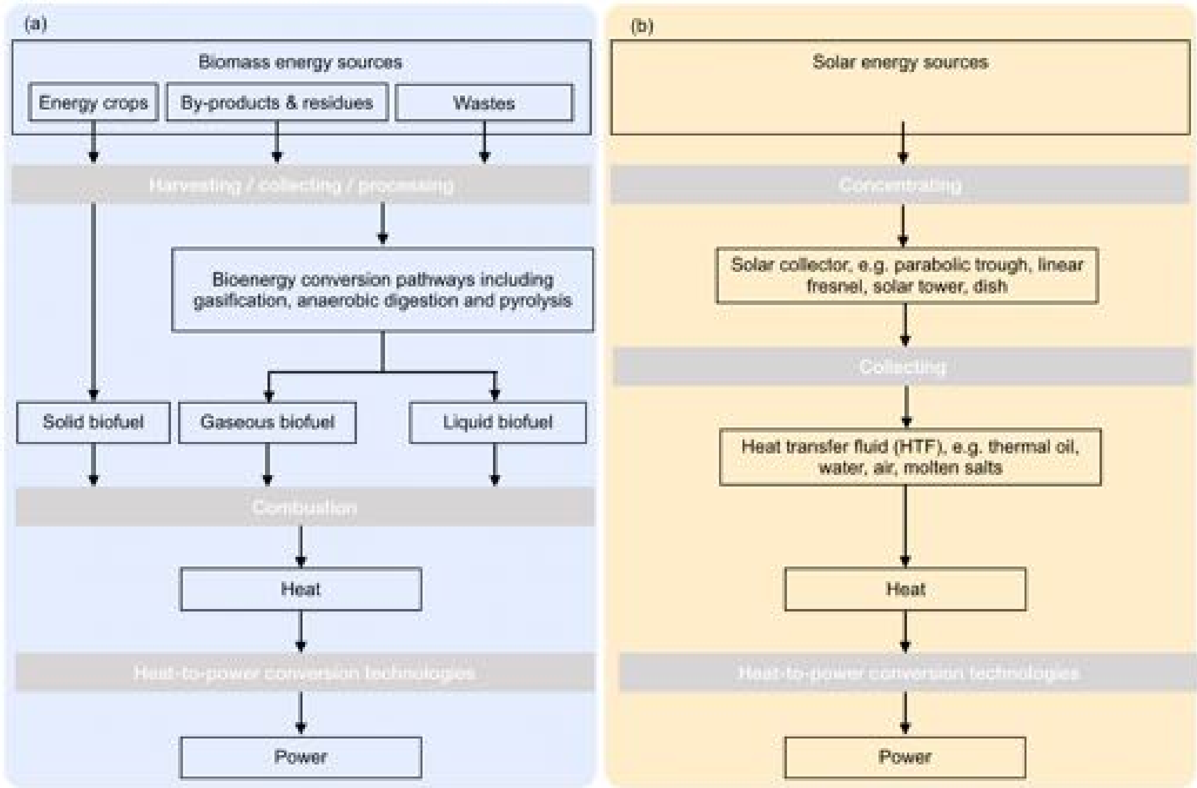


Figure 15: Energy conversion of (a) biomass and (b) solar resources.

The following sections will first describe the gaseous and liquid biofuel production as standalone and solar thermal integrated systems and will than review the different power generation technologies.

2.3.1. Gaseous and liquid biofuel generation: Technical and commercial maturity

This section of the literature review will focus on three gaseous and liquid biofuel production pathways: (i) anaerobic digestion (AD), (ii) gasification and (iii) pyrolysis. All three pathways will first be rated for their maturity as standalone system and then with solar integration.

(i) AD is the conversion of high-moisture (> 80%) biomass resources such as manure or organic waste, to a mixture of gaseous fuel (methane and CO_2 mix) during a multistage microbial process. Biogas from AD can be used as combustion fuel for electricity and heat generation. The energy conversion efficiency ranges between 10 – 16% [54]. AD is a mature process and one of the most common bioenergy technologies in Australia with high rankings in TRL and CRI as shown in Table 3.

(ii) During gasification biomass is partially oxidated at temperature between 800 – 900 °C and thereby converted into combustible gas, the so called syngas that is a mixture of H_2, CO, CH_3 and CO_3 [54].

Gasification derived syngas can be upgraded using the water shift reaction into pure hydrogen (steam gasification). While coal-gasification started in the 1970-80s and is a mature concept [55], biomass gasification is less mature. Small to medium-sized biomass gasifiers at the scale of 0.02 – 20 MW_{th}, are commonly deployed in many countries (especially in Germany, Japan and the United Kingdom) [55]. Larger systems at industrial scale, however, are still rare and technical and economic risks limit their deployment [55]. In Australia, there are a few pilot gasification plants [56]. These plants receive funding and their CRI is therefore low (Table 3).

(iii) Pyrolysis is the conversion of biomass to solid, liquid and gaseous fractions by heating the biomass in the absence of oxygen to 500 °C [54]. Products of pyrolysis are fuel gas, bio-oil and charcoal which can be used for electricity generation in different conversion processes. Similar to gasification, there are several plants in Australia, they all however received external funding and the technology therefore has a low CRI (Table 3).

2.3.2. Solar thermal integrated biofuel production: Technical and commercial maturity

(i) The integration of solar thermal into AD can increase temperatures to 35 – 65 °C [57], promoting microbial activities. Even though increased biogas production can be easily achieved in solar heated AD systems this hybridisation technology is not yet commercially available (Table 3).

(ii) In solar-aided gasifiers, solar thermal energy can account for the required gasification temperature of up to 800 – 1,300 °C. A research pilot plant is testing a 150 kW_e *SolSyn* reactor at the *Plataforma Solar de Almeria* in Spain [58].

(iii) Similar to solar-aided gasification, solar thermal energy can be used to account for the required thermal energy for pyrolysis processes with temperatures of up to 290 – 500 °C. The concepts for solar-aided pyrolysis are at their very early stages (Table 3).

Table 3: Technical and commercial readiness of biofuel production pathways.

	Technical readiness level	**Commercial readiness index**
Conventional technologies		
Anaerobic digestion	9 [59]	6 [59]
Gasification	5 - 9 [55], [59]	2 – 3 [59]
Pyrolysis	5 - 9 [59]	2 – 3 [59]
Solar thermal integration		
Anaerobic digestion	4 [60]	1 [60]
Gasification	5 [58]	1 [58]
Pyrolysis	2 [61]	1 [61]

2.3.3. Bioenergy for electricity generation: Technical and commercial maturity

During combustion the stored chemical energy in biomass resources is converted into thermal energy, which produces hot gases at 800 – 1,000 °C [54]. The generated thermal energy from combustion processes can directly be used (e.g. for industrial processes) or can be used in a number of thermal-to-electric energy conversion technologies, as shown in Figure 16. The different bio-electricity technologies are shown in Figure 16 and are rated for their technical and commercial maturity below. If solid biomass feedstocks are combusted, there are various combustion systems that can be distinguished such as pile, grate and fluidised-bed combustion systems [62]. For direct combustion, solid biomass resources preferably have a low moisture content (< 50%) and pre-drying is a common practice [62].

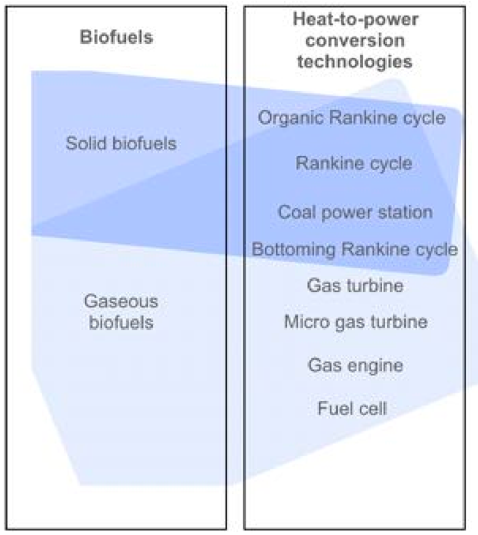


Figure 16: Most common bioenergy conversion pathways and their thermal electricity generation options.

(i) RC systems can be operated with direct biomass combustion and with biofuels (Figure 16). Biomass aided RC plants can reach net conversion efficiencies between 20 – 40%, depending on the working temperature and scale of plant operation [19] and are a mature technology (Table 4). Due to limited local biomass resources availability, standalone biomass combustion plants usually operate at a scale of about 10 – 100 MW_e [19]. Over 56% of all bioenergy in Australia use RC systems [34]. The Australian *NationalMap* [56][20] has recorded over 161 bioenergy projects on the Australian continent. Their geographical locations are shown in Figure 17. As of 2018, over 90% of all bioenergy projects in Australia were producing electricity, most of them using RC systems. For example, there are a number of large bagasse combustion plants in Queensland, such as the 50 MW_e *Invica plant* that combusts over 800,000 tonnes of bagasse per year (Figure 17).

[20] Formerly the *Australian Renewable Energy Mapping Infrastructure* (AREMI) data base [180].

(ii) Similar to RC systems are ORC systems. While RC plants are larger and operate at higher temperatures, ORC are often deployed for small-scale cogeneration, e.g. in the context of industries or commercial buildings. ORC systems are generally mature, however less often deployed than RC systems (Table 4).

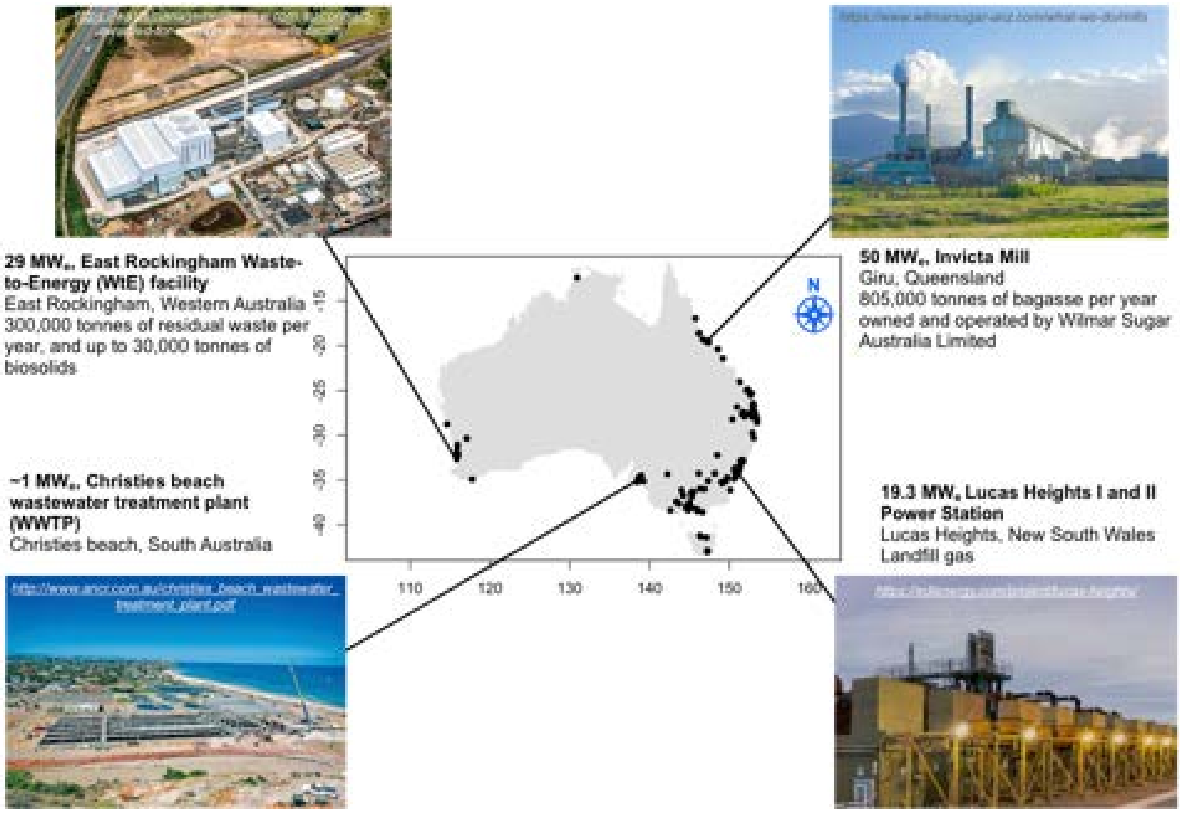


Figure 17: Locations of bioenergy projects (black dots) on the Australian continent, as well as four project examples.

(iii) Biofuels can be integrated into coal power stations (Figure 16). During biomass co-firing the feedstock is directly fed into the coal boiler or burned in a secondary boiler [63]. Coal power stations work on a nameplate capacity of up to 2,000 MW_e and the bioenergy share can reach between 1 – 5% [63]. Biomass co-firing is a mature concept (Table 4) and was also conducted in several coal combustion plants in Australia [54], such as *Wallerawang*, *Mount piper* [64] and *Vales Point* [65].

(iv) Biofuels can be integrated into bottoming RC systems, e.g. of combined cycle gas turbines (CCGT) (Figure 16). Whilst such systems have been described, to the author's knowledge no such plant is currently operating [66].

(v) Gaseous biofuels can be used in gas turbines. For example, biomass integrated gasification combined cycle processes involve the gasification of biomass and the following combustion of the generated syngas in a gas turbine [67], [68]. Biogas fuelled gas turbines have been tested at scales between 5 – 20 MW_e and operating temperatures between 800 – 1,000 °C, however, overall, the technology lacks technical and commercial maturity [67] (Table 4).

(vi) Biogas fuelled gas engines are common. In Australia, the technology is used in several landfill and waste water treatment plants [69]. Approximately 20% of all bioenergy plants in Australia use this technology [69].

(vii) Gaseous biofuels can be used in micro-gas turbines. This use of biogas is expensive and not common; however biogas fired micro gas turbines with output between 30 – 75 kW_e are employed in some countries of the world, mainly in the USA [59] (Table 4).

(viii) Fuel cells can extract energy from the chemical energy stored in fuels like methanol, and hydrogen. Biomass based fuel cells are still at a stage of research and development and are not commercially deployed [70].

Table 4: Technical and commercial readiness of bioenergy generation through direct combustion, mainly from CSIRO [59].

	Technical readiness level	**Commercial readiness index**
Rankine cycle	9 [59]	6 [59]
Coal power station	9 [59]	6 [59]
Bottoming Rankine cycle of combined cycle gas turbines	5 [66]	1
Organic Rankine cycle	9 [59]	6 [59]
Gas turbine	9 [59]	2
Biomass integrated gasification/combined cycle	7 [67]	1
Micro-gas turbine	9 [59]	3 [59]
Gas engine	9 [59]	6 [59]
Fuel cell	4 – 5 [70]	1 [70]

2.4. Concentrated solar power (CSP) generation

Figure 15b shows the energy generation pathway from solar resources. Solar energy is concentrated and collected through solar thermal collector technologies, in which the thermal energy is transferred to a heat transfer fluid (HTF). Each of the different solar collector types uses different HTFs. Linear focussing parabolic trough solar collectors are shown in Figure 18a and are usually deployed with the HTF thermal oil at temperatures < 400°C, but can also use molten salts [71], water and air [72], as shown in Table 5. Linear focussing fresnel collectors (Figure 18b) are usually deployed with water as HTF for direct saturated (sat.) and superheated (sup.) steam < 450°C generation. In some pilot plants, linear fresnel collector have also been deployed with molten salts and thermal oil as HTF (Table 5).

Solar tower collector are shown in Figure 19a. These collectors can reach temperatures > 500 °C, for which the HTFs water and molten salts are typical used. In the Australian context, the use of sodium as HFT has been researched by the Australian CSP developer *Vast Solar* [73]. Sodium offers the advantage that higher temperatures of up to 650 °C can be reached (compared to about 550 °C in regular molten salts plants).

(a) (b)

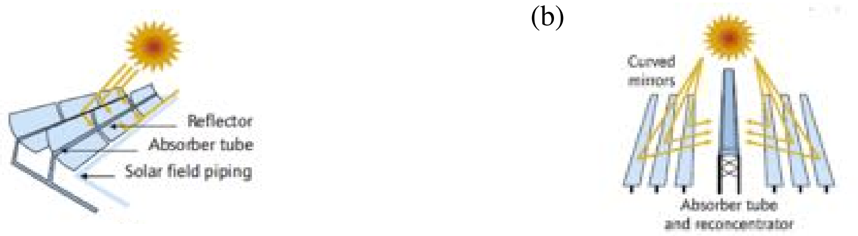


Figure 18: Linear focussing concentrated solar thermal (CST) technologies: (a) parabolic trough collector, (b) linear fresnel collector.

(a) (b)

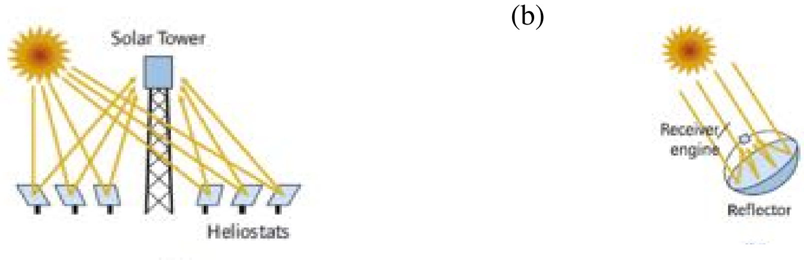


Figure 19: Point focussing concentrated solar thermal (CST) technologies: (a) solar tower with heliostat field, (b) parabolic dish collector.

Table 5: Concentrated solar thermal (CST) technologies with different heat transfer fluids (HTF): maximal temperature, global installed capacity, largest plant and number of plants in Australia.

	Maximal temperature [°C]	**Peak net efficiency [%]**	**Global installed capacity [MW_e]**	**Largest proposed and financed plant [MW_e]**	**Number of plants in Australia**
Parabolic trough collector					
Molten salts	530 [1], [74] – 550 [2], [75]	32.2 [13]	~150 [3]	64 [4]	0
Synthetic oil	393 [5], [77]	29.5 [13]	>5,000 [3]	250 [6] [7] [8]	0
Water - steam	400 [5], [77]	30.3 [13]	>10 [3]	5 [9]	0
Air	650 [10]	-	<5 [3]	3 [2]	0
Linear fresnel collector					
Molten salts	510 [11], [83]	-	50 [11]	50 [11]	0
Synthetic oil	393 [5], [77]	-	50 [12]	50 [12]	0
Water – steam	270 [13] – 450 [11]	32.5 [13]	~250 [3]	30 [13] – 125 [14]	2 [15] [16]
Solar Tower					
Molten salts	566 [17]	32.8 [13]	>2,500 [3]	450 [17]	1 [10]
Water – steam	566 [18]	33.0 [13]	>700 [3]	390 [18]	1 [19]
Air	680 [20]	-	<5 [20]	1.5 [20]	0

After the solar energy is concentrated and collected the generated heat can be used in a range of different heat-to-power conversion technologies, as shown in Figure 20. Because of the limited temperatures of the two linear focussing collectors (parabolic trough and linear fresnel) their integration is limited to ORC systems, renewable RC systems, coal power stations and bottoming RC (as described below). Solar tower systems can additionally be used for integration into gas and micro-gas turbines, while dish collectors are usually deployed with Stirling engines (Figure 20).

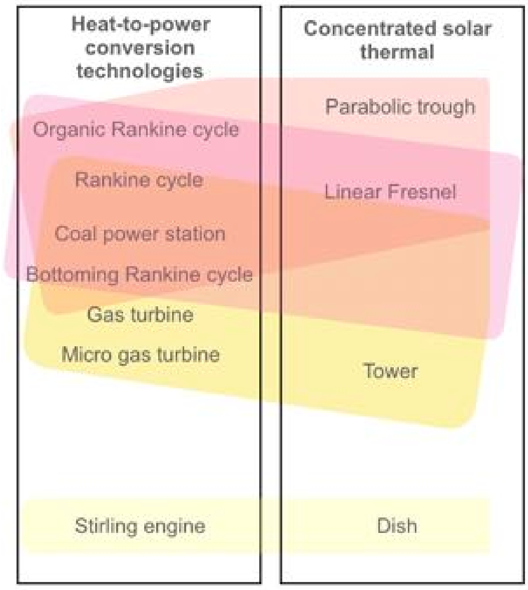


Figure 20: Concentrated solar thermal (CST) technologies and their electricity generation options.

2.4.1. CSP: Technical and commercial maturity

The technical and commercial readiness of the different CSP technologies is shown in Table 6. Each of the technologies is described in detail below.

(i) Most conventional CSP systems are solar thermal RC systems. These can operate as standalone (fully renewable) systems or can be hybridised with other technologies. In 2017, 5.1 GW_e of fully renewable CSP systems were installed globally [72], indicating a high technical and commercial deployment maturity (Table 6). In Australia, compared to the global context, CSP is currently underutilised. Lovegrove estimated that CSP systems could provide up to 15 GW_e of electricity [93], developed in off-grid as well as grid-connected locations and market segments. Even though the technology has a good siting potential, large-scale commercial projects never secured the required final investment (e.g. the 150 MW_e *Aurora project* in South Australia (SA) [94]). Australia has a substantial CSP research and development history, which led to a number of pilot systems. The largest successful system is the ~ 1 MW_e *Sundrop farms system* in SA, which has the ability to desalinate salt water and supply heat to a greenhouse (cogeneration) [91].

Table 6: Technical and commercial readiness of concentrated solar thermal (CST) systems.

	Technical readiness level	Commercial readiness index
Rankine cycle	9 [72]	6 [72]
Coal power station	9 [95]	4 [96]
Bottoming Rankine cycle of combined cycle gas turbines	9 [72]	6 [72]
Organic Rankine cycle	9 [97]	4 [97]
Gas turbine	3 [98]	1 [98]
Micro-gas turbine	9 [46]	3 [46]
Stirling engine	9 [59]	4 [59]

(ii) Solar thermal energy can be integrated into coal power stations. Solar thermal energy has been integrated into coal power stations as feedwater heater (e.g., at 270 °C and 55 bar [95]) or into the low-pressure turbine (e.g., at 370 °C and 60 bar [88]). In a conventional coal power station feedwater heating is facilitated through steam extraction in the expansion process from the turbine, which reduces the total amount of generated electricity. This can be avoided through the integration of solar thermal energy. In Australia, a solar thermal integration of 9.3 MW_{th} was chosen for the *Liddell* power station operating from 2012 to 2016 [87], [99]. Another solar thermal integration of 5 MW_e was proposed for the *Kogan Creek Solar Boost* power station in 2014, which was never commissioned [88]. Table 6 shows that the integration of CST at coal power stations has a good overall maturity.

(iii) Solar thermal energy can be integrated into the bottoming RC of CCGT. In these solar integrated combined cycle (ISCC) systems, hot steam exhaust from the gas turbine is enriched with solar thermal energy for additional power generation in a bottoming RC. Feed-in points into the bottoming RC are as feedwater heater or into the heat recovery steam generator (HRSG) [100]. Less common but potentially connected to higher plant efficiency would be the solar integration into high or low temperature turbine [101]. Existing ISCC plants are listed in Table 7, while Figure 21 (left) shows the 75 MW_e Martin Solar combined cycle plant in Florida, USA. Table 6 shows that the integration of CST into bottoming RC of CCGT is a mature technology.

Figure 21: 75 MW_e Martin integrated solar combined cycle plant in Florida, USA (left, from NREL [102]) and 9.3 MW_{th} solar integration at Liddell coal fire station in Liddell, Australia (right, from ProTender [103]).

Table 7: Integrated Solar Combined Cycle (ISCC) plants. Source: Lilliestam (2018).

Power station name	**Solar capacity [MW_e]**	**Total plant capacity [MW_e]**	**Country**	**Year finalised**	**Collector type**	**Status**
Aqua Prieta II ISCC	12	464.4	Mexico	2014	Trough	operational
Ain Beni Mathar ISCC	20	270	Morocco	2011	Trough	operational
Al-Abdaliya ISCC	60	280	Kuwait	future	Trough	construction
Martin Next Generation	75	1,150	USA	2010	Trough	operational
ISCC Hassi R'mel	25	150	Algeria	2011	Trough	operational
Kuraymat ISCC	20	150	Egypt	2011	Trough	operational
Dadri ISCC Plant	14	817	India	future	Fresnel	construction
ISCC Duba 1	43	605	Saudi Arabia	future	Trough	construction
Waad Al Shamal ISCC Plant	50	1,390	Saudi Arabia	future	Trough	construction
Medicine Hat ISCC	1.1	203	Canada	2014	Trough	operational
Yazd ISCC	17	467	Iran	2010	Trough	operational

(iv) Solar thermal energy can be integrated into ORC systems. A solar thermal ORC system is shown in Figure 28. The hot HTF can either be stored in a storage tank or be used directly to aid power generation. ORC systems operate at < 300 °C. This temperature can be supplied by line focussing CST collectors, which are therefore the common option for this technology. Several ORC plants operate with solar thermal integration world-wide, giving the technology a good technical and commercial readiness [45].

(v) Due to high working temperatures solar tower collectors can be used to preheat pressurised air in gas turbines as shown in Figure 22. Solar feed-in points include i) pre-heating in the pressurised air chamber before the combustion chamber, and ii) direct heating into the combustion chamber. Solar tower with direct air heating remain relatively immature existing only in one pilot system, the 1.5 MW_e

Jülich Solar Tower project in Germany [92]. A research project at the *University of Queensland*, Australia, is developing a small (< 5 MW_e) sized supercritical carbon dioxide system representing the next-generation of CSP plants [104]. Supercritical carbon dioxide systems are modified closed Brayton cycle systems using high pressure and high density carbon dioxide as working fluid for power generation at high efficiency (> 50%).

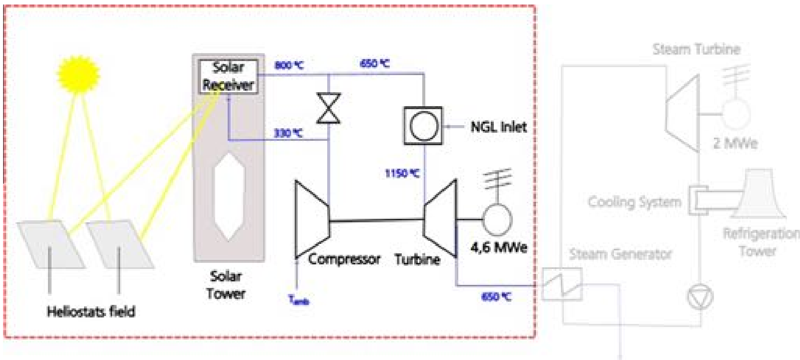


Figure 22: Scheme of *Solugas* solar-hybrid gas turbine with bottoming Rankine cycle (RC). Figure from Korzynietz et al. [105].

(vi) Similar to the solar gas turbines, micro-gas turbines (< 1 MW_e) can integrate solar thermal energy. Such plants were designed and built by the Israeli company *AORA Solar* (Figure 23). The *Tulip system* consists of a small solar field which operates the micro-gas turbine at 600 - 1,000 °C. If the incoming temperature is less than 950 °C the system additionally combusts fuel to reach the required temperature for the gas turbine. Three plants are currently operating in Israel, Spain and Ethiopia, mainly with diesel or natural gas [106]. Micro-gas turbines operate at small scales, with their heating and electricity output considered for energy demand of single houses or businesses (such as hotels, retail). They are believed to play an important role in future energy markets for employment during peak demand times and for local energy generation [106].

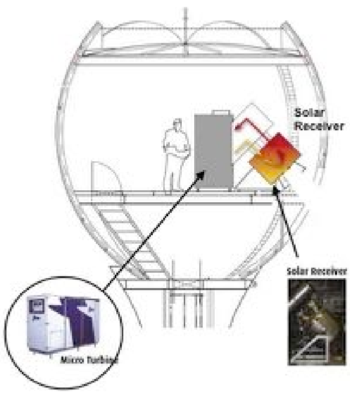


Figure 23: *AORA Solar TULIP* hybrid systems with natural gas fuelled micro-gas turbine and solar receiver. Source: helioCSP [46].

(vii) Dish collectors (Figure 19b) are point focussing CSP collectors with working temperatures of 500 – 1,000 °C. Even though they have the highest conversion efficiency, dishes are seldom deployed. The dish system is commonly deployed as Stirling systems at relative small scales of 3 – 30 kW_e [43], such as the CSP system in White Cliff, Australia [43].

2.5. HCSB systems for electricity generation

Hybrid systems combining solar thermal and bioenergy for the generation of electricity can be based on the technologies shown in Figure 24. Of the nine power generation technologies investigated in this review, six integrate both solar thermal and bioenergy, which will be the basis for further discussions about HCSB plants. While the integration into coal power stations and bottoming RC plants (of CCGT) are not highly renewable technology options and therefore less relevant for the context of thesis, these options will also be discussed for completeness. The renewable HCSB options are ORC systems, and RC systems, as well as the integration into gas turbines and micro-gas turbine. Excluded from further discussions are gas engines and fuel cells. These technologies can be operated with gaseous biofuels have however not been combined with solar thermal energy. Vice versa Stirling engines are commonly deployed with solar thermal dish collectors, however this heat-to-power conversion technology is not commonly used for bioenergy generation.

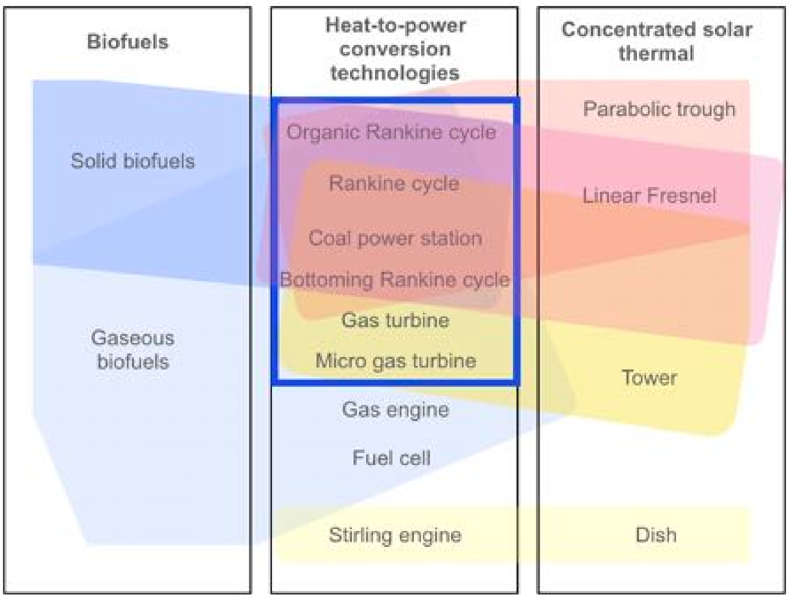


Figure 24: Electricity generation aided by bioenergy sources and concentrated solar thermal (CST) technologies.

2.5.1. HCSB power generation: Technical and commercial maturity

The technical and commercial readiness of the six selected technologies is shown in Table 8. Each of the technologies is described in detail below. An important factor indicating the compatibility of solar thermal and bioenergy in different power technologies is their operating temperature and scale, which are shown in Figure 25 and discussed below.

(i) RC systems are the most common power generation technology for both biomass and CSP plants. The typical scale of bioenergy plants is 5 – 50 MW_e (and up to 300 MW_e internationally), which is smaller than the typical scale of CSP plants usually > 50 – 150 MW_e (Figure 25). The operation temperature for both standalone systems is similar, ranging from 400 – 580 °C (see Appendix 8.A.5 and 8.A.6). Because of the good compatibility in temperature the integration of both technologies has been investigated intensively. During the second phases (Figure 26) of CSP deployment [72] and according to Soares [107] the impact of the global economic crisis coupled with the desire to phase out fossil fuels, resulted in the development of the first RC HCSB system. The second phase of CSP deployment was initiated by the Spanish feed-in tariff for CSP in 2007 [72] and led to the deployment of 49 standalone CSP systems in which natural gas was often used to overcome intermittencies in the solar resource. Natural gas was exchanged by biomass in the 22.5 MW_e *Termosolar Borges* plant in Leida, Spain [10] which was commissioned in 2012 and is shown in Figure 27. Because of this and other operating HCSB RC systems, this hybrid technology has a good technical maturity, as shown in Table 8. The commercial maturity can be rated as intermediate. Existing plants demonstrate economic feasibility, however their deployment is not common.

Within the group of RC HCSB systems, there are several options as to how the solar thermal energy is integrated. In the *Termosolar Borges* plant, the solar field produces saturated steam at 393 °C [10]. Before entering the high-pressure turbine of the RC system, the steam is superheated by the biomass boiler to temperatures between 450 – 520 °C. This operation 'in-series' leads to a solar share of 44% [10]. A similar HCSB system producing 15 MW_e started operating in Rende, Italy [108]. Another idea is the hybridisation of solar thermal and bioenergy 'in parallel'. Solar towers produce steam at > 500 °C and pressure > 100 bar (Table 5), which can be directly used in the steam turbine. In this plant layout solar and bioenergy can independently generate steam for the inlet of the RC turbine, which results in higher cycle efficiency [13]. This HCSB design was proposed for the 50 MW_e *PTC50 Alvarado* project in Spain, which was never commissioned owing to new regulatory frameworks that constrained the proposed project [109]. A third option for integration is demonstrated in the *Scalable CSP Optimised Power Plant Engineered with Biomass Integrated Gasification* project, which launched a 3 MW_e HCSB system in Barun, India in 2015 (mentioned by Soares [107]). In this plant design biomass combustion provides superheated steam for the high-pressure turbine, while CSP provides saturated steam for the low-pressure turbine.

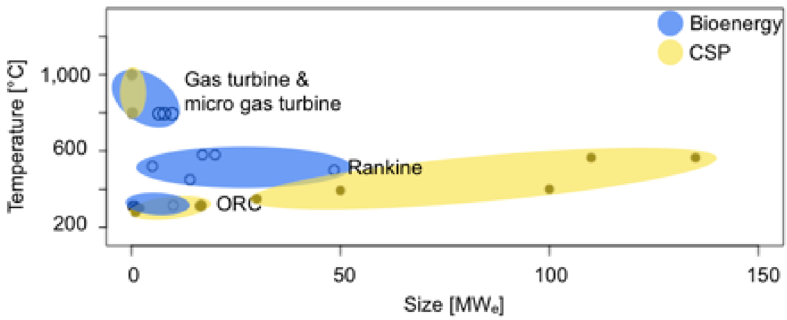


Figure 25: Temperature and size of electricity generation technologies fired by biomass and solar. The full list of bioenergy and concentrated solar power (CSP) plants shown in this graph can be obtained from Appendix 8.A.5 and 8.A.6.

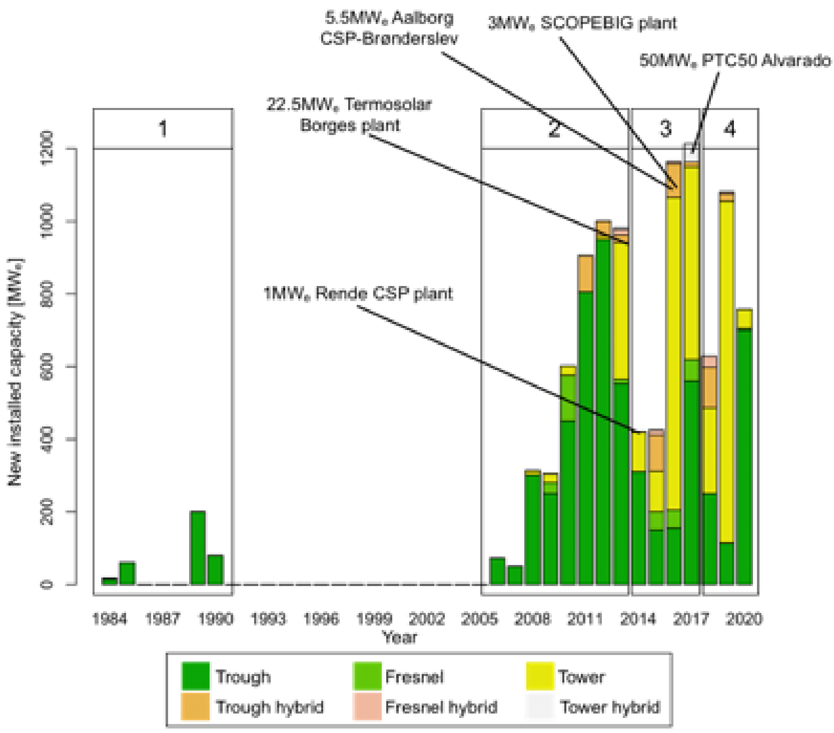


Figure 26: Four phases of global concentrated solar power (CSP) deployment [MW_e] per year between 1984 – 2018 (operating) and 2018 – 2020 (under construction), as well as years of hybrid concentrated solar biomass (HCSB) plant launching. Source of underlying data: Lovegrove et al. [72].

Figure 27: Photos of the *Termosolar Borges* plant in Leida, Spain from Cot et al. [110].

(ii) ORC cycle systems use working fluids which are limited to temperatures of about 220 – 390 °C. The typical operational scale of ORC systems fed by both solar thermal or bioenergy is < 20

MW_e (Figure 25). Several studies investigated ORC HCSB plant deployment and technical design concepts, e.g.: [111]–[113]. In 2017, both energy sources were combined in the 16.6 MW_{th} *Aalborg CSP* system in Brønderslev, Denmark, shown in Figure 28. Although the technical and commercial maturity of ORC HCSB systems is demonstrated (Table 8), ORC HCSB systems are not very common. ORC HCSB systems are especially interesting for cogeneration. Both renewable heat and electricity can be supplied to a local industry, or commercial building. The *Aalborg CSP* system supplies district heating and power to the local community of Brønderslev, Denmark [11]. If the solar thermal energy system cannot supply thermal energy to the city, woodchips are combusted in a biomass boiler, or natural gas is used to account for the heat demand [45]. This flexible operation is of great advantage and increases the economic feasibility compared to standalone solar thermal systems [45].

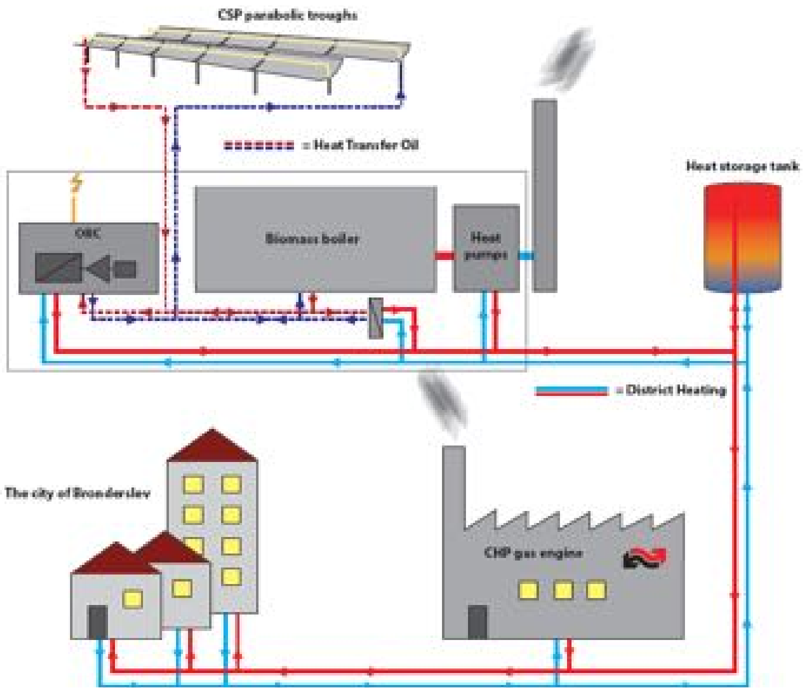


Figure 28: Technical sketch of the *Aalborg CSP* plant in Brønderslev, Denmark. Source: Aalborg CSP [11].

(iii) Solar thermal and bioenergy systems are compatible with conventional power stations. As of 2018, coal and gas supply the majority of Australia’s energy demand [114] and it is expected that fossil fuels will continue to play an important role during the following decade of the energy transition [115]. Solar thermal and bioenergy can be integrated into existing coal power stations, while keeping changes in the original plant layout marginal. By integrating low-cost renewable technologies, the fossil fuel feedstock requirement can be reduced and climate damaging CO_2-e can be avoided. Coal co-firing with biomass is a pragmatic way to decrease emissions and studies have shown that co-firing of 1 – 10% in all coal power stations globally, would be equivalent to 150 GW_e of bioenergy capacity and could reduce global CO_2-e by 45 – 450 million tonnes per year [63]. Solar thermal integration can reduce coal power generation by maximal 30 – 40% (however in most cases below 10%) [95]. Even though the integration of solar thermal or/and bioenergy in coal power stations is often discussed (and commissioned in a few plants) in the Australian context, the integration of both renewable feedstocks into the same coal power station has not been demonstrated. This idea was however discussed in two theoretical case studies by Tsupari et al. [83]. The *Liddell* power station integrated solar thermal energy from 2012 – 2015 [87]. Even though the integration of both technologies (solar thermal and bioenergy) into the same coal power station is technically mature, there is no current commercial example, and thus this hybrid option has a low commercial maturity ranking (Table 8). Feasibility studies [116] and commercial trials [87] of solar retrofits for coal combustion plants were conducted in Australia. The cancellation of the Kogan creek solar boost project in 2014 was a setback for the technology [88]. In NSW, four of the five currently operating coal power stations will be closed by 2035 [117]. Solar thermal integration has a lifetime > 25 years and requires an overall large capital investment, making it economically unviable for such short term deployment [116].

Table 8: Technical and commercial readiness of hybrid concentrated solar biomass (HCSB) systems for electricity generation.

	Technical readiness level	**Commercial readiness index**
Rankine cycle	9 [10]	3 [10]
Coal power station	9 [83]	1
Bottoming Rankine cycle of combined cycle gas turbines	7 – 8	1
Organic Rankine cycle	9 [45]	3 [45]
Gas turbine	3 [38]	1
Micro-gas turbine	9 [46]	1 – 2 [46]

(iv) Solar thermal and bioenergy can be theoretically integrated together into bottoming RC systems of CCGT. Globally, solar thermal integration in ISCC systems is commercially mature with over 175 MW_e installed capacity (Table 7). The economic feasibility and possible siting of ICSS systems in Australia was discussed by Peterseim et al. in 2015 [14]. Nevertheless, none of the proposed projects are operating in real life. Adding biomass combustion for additional steam generation into the bottom RC was never planned or commissioned to the authors knowledge. As such also the combination of solar thermal and bioenergy integration in the bottoming RC is only conceptual (Table 8).

(v) As previously discussed, the use of solar thermal energy in gas turbines (Figure 22) is commercially and technically immature (Table 6). Solar thermal gas turbines have been tested at scales < 1 MW_e in a limited number of commercial plants [118]. Similarly, offsetting natural gas combustion in gas turbines with biogas was considered uneconomic under current price settings (Table 4). Biogas fuelled gas turbines have been tested at scales between 5 – 20 MW_e and operating temperatures between 800 – 1,000 °C (Figure 24). Considering the low technical and commercial maturity of solar thermal and biofuel integration into gas turbines leads to the finding that HCSB integration into gas turbines is considered low (Table 6), which is confirmed by Nathan et al. [38].

(vi) *AORA Solar* is a developer of small-scale off-grid technology called *Tulip* hybrid systems (Figure 23). While all commissioned *Tulip* systems operate with natural gas, the system could also be operated with biogas [119]. Micro-gas turbines operate usually at scale < 1 MW_e (Figure 25) and at temperatures between 600 – 1,000 °C, which can be achieved by solar tower systems. With three operating *Tulip* hybrid systems, the technology is technically and commercially mature (Table 6). The economic feasibility of the system operated with biogas instead of natural gas would need to be tested in the individual context.

Thus, there are three identified technically and commercially mature HCSB design options, i) RC, ii) ORC, and iii) micro-gas turbine. Each of the design options generates electricity (and heat or cogeneration) at different scales suitable for deployment in various contexts described below:

- HCSB RC systems with scales of 5 – 50 MW_e can be used as grid connected electricity generator. The main advantages, compared to other renewable technologies is their ability to generate renewable and dispatchable energy. This will be increasingly important under the current rapid uptake of variable RE generator (solar PV and wind power stations) [30].
- ORC HCSB systems are an interesting solution for industries with low to medium heat demand and electricity demand < 5 MW_e. In particular, this includes industries in the production sectors 'food and beverage' (e.g. dairy and abattoirs), 'cement and lime', 'commercial and services' (e.g. hospitals and schools), 'bricks and ceramics', and 'pulp and paper' [23].
- HCSB micro-gas turbines could provide electricity to small off-grid communities or mines [46].

2.6. Conclusions

This desktop review rates different HCSB systems using the TRL and CRI ranking schemes. This ranking can help to justify the selection of HCSB technologies for further investigation in detailed case studies. HCSB plants can be designed to supply thermal and electric energy, (as well as help with the synthesis of biofuels). Thermal energy can be directly supplied by both solar thermal (captured from the sun) and biomass (combustion) to industrial or commercial buildings. For the generation of electricity, thermal energy from solar thermal and bioenergy can be used in a range of different heat-to-power conversion technologies. Specifically, electricity generation technologies can be based on i) renewable RC systems, ii) coal power stations, iii) bottoming RC systems, iv) ORC systems, and v) gas turbines and vi) micro-gas turbines.

The TRL and CRI of the different solar thermal, bioenergy and HCSB systems are listed in Table 9. HCSB systems based on renewable RC systems, ORC systems and micro-gas turbines have the best technical and commercial readiness. These three HCSB design options are demonstrated commercially, e.g. in the *Termosolar Borges* plant in Leida, Spain [10], the *Aalborg CSP* plant in Brønderslev, Denmark [45], and the *AORA Tulip* systems from Israel [46], respectively. These three HCSB systems are likely to be the best option for commercial deployment in Australia in the near future, because their deployment does not require further research and development.

Table 9: Technical (TRL) and commercial (CRI) readiness of bioenergy, solar thermal and hybrid concentrated solar biomass (HCSB) electricity generation technologies.

	Bioenergy		**HCSB systems**		**Solar thermal systems**	
	TRL	CRI	TRL	CRI	TRL	CRI
Rankine cycle	9	6	9	3	9	6
Coal power stations	9	6	9	1	9	4
Bottoming Rankine cycle of combined cycle gas turbines	5	1	7 – 8	1	9	6
Organic Rankine cycle	9	6	9	3	9	4
Gas turbine	9	2	3	1	3	1
Micro-gas turbine	9	3	9	1 – 2	9	3

3. Research design

3.1. Research scope

The overall aim of the doctoral research project is the investigation of HCSB plants as energy generators in the specific context of the energy transition in NSW, Australia's most populous state. This thesis acknowledges that social, political, environmental, technical and economic factors impact the success of new energy generation technologies. The focus of the thesis is, mainly, on the technical and economic deployment potential. Specifically, this thesis aims to assess potential, options and benefits of HCSB plant deployment, as illustrated in Figure 29, and expressed through the following research questions:

i) What is the HCSB plant deployment potential in NSW (considering resources, market access and energy demand)?,

ii) What are the technical design options of HCSB plants (considering technical feasibility and local energy demand)?, and

iii) What are HCSB plant deployment benefits in the context of local case studies?

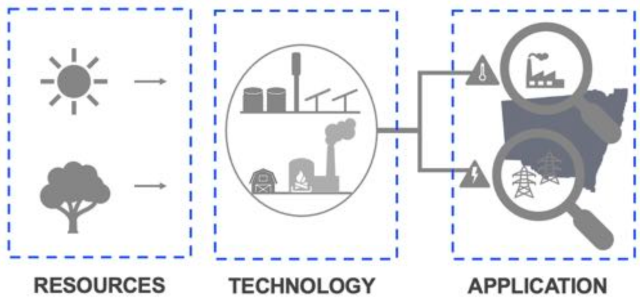


Figure 29: Research scope.

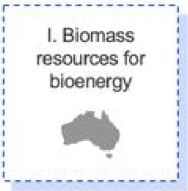
3.2. Research design and subsidiary research questions

In order to answer the three research questions (above) four research packages were designed. Based on the results of the literature review (section 2., p. 28), this thesis focusses on two types of HCSB plants that utilise mature technology components:

- a grid connected electricity generation HCSB plant design, and
- an industry connected cogeneration HCSB plant design.

Both HCSB plant options were investigated in the four research packages. Each of the four research packages considered furthermore detailed research questions.

i) Research package I assesses biomass resources on the Australian continent. HCSB plants are depending on two types of resources – solar and biomass. While for solar resources good resources maps are available as satellite derived data (e.g. [120]), this is not the case for biomass resources. Because reliable assumptions about the availability of local biomass resources are important to assess the application potential of bioenergy-based systems, including HCSB plants, this research packages investigates the biomass resources availability in Australia and answers the following questions:



Research package I

What is the resources availability of different biomass feedstock types in a spatial grid (at resolution of 5 x 5 km) of the different states of Australia?

What is the theoretical biomass feedstock availability [tonnes/year] at potential bioenergy sites in proximity to the electricity transmission infrastructure?

National scale of investigation

ii) Research package II is investigating the deployment potential of HCSB plants in NSW. Beside the biomass resources, which were already assessed in research package I, this chapter also considers solar resources, as well as access to the energy market (grid access). The research package answers the questions:

Research package II

What is the total energy generation (in terms of installed capacity [MWe]) and deployment potential (in terms of installed cost [AU$]) of HCSB systems in NSW?

What types of biomass feedstock can be supplied (within a transport radius of 50 km and 100 km) to potential sites of HCSB systems in NSW?

Which regions in NSW are the best suited (in terms of total number of potential deployment sites and installed capacity) for HCSB system deployment?

What is the emission abatement potential if all potential sites were to deploy HSCB systems?

Do HSCB systems comprise a technology with high siting potential in NSW, or are they limited to only a few sites?

NSW as scale of investigation

iii) Research package III is focussing on electricity generation. The techno-economic feasibility of HCSB plants in the context of the Riverina-Murray region of NSW is assessed. This research package answers the following questions:

Research package III

What is the best technical design of HCSB Rankine cycle systems for grid connected electricity generation in the Riverina Murray region of NSW?

What is the economic feasibility of such HCSB systems?

What is the energy generation and emission abatement potential of such HCSB systems?

What are specific benefits of HCSB plant deployment?

Local investigation scale

iv) Research package IV is investigating HCSB plants for industrial cogeneration. This research package presents a case study for a major beef abattoir in NSW. The research package is answering the following questions:

Research package IV

What is the <u>best technical design</u> of HCSB cogeneration systems for operation at red meat abattoirs in NSW?

What is the <u>economic feasibility</u> of such HCSB systems?

What is the <u>energy generation and emission abatement potential</u> of such HCSB systems?

What are specific <u>benefits of HCSB plant deployment</u> and what are the specific siting requirements?

Local investigation scale

The connection of the four research packages is shown in Figure 30. As explained above the scope of this research enhances mainly the techno-economic understanding of HCSB plants. Equally relevant, however outside the scope of this project is a detailed understanding of social (e.g. social license to operate), environmental (e.g. life cycle assessments), and political (e.g. incentives) aspects of HCSB deployment. The research design and overall structure can provide guidance to other projects which investigate novel energy generation technologies in the context of a specific jurisdiction. Especially relevant to following projects with a similar scope are the interconnectedness of the different research packages (Figure 30). The research packages are organised in such way, that the results of one package are important and have implementations for the following research packages. Another important aspect that can be relevant to other projects with a similar scope is that the four research packages follow a chronological that starts with broader topics like resources mapping (continent scale) and becomes narrower, focussing on market integration (state scale) and two case studies (local scale).

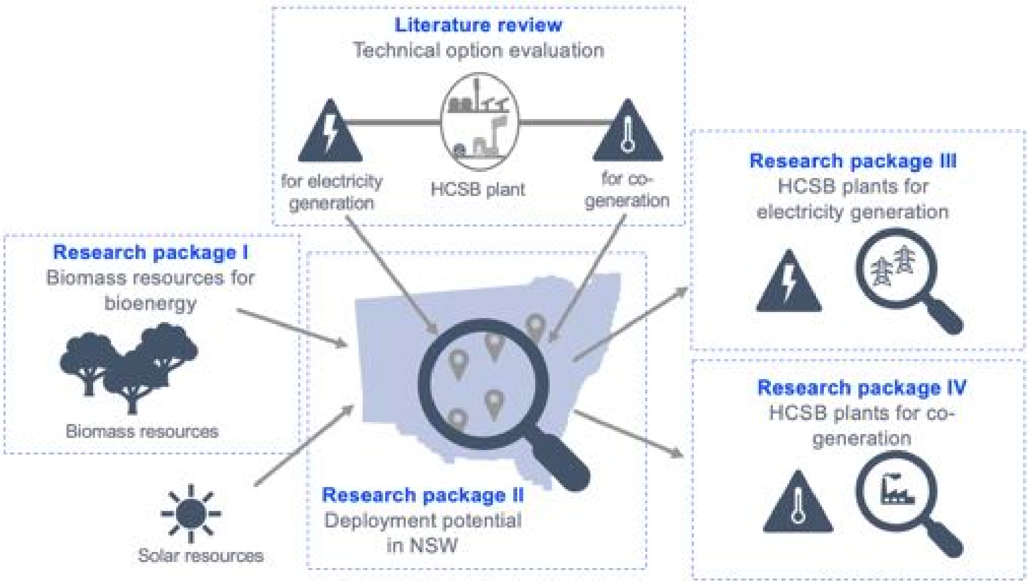


Figure 30: Research structure.

4. Research summary & synthesis of outcomes

The following sections provide a synthesis of the research findings and outcomes of the four research packages.

4.1. Bioenergy siting for low-carbon electricity supply in Australia

This work package has been published in the journal of *Biomass & Bioenergy* as:

E. Middelhoff, B. Madden, M. Li, F. Ximenes, M. Lenzen, and N. Florin, "Bioenergy siting for low-carbon electricity supply in Australia," *Biomass & Bioenergy*, vol. 163, no. August 2022, p. 106496, doi: https://doi.org/10.1016/j.biombioe.2022.106496.

The full manuscript is provided in Appendix 8.A.1. Bioenergy siting for low-carbon electricity supply in Australia and a synthesis is provided below.

This research package provides high-resolution (5 x 5 km grid cells) resources maps for different types of biomass feedstock (including straw, forestry waste and bagasse) in Australia. It also assesses potential bioenergy sites in proximity to the continent's electricity network infrastructure. Reliable assumptions about the availability of local biomass resources are important to estimate the application potential of bioenergy-based systems, including HCSB plants. In the broader context of the doctoral project, this research package is particularly relevant for research chapter II (Figure 31) in which the siting potential of HCSB plants is further examined using detailed biomass resources maps. The key findings of this research chapter are:

- Up to date, and high-resolution biomass resources maps for three important feedstock types (forestry waste, stubble and bagasse) on the Australian continent,
- Bioenergy generation potential considering operational bioenergy plants, spatial constraints, distances to transmission infrastructure, and maximum biomass transport distances,
- Identified bioenergy potential of up to 1,676 PJ of energy per year from these feedstocks,
- Sufficient resources to supply up to 28% of Australia's current electricity demand with dispatchable and renewable energy, and
- A database of prospective bioenergy sites for high-RE supply models provides new insights in terms of how and where bioenergy can be commissioned and the role of bioenergy in the Australian energy transition (which is lagging behind that in other jurisdictions [34]).

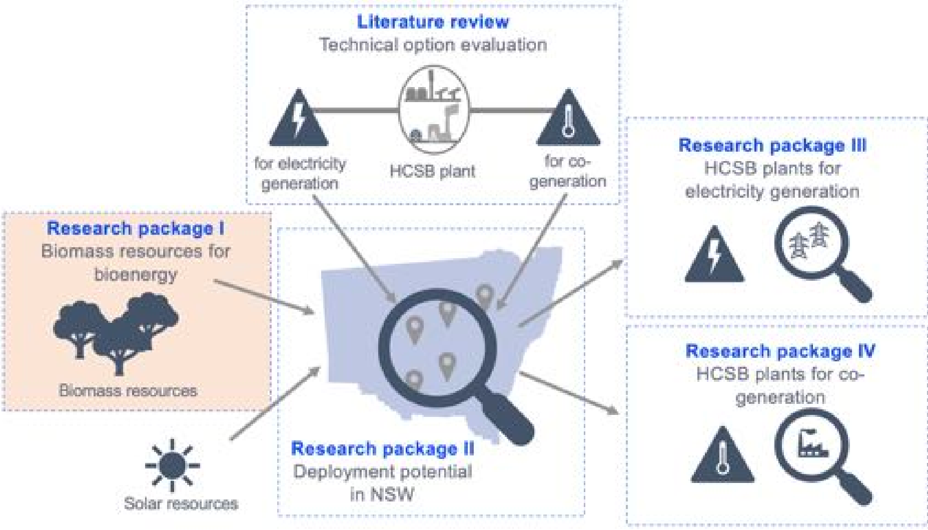


Figure 31: Research chapter I in the research structure (red).

Research questions and methods: A detailed description of the methodological approach of this research package is provided in Appendix 8.A.1. Bioenergy siting for low-carbon electricity supply in Australia, while a summary of the methods is given below. This research package answers the following research questions:

- What is the resources availability of different biomass feedstock types in a spatial grid (at resolution of 5 x 5 km) of the different states of Australia?
- What is the theoretical biomass feedstock availability [tonnes/year] at potential bioenergy sites in proximity to the electricity transmission infrastructure?

As a first step, low-resolution biomass resources maps and high-resolution land-use maps are combined in a dasymetric model to generate high-resolution biomass resources maps. Low-resolution biomass resources maps of the different states of Australia (as recently been published on the *NationalMap* [56][21]) present annual biomass resources [tonnes/year] at SA2 level[22] [121]. Due to their low spatial resolution, these biomass resources maps are not ideal for informing bioenergy siting, as biomass availability is collated for large regions and therefore unsuitable for determining biomass availability at a given location. The dasymetric model developed in this research package generates high-resolution (5 x 5 km) resources maps. In order to only show biomass resources that are actually available, already used biomass resources (e.g. for energy generation at existing bioenergy sites) are obtained from the biomass resources maps.

In a second step, spatial grid cells (with resolution of 5 x 5 km) close to (and in later iterations further away from) the existing power transmission lines are considered as potential bioenergy sites.

[21] Formerly included in the *Australian Renewable Energy Mapping Infrastructure* (AREMI).

[22] Statistical area 2 (SA2) regions describe medium-sized general purpose areas with about 10,000 inhabitants. The size of different statistical area 2 (SA2) regions can vary strongly, this is because Australia is strongly populated on the coasts and less populated towards the desert.

These grid cells are only considered as potential bioenergy site. These grid cells are only considered at potential bioenergy sites if they are not limited by spatial constrains (such as located in national parks or other restricted areas). For the remaining grid cells, biomass resources in a radius of 100 km are reported [tonnes/year]. The grid cells with the highest concentrations of biomass feedstock are reported as prospect bioenergy sites. The algorithm continues searching for prospective sites until all biomass resources are allocated.

Results and discussion: The research produced resources maps for bagasse, forestry residues and crop stubble at the Australian continent (with a spatial resolution of 5 x 5 km). These maps are presented in Appendix 8.A.1. Bioenergy siting for low-carbon electricity supply in Australia Bagasse residues are mainly available along the coast of Queensland, while other agricultural residues like crop stubble are prevalent in NSW, Victoria (VIC), SA and Western Australia (WA). Forestry residues are available in many coastal areas of the continent. For all states and feedstock types, this study proposes over 180 prospective and strategic bioenergy sites with the potential to utilise over 46 million tonnes of biomass residues. The sites are summarised for the three resources types in Table 10. Figure 32 shows the locations of the proposed bioenergy sites for bagasse, forestry residues and stubble residues for the Australian continent in square, round and triangle symbols, respectively.

Table 10: Number of prospective bioenergy sites, available resources and their minimal and maximal distance from transmission infrastructure for three biomass feedstock types.

Biomass feedstock type	**Number of prospective sites**	**Available resources [tonnes/year]**	**Distance from transmission lines [km]**
Bagasse	4	1,093,123	0.0 - 0.8
Forestry residues	51	16,576,883	0.0 - 111
Stubble residues	169	28,651,836	0.0 – 230.3

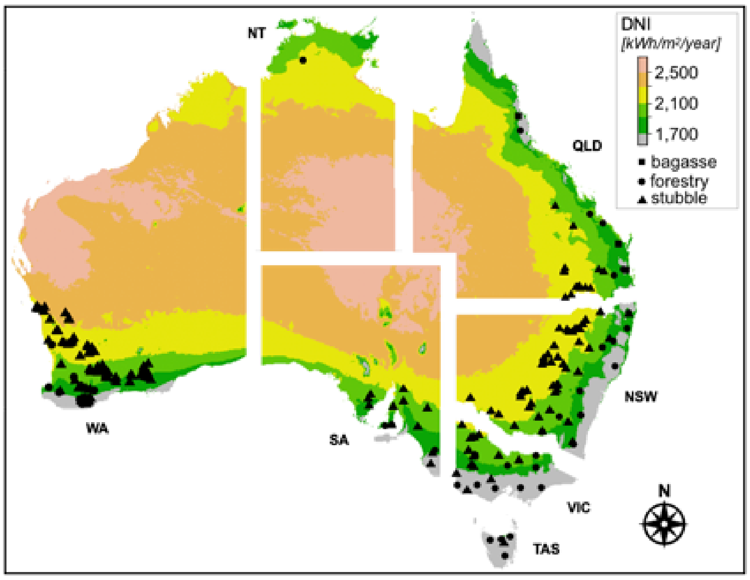


Figure 32: Direct normal irradiation (DNI) [kWh/m^2/year] in Australia at spatial resolution of 5 x 5 km from BoM [120]; and potential sites of bioenergy plants based on bagasse, forestry and stubble resources.

The results of this research package are important in several respects. First, the results allowed for a detailed and up-to-date assessment of the bioenergy potential on the Australian continent. The estimated energy content of the considered biomass resources is 1,676 PJ/year, which corresponds to an approximate electricity generation potential of around 57.6 TWh/year –equivalent to around 28% of the Australian electricity demand (858 PJ/year) of 2019/20 [122]. Australia's bioenergy industry is underdeveloped compared to other countries and these updated figures highlight the great potential of bioenergy. This is particularly important when considering the broader background and challenges of the current energy transition in Australia. Furthermore, this study provides a list of prospective sites (defined coordinates) for bioenergy plants, considering spatial constrains and prioritising proximity to transmission network. This differs from other studies that have largely focussed on resources use on the entire Australian continent [123], [124], [125], without consideration specific sites or siting constrains.

Finally, the results of this study are also important inputs for the further research packages of this thesis. As an extension of the results from the publication, Figure 32 shows the Australian solar resources[23] at high-resolution (5 x 5 km). In addition to biomass resources, solar resources are also important for HCSB deployment. Figure 32 shows that solar resources exceed 1,700 – 1,800 kWh/m^2/year [126], [127] (the minimum threshold for HCSB plant deployment) at the majority of the identified prospective bioenergy sites. This indicates the substantial siting potential of HCSB plants in Australia. Based on this preliminarily result, the HCSB siting potential in NSW is further discussed in the following research chapter II.

<u>Further outcomes:</u> The results of this research package were also important for a follow-up research study in collaboration with the *University of Sydney*. The results of this follow-up study have been published in the journal of *Resources, Conservation & Recycling* as: M. Li, E. Middelhoff, F. Ximenes, C. Carney, B. Madden, N. Florin, A. Malik, M. Lenzen, "Scenario modelling of biomass usage in the Australian electricity grid," Resources, Conservation and Recycling, vol. 180, no. May 2022, p. 106198, doi: https://doi.org/10.1016/j.resconrec.2022.106198. In this project, the list of prospective bioenergy sites was used to improve the bioenergy simulation in high-RE supply model. In previous studies the bioenergy simulation in high-RE supply models was limited. In this follow-up study, and additionally to the updates around the prospective bioenergy siting various bioenergy bidding strategies and cost assumptions were tested. The study found that with the increase of carbon prices, bioelectricity can be a cost-effective electricity generation option, reaching up to 9 – 12% generation share. Since biomass-based power generation is flexible, it can facilitate grid stabilisation and load balancing, and is therefore particularly important given the current rapid uptake of variable RE generation from solar PV and wind power stations.

[23] Using satellite derived direct normal irradiation (DNI) resources maps from the Australian Bureau of Meteorology [120].

4.2. Assessing energy generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia

This work package is divided into the siting potential assessment of the electricity and the siting potential assessment of cogeneration HCSB plants in NSW. The assessment of the electricity generation potential has been published in the journal of *Applied Energy*:

E. Middelhoff, B. Madden, F. Ximenes, C. Carney, and N. Florin, "Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia," *Appl. Energy*, vol. 305, no. September 2021, p. 117942, doi: https://doi.org/10.1016/j.apenergy.2021.117942.

The full manuscript is provided in Appendix 8.A.2. Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia and a synthesis is provided below. The assessment of the cogeneration siting potential can be found as part of the synthesis below. This research package assesses the siting potential of HCSB plants in NSW. The assessment considers three main requirements for HCSB deployment: i) easy access to the energy market (which are the transmission infrastructure and industries with heat demand), ii) sufficient solar, and iii) sufficient biomass resources. In the context of the entire doctoral project, this chapter informs the selection of the two case study region in research package III and IV (Figure 33).

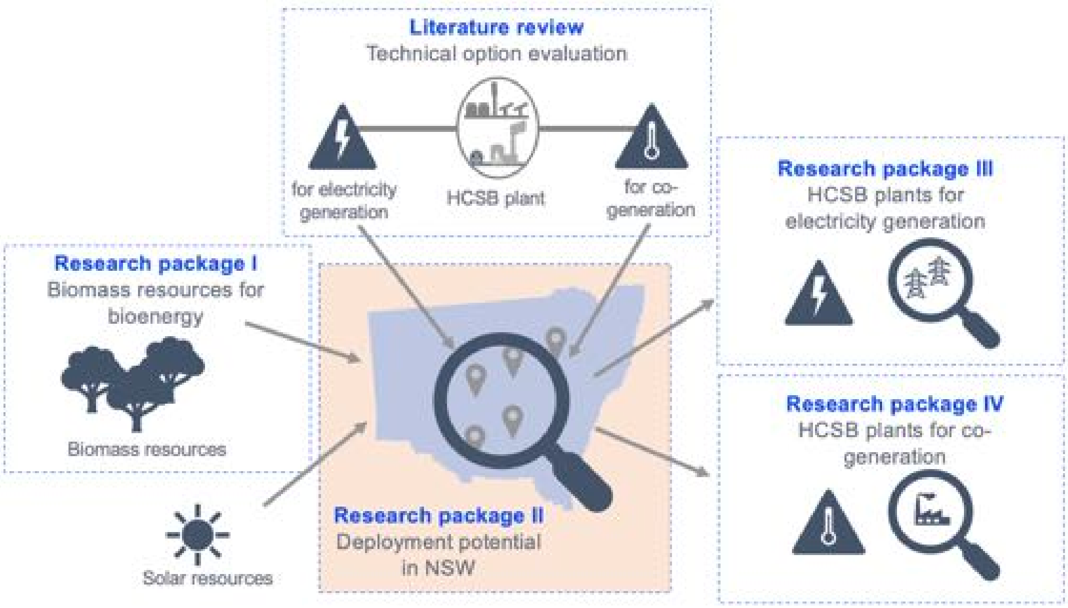


Figure 33: Research chapter II in the research structure (*red*).

The key findings of this research package for the assessment of electricity generation potential of HCSB plants in NSW are:

- Zone substations with new connection capacity allow for cheap and ready-to-use grid access,
- NSW has sufficient biomass and solar resources for HCSB plant deployment at up to 138 substations, with up to 874 MW_e of installed capacity,
- If HCSB plants are deployed at all substations this allows for a total installed cost of up to AU$ 6.3 billion (±11%) using up to 4.3 million tonnes of biomass feedstock, and
- This allows to abate up to 6.2 billion kg of CO_2-e per year.

Further key findings, not reported in the journal publication (Appendix 8.A.2. Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia), but relevant to the cogeneration potential of HCSB plants in NSW:

- HCSB plants for cogeneration need to be directly deployed and integrated at the industrial site in order to supply heat and electricity,
- One possible industry that can benefit from HCSB plant deployment is the red meat industry, and
- Resources mapping in proximity to the existing abattoirs in NSW show that there are sufficient resources to operate HCSB plants at all abattoirs in NSW and that HCSB plant deployment makes therefore sense from the resources supply perspective.

Research questions and methods: A detailed description of the methodological approach of this research package is provided in Appendix 8.A.2. Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia, while a summary of the methods is given below. This research package aims to answer the following research questions:

- What is the total energy generation (in terms of installed capacity [MW_e]) and deployment potential (in terms of installed cost [AU$]) of HCSB systems in NSW?
- What types of biomass feedstock can be supplied (within a transport radius of 50 km and 100 km) to potential sites of HCSB systems in NSW?
- Which regions (SA2 regions) in NSW are best suited (in terms of total number of potential deployment sites and installed capacity) for HCSB system deployment?
- What is the emission abatement potential if all potential sites were to deploy HSCB systems?
- Do HSCB systems comprise a technology with high siting potential in NSW, or are they limited to only a few sites?

To answer the research questions, a GIS model was developed in the software package R [128]. This model includes the biomass resources maps [tonnes/year] for NSW from research package I. The model further considers solar resources maps, considering the direct normal irradiation [$kWh/m^2/year$]

in NSW from the Australian Bureau of Meteorology (BoM) [120]. (The solar resources availability in NSW are also shown in Figure *32*, and discussed below.) As a third consideration, the GIS model takes market integration points into account where HCSB plants can be installed to deliver the energy they produce. In the case of electricity generating HCSB plants, these market integration points are zone substations with new connection capacity from the *NationalMap* [56][24]. In the case of cogeneration HCSB plants, these market integration points are the industrial sites. The GIS model determines the resources availability for solar and biomass resources for each of the market integration points and interpretated them for siting suitability. Biomass resources supply is hereby considered in a collection radius of 50 or 100 km. For electricity generation in HCSB plants the study furthermore determines the:

- Total installed capacity [MW_e] potential of HCSB systems for electricity generation in NSW, considering technology efficiency estimates [%/MW_e] of a RC HSCB system that was designed and thermo-dynamically modelled in research chapter IV;
- Total installed value [AU$] of HCSB systems for electricity generation in NSW, considering technology cost estimates [AU$/$MW_e$] from research chapter IV;
- Total emission abatement potential [$MtCO_{2\text{-}e}$/year] of HCSB systems for electricity generation in NSW, considering scope 2 emissions of electricity in the grid [tCO_2-e/MWh] and emissions of biomass feedstock harvest and transport [kg CO_2-e/tonne]; and
- Regions that have a good HCSB deployment potential [MW_e/region].

<u>Results and discussion:</u> For electricity generating HCSB plants, substations with new connection capacities allow easy and ready-to-use grid access for systems operating at a scale of 5 – 50 MW_e. The substations that qualify for HCSB plant deployment in NSW are shown in Figure 34. There are sufficient biomass resources to supply 157 and 195 substations within biomass collection radius of 50 km and 100 km, respectively. Previous siting feasibility studies for the HCSB technology have declared 1,700 – 1,800 kWh/m^2/year as minimum required solar resources [37], [126], [127]. Under the condition of sufficient solar resources (>1,800 kWh/m^2/year) for the deployment of HCSB plant systems, 111 and 138 substations are suitable for technology deployment in 50 km and 100 km collection radii, respectively (Figure 34). The availability of biomass resources at these substations enables for simultaneous HCSB operation at 61 substations with installed capacity of 830 MW_e and installed cost of Australian Dollar (AU$) 6.3 billion[25] (± 11%). If all these sites were to be deployed, more than 6 $MtCO_2$-e/year could be abated in NSW. In addition, around 4.3 million tonnes of biomass waste materials could be used for electricity generation in HCSB plants in NSW.

[24] Formerly included in the *Australian renewable energy mapping infrastructure* (AREMI).
[25] It needs to be noted that the current COVID-19 pandemic and the associated temporary slowdown in production and trade is causing an extreme increase in raw material and steel prices. This study assumes the pre/post-pandemic prices to reflect usual market conditions.

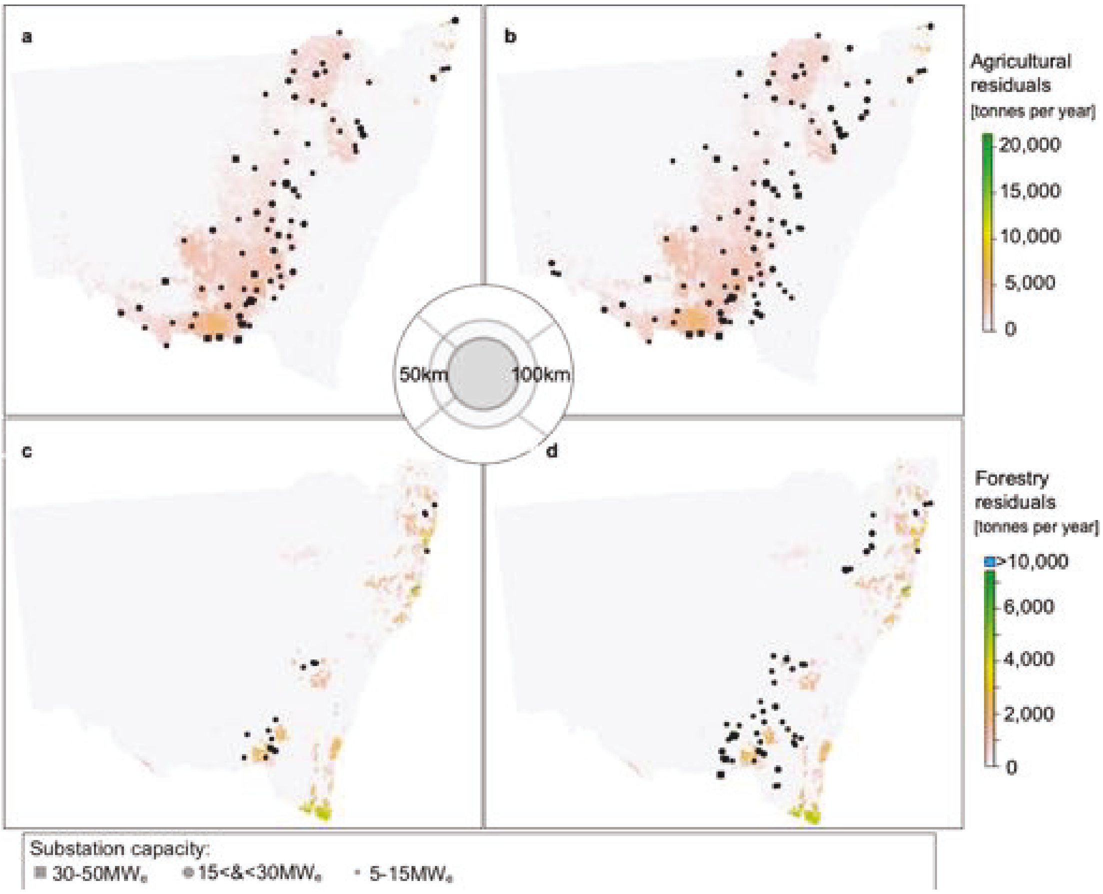


Figure 34: Agricultural (a and b) and forestry (c and d) residues [tonnes/year] in NSW and locations of substations with new connection capacity, which can be supplied by sufficient (to generate min. 5 MW_e) biomass resources in 50 km (a and c) and 100 km (b and d) resource collection radii and solar resources > 1,800 kWh/m²/year.

The assessment compares two different biomass feedstock types, agricultural and forestry waste residues, for the delivery to the identified sites for HCSB plant deployment. Compared to forestry waste residues (which are located closer to the coast), agricultural wastes have a stronger overlap with solar resources and are therefore very suitable for the use in HCSB plants. In addition, stubble, straw and other agricultural waste is an underutilised bioenergy feedstock in Australia, in contrast to forestry residues, which are already commonly used feedstocks for existing bioenergy projects, [129]. On the other hand, straw as a bioenergy feedstock needs to carefully be considered for lifecycle emissions in site-specific settings to guarantee effective carbon mitigation [130]. Implications for reductions in sequestered carbon associated with the harvest of agricultural residues need to be evaluated for different crops and land management systems [130]. Specifically, straw management systems which include ploughing and mulching can stabilise terrestrial carbon sequestration in soils and can reduce overall emissions from land management. However, in this assessment and in the context of NSW, only sustainable straw residues are considered and the use of agricultural harvest (e.g. straw) and processing (e.g. husk) are attractive options for bioenergy projects [130]. Furthermore, common practices, like on-field stubble burning are common in NSW and have adverse impacts on local communities and ecosystems as well as emitting carbon to the atmosphere. For these resources the alternative use as bioenergy feedstock is advantageous. The Riverina-Murray region in central-southern NSW is the most prospective region for HCSB siting in terms of availability of agricultural wastes and number of substations (and new connection capacity).

The GIS model was also used to assess the deployment potential of HCSB cogeneration plants at red meat abattoirs in NSW. This section extends the content of the journal publication by providing these further findings. Specifically, the GIS model is used to investigate the solar and biomass resources in 50 km radius to the 13 existing beef abattoirs in NSW. The results presented in Figure 35 and Table 11 show the solar and biomass resources availability (comparing four biomass feedstock types). Former siting feasibility studies on the HCSB technology have declared 1,050 kWh/m^2/year as the minimum solar resource threshold [37], [126], [127] for cogeneration systems [45]. Figure 35 shows that NSW has excellent solar resources and all abattoirs could be considered for solar thermal integration. Each abattoir can make use of different local biomass residues, which are varying for different parts of the state. Table 11 shows that abattoirs located in the central southern part of the state (abattoir 3, 7, 8, and 10) around the Riverina region could consider the use of agricultural residues like stubble. Forestry residues are the most abundant residues for abattoirs located closer to NSW's coast. The Casino abattoir is the only beef abattoir located in the Richmond-Tweet region. Figure 35 shows that mixing of forestry and agricultural residues can be considered for a few abattoirs. In general, all abattoirs in NSW could use local waste residues for renewable and dispatchable energy generation.

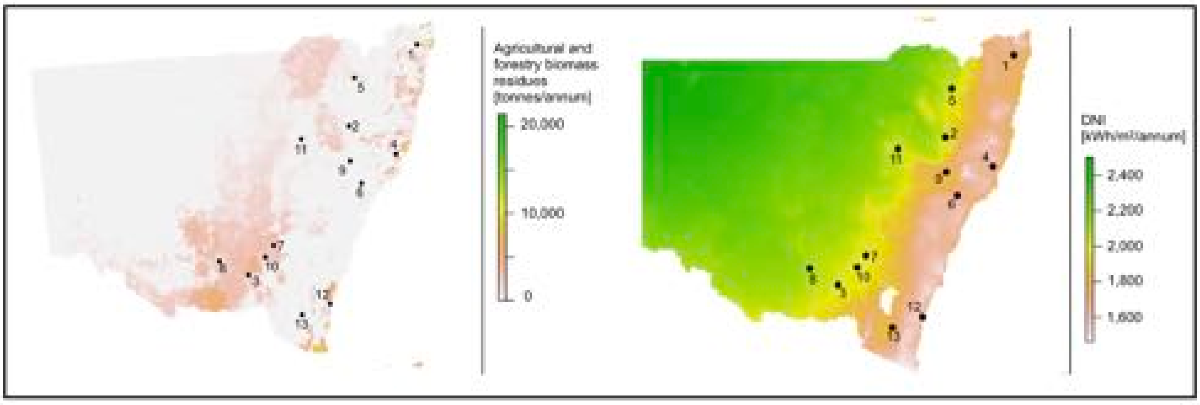


Figure 35: Agricultural and forestry biomass residues [tonnes/year] and direct normal irradiation [kWh/m^2/year] at beef abattoirs in New South Wales (NSW).

Table 11: Agricultural and forestry biomass residues [tonnes/year] and direct normal irradiation [kWh/m^2/year] at beef abattoirs in New South Wales (NSW).

	Location	DNI [kWh/m^2 /year]	Bagasse [tonnes/year]	Stubble [tonnes/year]	Forestry waste [tonnes/year]	Manure [tonnes/year]
1	Casino	1,745	105,173	8,286	79,993	57,035
2	Tamworth	2,031	0	82,587	5,199	95,960
3	Wagga Wagga	2,013	0	654,667	3,162	13,588
4	Wingham	1,686	0	0	164,156	35,111
5	Inverell	2,030	0	55,399	0	0
6	Whittingham	1,720	0	1,004	10,848	86,511
7	Young	1,993	0	476,614	115	14,516
8	Yanco	2,087	0	552,495	2,978	21,343
9	Scone	1,813	0	22,069	747	23,972
10	Cootamundra	1,992	0	602,221	0	9,599
11	Monuya	1,658	0	1,635	88,905	0
12	Wattle Spring	2,063	0	44,191	1,101	1,761
13	Polo Flat	1,772	0	7,450	16,551	0

Further outcomes: The value of this research chapter is demonstrated by its application in an online tool from CSIRO, which is currently under development as part of the *Biomass for Bioenergy Project* [131]. In this spatial online tool, land owners and technology developers can assess the local siting potential of HCSB plants in NSW. The results of this research package can therefore actively contribute to local land planning activities.

4.3. Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia: Design and evaluation of techno-economic and environmental performance

This work package has been published in the journal of *Energy Conversion and Management*:

E. Middelhoff, L. Andrade Furtado, J. H. Peterseim, B. Madden, F. Ximenes, and N. Florin, "Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia : Design and evaluation of techno-economic and environmental performance," *Energy Convers. Manag.*, vol. 240, no. July 2021, p. 114244, doi: http://doi.org/10.1016/j.enconman.2021.114244.

Furthermore, some of the results have been presented at the 2020 European Biomass Conderence:

Middelhoff, E., Andrade Furtado, L., Florin, N., Ximenes, F. Reis Parise, José Parise, 2020, Hybrid concentrated solar-biomass plants – Electricity generation in New South Wales, Australia, Papers of the *28th European Biomass Conference*, Proceedings of the International Conference held virtually, 6 – 9 July 2020.

The full manuscript is provided in Appendix 8.A.3. Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia : Design and evaluation of techno-economic and environmental performance and a synthesis is provided below. This research package evaluates HCSB RC systems as standalone, grid connected electricity generators. The Riverina-Murray region was selected as a case study region and the study evaluates technical design, economic feasibility, and local benefits of deployment. In the context of the broader doctoral project, this chapter is the first of two detailed case studies, investigating the benefits and potential of HCSB plants in a specific context (Figure 36). The key findings of this research package are:

- Detailed HCSB plant design with a CSP tower system and thermal energy storage achieving a net energy efficiency of 34%, comparable to the energy efficiency of standalone bioenergy plants,
- Economically viable deployment with an electricity price of AU$ 120 – 350 /MWh, and
- Potential benefits to the environment and local community through carbon emission mitigation, improved air quality and local job creation.

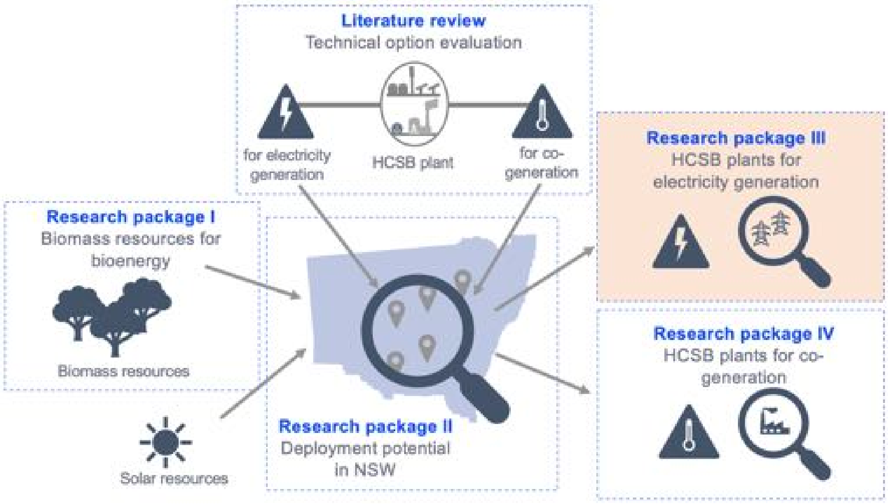


Figure 36: Research chapter III in the research structure (red).

Research questions and methods: A detailed description of the methodological approach of this research package is provided in Appendix 8.A.3. Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia: Design and evaluation of techno-economic and environmental performance, while a summary of the methods is offered below. This research package answers the following questions:

- What is the best technical design of HCSB RC systems for grid connected electricity generation in the Riverina Murray region of NSW?
- What is the economic feasibility of such HCSB systems?
- What is the energy generation and emission abatement potential of such HCSB systems?
- What are specific benefits of HCSB plant deployment?

As a first step a HCSB plant for standalone grid connected electricity generation was designed considering and discussing different options for the various plant components. E.g. aligning with former research the efficiency of different CSP collector types was discussed [13] and the plant layout was designed to be efficient and mature. For this case study, a HCSB Rankine cycle system with concentrated solar tower for scales of 5, 15, 30 and 50 MW_e was chosen. As a second step, and to understand the economic feasibility, an economic model was developed which is following the *dispatchable renewable energy spreadsheet* [19]. Through this approach the economic results can be easily compared to other dispatchable RE technologies that are covered by the spreadsheet. The assessment of the emission abatement potential considers emissions for the harvest, processing and transport of the used biomass feedstock. This case study focused on rice straw as feedstock. Finally the study discusses local employment potential and benefits for local farmer (such as income diversification).

Results and discussion: The HCSB system is designed so that both the solar thermal and bioenergy unit can generate steam to feed the high pressure turbine. This design allows for independent operation as shown in Figure 37, where the solar thermal unit can account for most of the steam generation during the day while the biomass boiler operates at night. This HCSB design can achieve high thermal efficiency reaching 21 – 34% depending on the size HCSB plant.

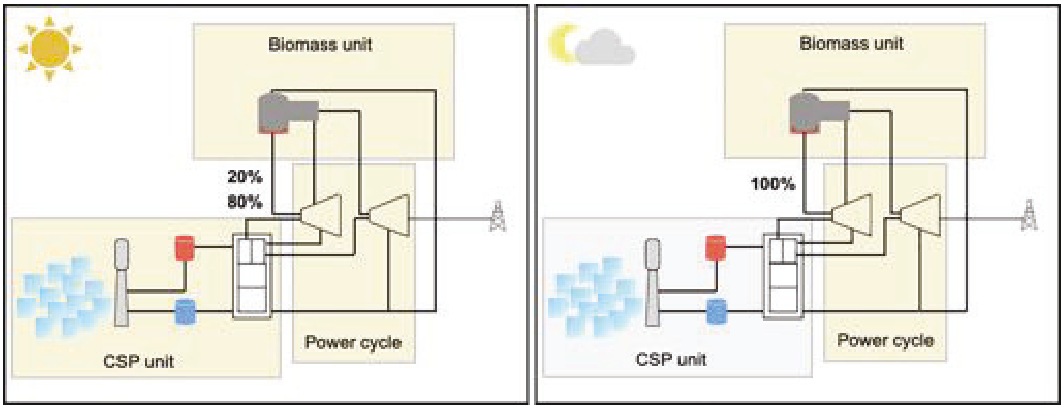


Figure 37: Operational strategy of the hybrid concentrated solar biomass (HCSB) plant for electricity generation.

This study developed an economic model of HCSB systems that describes the capital cost, which ranges between 50 – 333 million[26] (for the assumed sizes of 5 – 50 MW_e). Assuming an internal rate of return (IRR) of 11%, profitable deployment requires a grid electricity price of AU$ 120 –350 /MWh. These HCSB systems can be located at zone substations with new connection capacity offering economical grid access, 16 of which are located in the Riverina Murray region of NSW. While other existing bioenergy plants in Australia use bagasse (e.g. [132]), forestry resides, or liquid waste streams [34], the dominant biomass resources in the Riverina Murray region are agricultural residues. At 15,000 – 256,000 [tonnes/year], rice straw is a common agricultural residue. The resource is often burned on the field after crop harvest and therefore responsible for poor air quality and other environmental risks. This case study examines the alternative to using rice straw as a feedstock for HCSB systems. Another aspect of HCSB systems is the potential creation of local jobs.

<u>Further outcomes:</u> The results of this research package were used to inform a social research project investigating the 'social license' of HCSB plants in NSW. For any potentially disruptive facility or project, its social license to operate (SLO) needs to be investigated carefully to ensure local communities are consulted. As the literature amply shows, this is also critically important for new energy generation projects, with consideration to SLO to be given from the earliest stages of the project [133]. A/Prof Brent Jacobs and Dr Rebecca Cunningham, from ISF, investigated the potential social licensing to operate of HCSB systems in the Riverina-Murray. A focus group of members from the

[26] It needs to be noted that the current COVID-19 pandemic and the associated temporary slowdown in production and trade is causing an extreme increase in raw material and steel prices. This study assumes the pre/post-pandemic prices to reflect usual market conditions.

local community were invited and informed about important aspects and impacts of HCSB plants. They were then asked for their opinions, preferences and concerns about the technology. Quantitative results of this research package were used to generate an info-graphic which informed the social research.

4.4. Hybrid concentrated solar biomass (HCSB) plants for renewable cogeneration for beef abattoirs in New South Wales, Australia

This work package has been published in the journal of *Energy Conversion and Management* as:

E. Middelhoff, L. Andrade Furtado, J. Reis Parise, F. Ximenes, and N. Florin, "Hybrid concentrated solar biomass (HCSB) systems for cogeneration: Techno-economic analysis for beef abattoirs in New South Wales, Australia," *Energy Convers. Manag.*, vol. 262, no. June 2022, p. 115620, doi: https://doi.org/10.1016/j.enconman.2022.115620.

The full manuscript is provided in Appendix 8.A.4. Hybrid concentrated solar biomass (HCSB) systems for cogeneration: Techno-economic analysis for beef abattoirs in New South Wales, Australia and a synthesis is provided below. This research package examines HCSB plants for their potential to provide renewable cogeneration to an abattoir and tannery owned by the *Northern Co-operative Meat Company* (NCMC). Two detailed HCSB plant design options for renewable, dispatchable cogeneration in the major beef abattoir were designed. Specifically, this research chapter investigates the technical design, operation and economic feasibility of this technology at the NCMC abattoir. In the context of the overall doctoral project, this chapter is the second of two detailed case studies, investigating the benefits and potential of HCSB plants in a specific context (Figure 38).

The key findings of this research package are:

- Both HCSB design options increase the energy self-sufficiency of the abattoir and can produce additional electricity for the grid,
- The two HCSB system cost around AU$ 25 million, and
- By incorporating this technology in all beef abattoirs in New South Wales up to 1.3 MtCO_2-e could be avoided.

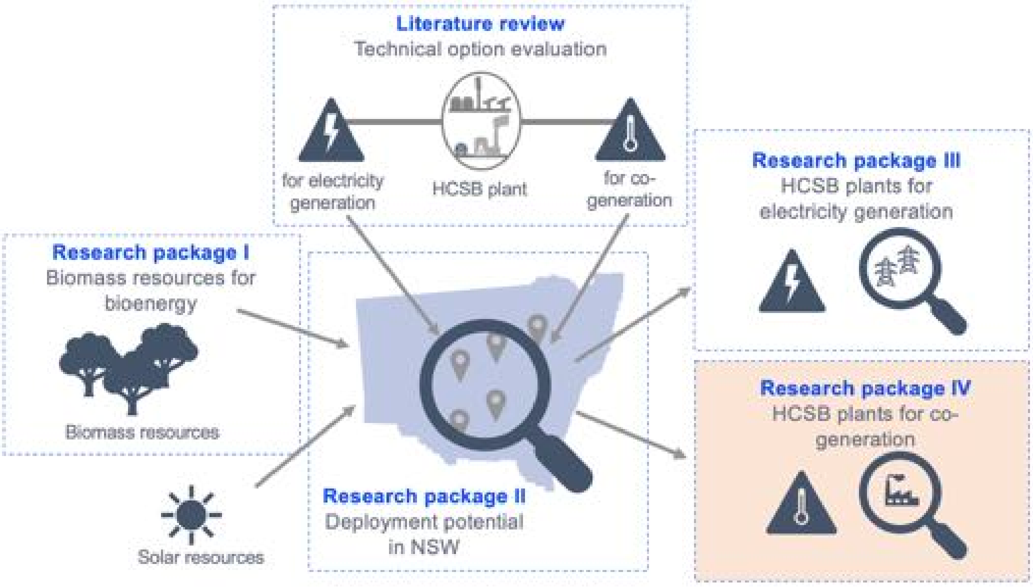


Figure 38: Research chapter V in the research structure (highlighted in red).

Research questions and methods: A detailed description of the methodological approach of this research package is provided in Appendix 8.A.4. Hybrid concentrated solar biomass (HCSB) systems for cogeneration: Techno-economic analysis for beef abattoirs in New South Wales, Australia, while a summary of the methods is given below. This research package answers the following questions:

- What is the best technical design of HCSB cogeneration systems for operation at red meat abattoirs in NSW?
- What is the economic feasibility of such HCSB systems?
- What is the energy generation and emission abatement potential of such HCSB systems?
- What are specific benefits of HCSB plant deployment and what are the specific siting requirements?

As a first step, HCSB systems are designed which can be integrated with the existing thermal energy system at the abattoir. This step requires thermodynamic modelling and detailed technology selection. As a second step the economic feasibility of these HCSB plants is assessed by considering technology costs, which are informed through literature reviewing and consultation with technology experts. To understand the specific energy generation, this research project considered hourly solar irradiation data and simulated the output of the proposed systems. The emission abatement potential was evaluated considering scope 2 emissions which result from reduced electricity purchase from the grid. Finally, the size of different technical components of the proposed HCSB systems were evaluated and the solar field siting is discussed for the marginal land of the abattoir.

Results and discussion: Red meat abattoirs have demand for thermal and electric energy. Currently, NCMC's thermal energy demand is supplied by the simple biomass boiler which supplies hot water and steam, while electricity is purchased from the grid. Another promising option is cogeneration of heat and power in the same system. However, the simple (currently deployed) combustion boiler at NCMC does not provide an ideal basis for cogeneration, as its steam generation is too low for power generation. In HCSB plants heat and power can be provided by combined solar thermal and bioenergy. The integration of solar thermal energy can supply additional heat to the thermal system of NCMC, and the combination of solar thermal and bioenergy can reach steam conditions, sufficient for steam turbine inlet.

This project designed and compared two options of HCSB systems:

Design option 1 is an ORC HCSB system. A solar thermal ORC system is preheated by the existing simple biomass boiler (Figure 39). The ORC HCSB system produces 5 MW_e output (Figure 39) and is preheated by the simple biomass boiler. The hourly heat and electricity demand in abattoirs varies depending on the industrial processes (load curve). To avoid energy spillage, the ORC HCSB system has three operational modes (‘combined heat and power’, ‘heat only’ and ‘electricity only’ generation). The selection of the operational mode depends on the availability of solar thermal energy and the thermal energy demand of the abattoir.

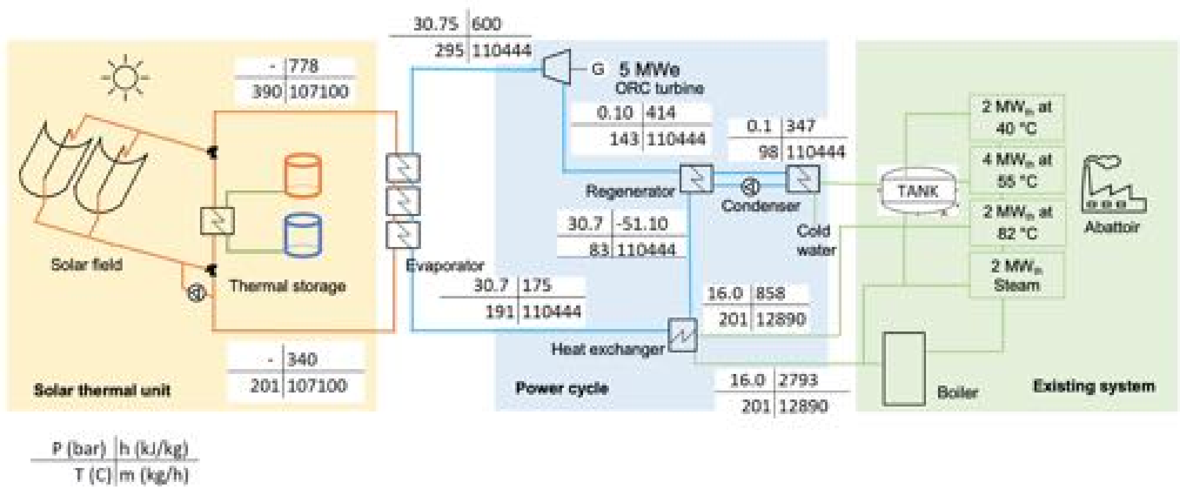


Figure 39: Proposed hybrid concentrated solar biomass (HCSB) system: design option 1 solar thermal organic Rankine cycle system, preheated by a simple existing biomass boiler

Design options 2 is a hybrid combined cycle (HCC) system supplied by the existing simple biomass boiler, CST and biogas superheating system (Figure 40). For this design option NCMC would need to use its liquid waste streams for biogas production via anaerobic digestion. 4.4 MWh_e is produced in a gas engine topping cycle and a steam turbine. Similar to HCSB design option 1, the HCC HCSB system has three operational modes (‘combined heat and power’, ‘heat only’ and ‘electricity only’ generation). The heat exhaust from the gas engine is used to preheat the boiler feedwater. This design increases the overall efficiency of the cycle compared to standalone biogas engine systems.

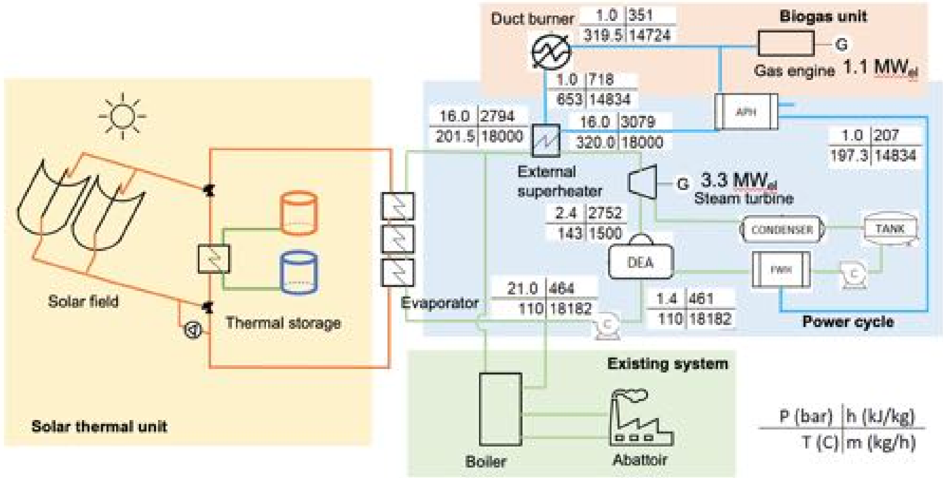


Figure 40: Proposed hybrid concentrated solar biomass (HCSB) system: design option 2 hybrid combined cycle (HCC) system, superheated by a biogas unit.

Both HCSB design options cost around AU$ 25 million[27] (Table 12). For the ORC HCSB system, electricity generation depends on the availability of solar thermal energy, while in the HCC HCSB system much of the generated electricity is facilitated by biogas. Because of this difference the solar field of the ORC HCSB system is larger than the one of the HCC HCSB system, with implications for space requirements. The ORC HCSB system requires about 20 hectare for the solar field, compared to about 5.5 hectare for the HCC HCSB system. The solar field needs to be mounted on flat and stable ground (not prone to flooding). To avoid thermal energy losses the solar field should be located within 1.5 kilometres from the rest of the plant.

The HCC HCSB system produces more than 21,000 MWh_e per year, while the ORC HCSB system produces 12,660 MWh_e. This is because much of the electricity generation in the HCC HCSB system depends on biogas, which is a more reliable resource than solar energy. Because more electricity can be generated in the HCC HCSB system, its economic feasibility (with levelised cost of electricity (LCoE) of AU$ 151.7 /MWh_e) is better than the one of the ORC HCSB system. During some of the operating hours the HCSB systems produce less electricity than needed for the abattoir, while in other periods more electricity is generated than needed. The excess electricity is about 5,400 and 8,700 MW_e per year, and about 14,500 and 9,000 MW_e per year needs to be purchased from the grid for ORC and HCC HCSB systems respectively. Both systems would result in carbon abatement of about 60 – 100 $tCO_{2\text{-}e}$ (scope 2 emissions) per year, compared to current operations of *NCMC*.

[27] It needs to be noted that the current COVID-19 pandemic and the associated temporary slowdown in production and trade is causing an extreme increase in raw material and steel prices. This study assumes the pre/post-pandemic prices to reflect usual market conditions.

Table 12: Comparison of the two design options of hybrid concentrated solar biomass (HCSB) systems at the abattoir

	Unit	ORC HCSB system	HCC HSCB system
Economic comparison			
Total CAPEX	Million AU$	25.0	24.3
Solar thermal unit	Million AU$	16.4	8.8
Biogas unit	Million AU$	-	11.2
Power cycle	Million AU$	8.6	4.3
Levelised cost of electricity	AU$/$MWh_{el}$	255.9	151.7
Levelised cost of heat	AU$/$MWh_{th}$	65.9	66.0
Space requirement			
Reflective area	[m^2]	39,240	19,620
Solar field space requitement	[ha]	19.7	5.5
Energy self-sufficiency			
Solar capacity factor	[%]	29	17
Total generated electricity	[MWh_{el}/year]	12,660	21,390
Electricity purchase from grid	[MWh_{el}/year]	14,471	8,996
Total excess electricity	[MWh_{el}/year]	5,444	8,699

There are three key options for using the excess electricity:

i. The abattoir could analyse the hourly electricity demand and consider load shifting. Operations with high electricity demand are shifted into hours in which the HCSB plant is generating electricity.

ii. The excess electricity can be sold with power purchase agreements to the electricity network or to local industry. Especially during evening hours, the HCSB plant can provide electricity at lower costs than the electricity grid.

iii. The abattoir could add another electrical machine into its operation, which could use the electricity during hours with less demand for the abattoir (e.g. during weekends). An interesting option is a biomass briquetting machine. Raw biomass feedstock, grown on the abattoir land could be harvested, dried, and pressed into briquettes, which are then sold as energy product or used for combustion in the biomass boiler.

Outcomes: Meat processing accounts for over 1.3 $MtCO_{2-e}$ per year [134], thus the transition to RE technologies is urgently required. The knowledge gained from the research study explains little about the general integration potential of HCSB systems into red meat abattoirs. An issue that does not allow to answer the 'standard solution' question quickly, is the high diversity of energy supply systems that are currently used at abattoirs. For their current energy supply, the meat industry relies mainly on grid electricity, coal and natural gas combustion systems. To avoid high technology costs, it is advantageous to integrate solar thermal and bioenergy into the existing systems, and this needs to be assessed on a case-to-case basis. Nevertheless, the presented study for the Casino abattoir holds important results with implication to other abattoirs: The study investigates the incorporation of biogas from AD of liquid waste streams from the abattoir. Waste management, and a common solution, anaerobic digestion, are often discussed in the context of abattoirs [135], [136]. Nevertheless, the harvested biogas alone, is not enough to account for the total energy demand of the abattoir. Thus, this study presented that the integration of solar thermal and bioenergy can offer a solution for high percentages of RE supply while utilising the local biogas resources efficiently.

Outside the scope of this research project, but nevertheless important in the broader context of rising greenhouse gas emissions and climate change, is the general discussion around red meat consumption. Red meat consumption has been shown to contribute to a range of global change problems, including environmental degradation (incl. deforestation for pasture land) [137], greenhouse gas emissions (not just for meat processing, but especially during meat production) [137], as well as a number of diseases (e.g. colon cancer) [138]. This means that the renewable energy options explored in research package IV should be placed in the shorter-term, local energy context of NSW rather than taken as a proposition amenable to scaling up and scaling out.

4.5. Synthesis of outcomes

This synthesis section aims to summarise the main outcomes of the four research packages and the literature review in relation to the golden thread of the thesis and HCSB plant options, deployment potential and benefits. HCSB **technical options** were examined as follows: First, various (formerly proposed) HCSB design options were listed and ranked according to their technical and commercial maturity (section 2., p. 28). This literature review offered the empirical contribution of a detailed numerical maturity ranking for different systems. In addition, two ready-to-use HCSB design options were selected for further investigation in the context of two case studies in NSW. For both systems, RC and ORC HCSB plants, different plant components (e.g. solar collector types, working fluids, biomass feedstock types) were reviewed, discussed, selected and their performance was evaluated using a thermodynamic approach. These simulations provided novel theoretical and empirical knowledge and provided case studies to support HCSB deployment in NSW and further investigations in other countries.

The **deployment potential** of HCSB plants was studied considering spatial constrains (protected land) and opportunities (resources availability, section 4.1, p. 53), as well as considering different market integration points (zone substations and industrial sites). As an additional methodological result from this work, a GIS model was developed. The applicability of this model is demonstrated by the fact that it is used for the implementation in an online tool (section 4.2, p. 57). The model could also be applied to other jurisdictions worldwide. In the context of NSW, the GIS model supported the empirical understanding of the HCSB deployment potential in regards of installed capacity (technology potential) and emission abatement potential (support of the energy transition of NSW).

Benefits of deploying HCSB plants included an understanding of how HCSB plants can support the specific challenges of NSW's energy transition. Here the main opportunities lay in the provision of dispatchable RE and cogeneration for local industries. In addition, the advantaged of using HCSB systems were examined with regards to their economic feasibility. For this study, an economic model was developed which enables easy comparability of HCSB plants to other RE technologies in the context of Australia (section 4.3, p. 63). Last but not least, the benefits of using HCSB plants for local communities were discussed within the framework of two case studies (sections 4.3., p. 63 and section 4.4., p. 67). A further discussion of the thesis results is provided in the following sections.

5. Discussion

This thesis presents a literature review and four research packages contributing insights to the overall question of the potential (resources availability and application potential), options (technical design and maturity) and benefits (context of local case studies) of HCSB plant deployment for NSW's clean energy transition. Specifically the thesis provided the following key outputs:

(1) A novel technology pathway to support solar thermal and bioenergy industry development and technology demonstration in Australia,

(2) A detailed investigation of technical design, market integration, and economic feasibility of a prototype HCSB plant for dispatchable electricity generation in the electricity grid of NSW, and

(3) A detailed technical discussion of HCSB plants for cogeneration in NSW's industries with low to medium process heat demand.

This discussion section will elaborate on the deployment potential of HCSB plants and focus on the following points: i) benefits of HCSB plant deployment in NSW, ii) the role of HCSB plants in supporting the clean energy transition, iii) HCSB plants as industrial cogeneration systems, iv) HCSB plant electricity market integration, v) HCSB plants for dispatchable electricity generation, vi) the temporal and policy context of the work, and vii) next steps towards HCSB plant deployment in NSW. Each of these points will also be discussed in the context of benefits for different stakeholder groups.

5.1. Benefits of HCSB plant deployment in NSW

In the introduction of this thesis (section 1.3, p. 24), general advantages of HCSB plants were compared against standalone solar thermal and bioenergy plants. The findings of the thesis give further emphasis on these benefits of HCSB plant deployment in the specific context of NSW.

The advantage of reduced biomass feedstock use in HCSB plants compared to standalone bioenergy plants is important in the context of NSW. Although NSW has ample availability of biomass resources [139], as further evaluated in research package I (section 4.1, p. 53), the local availability of resources for bioenergy production varies widely. Additionally, the amount of available biomass feedstocks on the Australian continent varies strongly between years based on nutrient and water supply during biomass growth [140] and is impacted by recurrent droughts and bushfires [141]. In order to increase supply of locally availably biomass resources, dedicated biomass energy crops[28] can be grown on marginal or unproductive land (about 20 million hectares

[28] Dedicated energy crops are specifically grown for bioenergy generation purposes. They are typically fast growing, and in the case of woody crops they can often be harvested and regrown naturally (e.g. after harvest, they can regrowing from the stump, also known as coppicing). Dedicated energy crops can increase biomass feedstock availability in regions with low resources. For farmers, or industries, that grow dedicated energy crops on marginal land, revenue is generated from the sale of the biomass and potentially from access to carbon credits. In addition, they may generate multiple environmental benefits, such as soil improvement, provision of shade and shelter, increased biodiversity and provision of wind breaks.

in NSW [139]). Another option is the integration of solar thermal energy into bioenergy plants which minimises the dependency on biomass resources.

The fact that HCSB plants can be operated using less biomass feedstock that standalone bioenergy plants can be important for the social viability of new energy generation plants. During focus group meetings, members, that belonged to the local community of Griffith, were asked about their concerns and thoughts about HCSB plant deployment in their region (further explained in section 4.3, p. 63). During this focus group meeting concerns about the potential traffic increase due to biomass feedstock transport to a new bioenergy facility were expressed. In Australia, many goods are transported as road freight, which has a major impact on traffic and local communities during harvesting times and in agricultural regions[29]. Because HCSB systems can be designed to require less biomass feedstocks, less biomass transport is needed and the social acceptance might increase compared to standalone plants.

As discussed in section 1.3. (p. 50) HCSB plants need a smaller solar field and thermal energy storage than standalone solar thermal plants. The findings from research chapter III (section 4.3., p. 63) underline that this brings the technology into a better financial situation of HCSB plants, due to reduced overall plant costs. Due to the reduced plant costs, HCSB plants become economically feasible at smaller scales. In research package III (section 4.3., p. 63) a HCSB plant was compared to a standalone CSP plant, both generating about 220,000 MWh/year. While the standalone CSP plant required a capital investment of AU$ 303 million, the investment of the HCSB plant was AU$ 167 – 230 million. This reduction in capital cost is especially advantageous in the context of Australia because previously the high initial investment was a problem for commissioning standalone CSP plants, like the 150 MW_e *Aurora* plant in Port Augusta [94]. Similarly, the required electricity price for economic operation of the standalone CSP plant was found to be AU$ 220 /MWh compared to AU$ 135 – 200 /MWh for the HCSB plant.

Research package II (section 4.2., p. 57) investigated the siting potential of HCSB plants in NSW. Compared to standalone CSP plants, HCSB plants only require direct normal irradiation of around 1,700 – 1,800 kWh/m^2/year [127] for electricity and 1,050 kWh/m^2/year [11] for cogeneration, respectively. While standalone CSP plants can only be sited in the western part of NSW (Figure 41), the HCSB plant siting potential is considerable for most regions of the state (solar resources exceed > 1,300 kWh/m^2/year in most parts of NSW). This increased siting potential has the additional advantage that energy generation can happen closer to the coast, where the larger cities and centres of energy demand are located. This also increases the access to the transmission line infrastructure.

[29] Result from focus group meetings with local communities in Griffith, Australia in spring 2019.

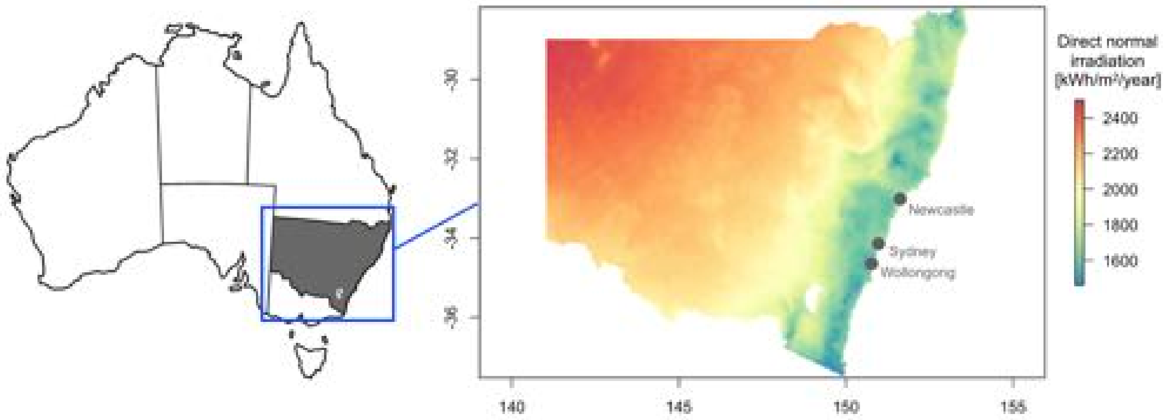


Figure 41: Map of Australia (left) and New South Wales (NSW) (right) with direct normal irradiation and cities with more than 200,000 inhabitants.

From the described advantages of HCSB plant deployment in NSW it can be speculated that HCSB plants are a promising technology to support the local energy transition. Particularly, the technology can also support the development of the Australian bioenergy and CSP industry, because of its advantages compared to the standalone systems. The development of both industries, bioenergy and CSP, is underdeveloped in the context of Australia but also described to be important for the success the clean energy transition, as further described below:

- The support and development of the bioenergy industry is particularly important because recent bioenergy assessments show that Australia's bioenergy industry is lagging behind that of other jurisdictions [34], [142]. Compared to other developed countries with a bioenergy share > 4%, Australia's bioenergy share is 1.4% [34], [143]. The low deployment of bioenergy is contrasted to projections in which bioenergy will play an important role in the future clean energy supply system: The *Intergovernmental Panel on Climate Change* has released scenarios that project a high importance of bioenergy (and carbon capture and storage) of up to 30% for global electricity generation by 2050 [115]. To overcome the discrepancy between current and prospective bioenergy use the *Australian Government* supports the development of a strong bioenergy industry as outlined in the recent Bioenergy Roadmap [144]. In this context, the specific benefits of HCSB plants can become important in supporting and establishing a strong and socially acceptable bioenergy industry in Australia.
- Similarly, also the solar thermal industry sector can be supported through the deployment of HCSB plants. Because of Australia's great solar resources, solar thermal systems have great potential as part of the range of RE solutions considered for the future clean energy supply on the continent [93]. Nevertheless, there are currently no commercial CSP plants on the continent and the solar thermal industry in Australia is lagging behind that of other jurisdictions [43]. As described above, HCSB plants have a number of advantages compared to standalone solar thermal systems and might therefore be a good option to support the solar thermal industry development. Once a few HCSB plants are commissioned in NSW, better price estimates for solar thermal components would be available and local supply chains could develop, which would support the deployment of standalone HCSB plants.

5.2. The role of HCSB plants in supporting the clean energy transition

Besides the above mentioned technological advantages, the research has also highlighted potential contributions of HCSB plants to support the current state of energy transition in the different sectors and for different energy types in NSW. As explained in the introduction (section 1.2., p. 20), the energy transition for different sectors and energy types is being accompanied via several pathways with different challenges (Table 13).

Table 13: Overview of energy transition approaches for key economy sectors including associated technical challenges and potential for HCSB deployment as summary of thesis section 1.2., p. 20.

Sector	Success in energy transition	Energy transition approaches	Technical challenges	HCSB deployment to support energy transition
Electricity generation	Low to intermediate (~ 21% renewable energy (RE) supply)	Renewable alternatives	Load balancing	Good potential as dispatchable renewable technology
Industrial	Low (~ 7% RE supply)	Electrification, increase in energy efficiency, renewable alternatives (e.g. bioenergy)	Finding renewable alternatives	Good potential for industrial heat supply (low to medium)
Commercial	Low (~ 13% RE supply)	Electrification (e.g. heat pumps), increase in energy efficiency (e.g. insulation), roof top solar		Intermediate potential (small to medium size electricity or cogeneration system)
Residential	Low to intermediate (~ 24% RE supply)	Electrification (e.g. heat pumps), increase in energy efficiency (e.g. insulation), roof top solar		Low to intermediate potential (small size electricity or cogeneration system)
Transport	Low (~ 1% RE supply)	Electrification, alternative fuels (e.g. hydrogen, biofuel)	Finding renewable alternatives	Low potential (some potential to support biofuel production)

As Table 13 shows, HCSB plants are expected to play only a minor role in the energy transition of the residential and transport sectors of NSW. This is because the small operation-scale (< 5 MW_e) required in the residential sector is less suitable for HCSB plants, which only become economic at scales > 5 MW_e, as discussed in research chapter III (section 4.3., p. 63). Previous studies from Europe have investigated the use of HCSB plants for supplying renewable and thermal energy to the local community of Brønderslev in Denmark [11]. This option is less suitable in the context of NSW, because NSW's municipalities have a relatively low heating demand. In the context of the energy transition in the transport sector, HCSB plants are discussed to support the development and synthesis of alternative fuels like solar fuels [145] and bio-diesel, however these technologies are still immature (section 2., p. 28).

In contrary to this, and as shown in Table 13, HCSB plants can support the energy transition of the electricity generation and the industrial sector. The findings of this thesis indicate that HCSB plants are primarily useful in supporting NSW's energy transition: i) of the electricity sector, by providing dispatchable electricity as grid connected system (section 4.3., p. 63), and ii) of the industrial sector, as a cogeneration system (section 4.4., p. 67). Hereby, research chapter II (section 4.2., p. 57) and III (section 4.3., p. 63) of this thesis further investigated HCSB plants as medium to larger scale (> 5 MW_e) grid-connected, electricity-generating plants, while research chapter IV (section 4.4., p. 67) investigated HCSB plants for cogeneration for industrial applications. In this thesis, red meat abattoirs were used as a case study to investigate the deployment of HCSB plants for cogeneration (section 4.4., p. 67).

Section 1.2. (page 20) of this thesis gave an overview over the key objectives of the energy transition of the NSW Government [19]. The findings of this doctoral project underline that HCSB plants *can* support these key objectives. The four key objectives of ongoing, affordable, secure and reliable energy supply for NSW as specific ambitions to achieve net-zero emission by 2050 are further elaborated in Table 14. HCSB plants can support these ambitions providing dispatchable and reliable energy. The technology is furthermore of *low risk* to both the environment and local communities. The affordability of HCSB plants is comparable to that of other dispatchable RE technology, as discussed in research chapter III (section 4.3., p. 63) and IV (section 4.4., p. 67) and below. The results of this thesis are therefore relevant to positioning HCSB plants as a suitable RE technology option and communicating their advantages to local policy makers.

Table 14: New South Wales (NSW)'s key objectives of energy transition [19] and support options of hybrid concentrated solar biomass (HCSB) plants.

ONGOING	AFFORDABLE	SECURE	RELIABLE
Continuous RE energy supply at all future times, implying an establishment of a well-integrated and interconnected network.	Deployment of mature technologies, which are suitable for the available renewable resources in NSW and are easily financed and cheap to be operated.	Deployment of technologies with low operational risks and low negative social and environmental impact.	Reliable, continuous RE energy supply at all times, which is strongly connected to the use of technologies with storage or ability to respond quickly to changes in energy demand and supply.
HCSB can be integrated into the electricity grid (research chapter II) and can as such supply electricity using the already established infrastructure.	The literature review of this thesis presented two mature HCSB plant options, research chapter I and II discussed and show the great resources availability in NSW, research chapter III and IV showed that HCSB plants have a good economic feasibility.	Research chapter III and IV discussed the social and environmental impacts of HCSB plants in NSW. Both studies found that HCSB plants have a low operational risk and offer several benefits to the local communities.	As repeatedly explained throughout the thesis, HCSB plants include up to two energy storage systems and can as such generate energy continuously.

5.3. HCSB plants as industrial cogeneration systems

In the literature review conducted for this thesis (section 2., p. 28), two types of HCSB plants were identified for further investigation, of which HCSB plants for industrial cogeneration were further investigated in research package IV (section 4.4., p. 67). The Australian red meat industry was chosen as a case study, because (i) red meat abattoirs have a high demand of thermal and electric energy, (ii) it is a major industry, contributing over AU$ 17 billion to the national economy [146], and (iii) the industry has strong ambitions to reduce their carbon emissions [134]. Commitments to limit global warming to below 1.5 °C [9] by achieving net-zero greenhouse-gas emissions by the middle of the century [1], [147] are putting pressure on the industry. The processing of Australian red meat accounts for approximately 1.3 $MtCO_{2\text{-}e}$ per year [134]. One reason for this is that energy-intensive processes including cooling, equipment sterilisation, plant wash-down, carcase processing, rendering and blood cooking [148], are currently mainly powered by grid electricity (32%) and the onsite combustion of natural gas (37%) and coal (19%) [149]. Tighter environmental regulations, emission abatement incentives, increasing natural gas and electricity costs, as well as ageing equipment is driving the red meat industry to updating and replacing their equipment and energy supply systems. As shown in research package IV (section 4.4., p. 67), HCSB plants can effectively be used at abattoirs, to reduce carbon emissions and to guarantee renewable energy supply. Furthermore, as shown in research package II (Figure 35), all existing red meat abattoirs could deploy HCSB plants from a resources supply perspective.

HCSB plants can supply thermal energy at temperatures up to 350 – 450 °C [111], [150], [151]. There are other industries in NSW which are similar to red meat processing in terms of size, energy demand, and urge for energy transition. These industries are interesting for further investigation of HCSB plant deployment: agricultural sector, mining, food, beverage and textile production, wood, paper, and printing, chemical production, water and waste management, and construction. Additionally, many commercial buildings have heat demand and the findings of the literature review showed that as cogeneration systems, HCSB plants can be a feasible solution for larger buildings like hospitals, schools/offices [152], shopping centres, and hotels [150].

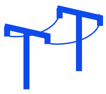
HCSB plants for industrial cogeneration need to be designed for each industry individually, to meet the local and specific energy demand. The best technology components need to be selected considering space availability and other local constrains. This is different to HCSB plants for electricity generation, which can be prototyped (e.g. as presented in research package III) and can as such be deployed in many different areas of NSW.

5.4. HCSB plant electricity market integration

RE technologies can be integrated into the electricity grid at several market integration points. Research package I (section 4.1., p. 53) considered bioenergy siting in proximity to the transmission infrastructure, while research package II (section 4.2., p. 57) investigated the siting potential of HCSB plants at zone substations with new connection capacity in NSW. Research package IV (section 4.4., p. 67) investigated HCSB plants that are connected to industrial sites. The following discusses all these and other market integration options of RE technologies in NSW, and discuss which ones are specifically suitable for HCSB plants and why.

Most of NSW's electricity is supplied via the electricity transmission network[30]. Other market integration options can be found all along the energy supply chain and even right at the energy demand site (on-side generation). Table 15 shows how the energy has been supplied traditionally (and still mostly today[31]). Electricity is generated in large, decentralised power stations which are mainly fed by coal and natural gas and is transported to the centres of energy demand using the transmission and distribution grid. The transmission and distribution network was explicitly designed to connect the fossil fuelled power stations with cities and regions of energy demand.

Table 15: Traditional electricity supply system in New South Wales (NSW).

	**Large-scale power stations** Power generation in large and decentralised coal and gas power stations (almost 100% of total share), overall low electricity prices (compared to other countries) due to oversized capacity [28]
	**Transmission network** The electricity grid of the *National Electricity Market* brings the electricity from the large power stations to the centre of energy demand
	**Zone substations** Substation are part of every electricity network and traditionally transform the high-voltage power of power stations to low-voltage level for the safe usage in the distribution network
	**Distribution network** Distribution infrastructure transports the electricity from the transmission network to the single households, commercial sites and industries
	**Electricity consumer** Electricity consumer purchase electricity from electricity retailers at commercial and residential power purchase agreements

This traditional concept of electricity supply only works to a limited extent for RE technologies. RE plants often operate at much smaller scale than fossil fuel power stations, and expansions of the electricity grid

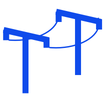
[30] The Australian continent has two independent electricity networks. New South Wales (NSW) is part of the *National Electricity Market* which is supplying the eastern states (Queensland, NSW, Australian Capital Territory, Victoria, South Australia, and Tasmania) with electricity. The *National Electricity Market* is the largest interconnected electricity network in the world, spanning over 5,000 km [181]. Since 2009, matching of electricity demand and supply is facilitated by the *Australian Electricity Market Organisation*. Wholesale electricity trading is based on a spot price market approach: Generators offer electricity in a five minute interval, the *Australian Electricity Market Organisation* decides which generators are required to supply electricity and chooses the most cost-efficient offers [28], [181].

[31] By 2035, most coal-fired power stations in New South Wales (NSW) will have reached their end of life. The renewal of these fossil fuelled power stations or the construction of new plants is not planned because this would not be economic and hinder national goals of decarbonisation of 40% by 2030 (of the emissions in 2005) and 100% by 2050 [182].

are often not economic. For some large-scale (>> 100 MW_e) RE projects, that are decentralised and subsided, such as the *Snowy Mountain* hydro dam, these transmission line network expansions are however affordable [153]. For HCSB plants, network expansions are not affordable as they are likely to be deployed at scales < 100 MW_e, as explained in research chapter II (section 4.2., p. 57). As such as HCSB plants need to be integrated at market integration points of the existing energy supply system.

With the depletion of fossil-fuelled electricity generation in NSW, the electricity transmission infrastructure faces the challenges of accommodating multiple new plants at a small scale and different locations. Table 16 shows how RE technologies can be integrated into the existing electricity network of NSW. A difficulty is that these generators need to fulfil the siting requirements of sufficient resources availability (e.g., sufficient solar resources) while also being located in proximity to the existing transmission lines [14], [37]. The grid connection to zone substations with new connection capacity, as discussed in research chapter II (section 4.2., p. 57), is particularly suitable. Another option for RE siting are the *Renewable Energy Zones* (REZ) and *Special Activation Precincts*. REZ are dedicated regions of Australia in which the transmission lines are extended such that multiple new RE plants can be connected to the grid [153]. REZ are located in regions that are especially rich in the availability of renewable resources and are already interconnected with the existing grid system [153], as shown in Figure 42. Likewise, *Special Activation Precincts* are dedicated regions of NSW [154]. *Special Activation Precincts* are developed within specific planning frameworks to support new industrial and commercial infrastructure projects [154]. HCSB plants can be designed to support the additional energy demand for these precincts and new industrial sites, as discussed in research chapter IV (section 4.4., p. 67). Last but not least, in the context of single commercial or industrial buildings, or in remote off-grid areas, HCSB plants can be deployed as a microgrid solution.

Table 16: Integration of renewable electricity generator in the electricity grid of NSW.

	**Large-scale power stations** Decentralised power stations become rare. Exceptions are e.g., the Snowy Hydro Scheme [153].
	**Transmission network** Major transmission line extensions are planned to stabilise the electricity supply. Electricity generation in one part of the continent can stabilise electricity supply in other parts. In *Renewable Energy Zones* (REZ) transmission line extension is planned to accommodate new generator capacity.
	**Zone substations** New small scale (< 50 MW_e) electricity generator can seek grid access through zone substations with new connection capacity.
	**Distribution network** With the growth of the Australian population and industries the distribution network in Australia needs to extend to reach new communities and industrial sites.
	**Electricity consumer** Renewable power generation can be facilitated directly at the commercial, residential or industrial site.

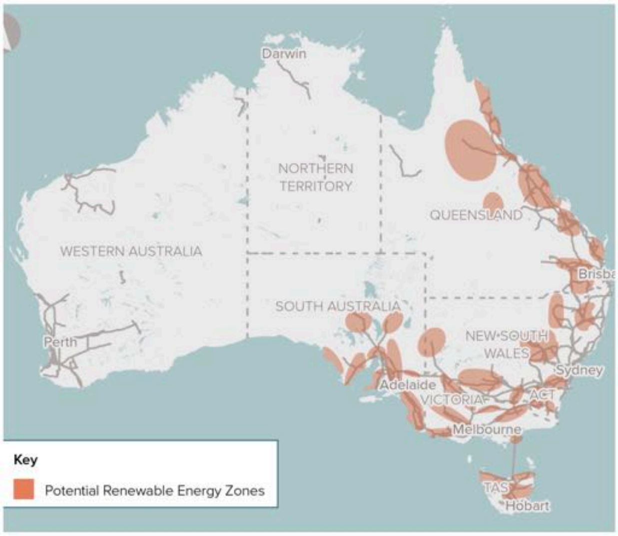


Figure 42: Geographic map of potential *Renewable Energy Zones* (REZ) in Australia. Source: Commonwealth of Australia [155].

5.5. HCSB plants for dispatchable electricity generation

This section will further discuss grid connected HCSB plants. In the following sections, the findings of the different research packages will be used to compare HCSB plants to other commonly discussed dispatchable RE technologies in Australia. Figure 43 shows these commonly discussed technologies: Bioenergy, geothermal, CSP, and hydro dams, hydrogen, batteries and pumped hydro energy storages (PHES) [28]. The comparison is informed by findings from this thesis and is structured along different technology characteristics including technology scale of operation, dispatchability and flexibility of energy generation, life time, costs, and other important parameters.

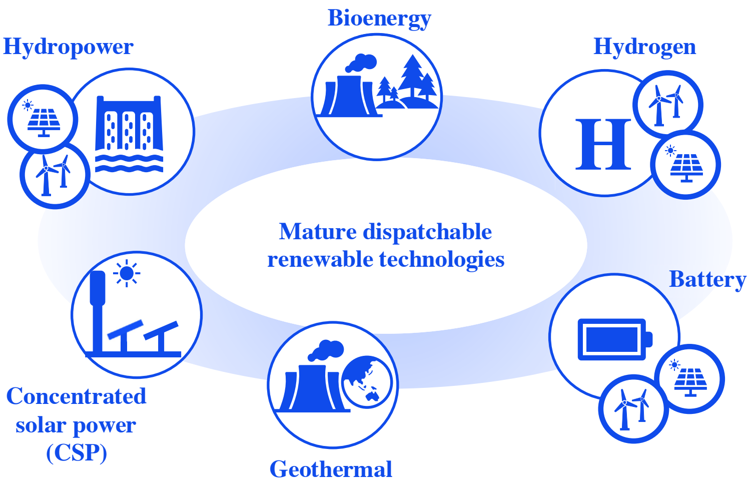


Figure 43: Mature and dispatchable renewable technologies.

If technology developers are asked to explore the technical options for providing dispatchable renewable energy at a specific location, their choice will depend (among other factors) on the parameters of energy demand and availability of local renewable resources. With their typically deployment scale [MW_e], HCSB plants can be installed to generate grid connected electricity generator in places with electricity demand between 5 – 50 MW_e (research package II and III) and potentially up to 150 MW_e. Other commonly deployed

RE technologies at this scale are standalone bioenergy and geothermal plants (Table 17). Their similar deployment scale results from their common use of steam turbines for electricity generation. Furthermore, standalone solar PV and onshore wind power stations are deployed at a similar scale to HCSB plants. These technologies are commercially very mature and their electricity generation can be made dispatchable by installing batteries which are very flexible in scale because they consist of modular units. Other RE technologies like PHES systems and standalone CSP are deployed at much larger scales than HCSB systems and in most cases exceed 100 – 150 MW_e.

Energy generation technologies can also be compared for parameters like the required ramp up time to operate at full capacity or the technology lifetime. In these regards, HCSB plants are similar to other RE technologies (research package II and III). HCSB plants, standalone bioenergy systems, geothermal plants, and CSP stations are commonly designed with steam turbines that require about 30 minutes for ramp up. If a location requires fast-reacting and flexible RE, other dispatchable RE technologies are more competitive. Hydrogen, used in gas turbines, as well as PHES and batteries only require seconds or minutes for ramp up, as further discussed in Table 17. Table 17 also compares the lifetime of different dispatchable RE technologies. The lifetime does not vary greatly between the different technologies and most technologies operate for between 20 to 30 years.

Another performance indicator for the comparison of different RE technologies is the dispatchability of energy generation. The dispatchability of RE technologies varies strongly (Table 17). In this regard HCSB plants are very competitive because they can be deployed with up to two different storage systems (a thermal energy and a biomass storage) and can therefore generate electricity very flexible (discussed in research package III). Biomass storage are among the cheapest energy storage systems and can aid biomass combustion continuously for up to several weeks [19]. Other renewable technologies with great dispatchability are hydrogen (especially when integrated into the gas network), PHES and geothermal systems that can operate continuously for several days or months [19]. RE technologies with less dispatchability are standalone CSP systems that are usually deployed with a thermal energy storage at capacity to generate energy for 8 – 20 hours [19]. Larger thermal energy storages in CSP plants are technically possible, however the solar field needs to be oversized dramatically in order to supply energy into such a large storage. This is often uneconomic because it increases the overall plant cost [156]. The smallest dispatchability is achieved for batteries that are most economic when designed to only dispatch energy for about 30 minutes [19].

Table 17: Differences of most common and commercially used dispatchable renewable electricity generator, compared to hybrid concentrated solar biomass (HCSB) plants. Dark blue bars represent 'typically deployed at/with', while light blue bars represent 'minimal and maximal deployed at/with'.

	Hybrid concentrated solar biomass (HCSB) plants	**Bioenergy**	**Concentrated Solar Power (CSP)**	**Battery**	**Pumped Hydro Energy Storage (PHES)**	**Hydrogen**	**Geothermal**
Scale	Small domestic systems (0.5 MW_e) to large-scale power stations (100 MW_e) [13]–[15], [38]	Small domestic systems (0.5 MW_e) to large-scale power stations (100 MW_e), cost effective limitations of biomass transport distances limits size to about 20-50 MW_e [30]	Plants become economic > 50 MW_e, most plants are however even larger with capacities between 150 – 250 MW_e [43], [72]	From residential (10 kW_e) to transmission connected (100 MW_e) [30]	Very dependent on the location, from small scale (5 MW_e) to large-scale power stations (> 1,000 MW_e), generally around 200 MW_e [30]	Typical scale is e.g. 30 MW_e electrolyser with 1,000 hours of salt cavern storage and a 30 MW_e combined cycle hydrogen turbine [30]	Typical size around 50 MW_e [30]
Flexibility [minutes]	Steam turbines need about 30 minutes to ramp up completely	Steam turbines need about 30 minutes to ramp up completely, Biogas in gas turbines can be ramped up within a few minutes	Steam turbines need about 30 minutes to ramp up completely	Immediately within milliseconds, which makes them suitable to smoothing of sudden changes in resource levels of VRE	Ramp up within a few minutes or seconds if gas is running synchronously	Hydrogen in gas turbines can be ramped up within a few minutes	Steam turbines need about 30 minutes to ramp up completely
Lifetime [years]	30 years [33]	20 – 25 years [30]	30 years [30]	30 years [30]	30 years, long life-time without losing capacity [30]	30 years [30]	30 years [30]
Dispatchability [hours]	Variable deployment of up to 24 hours per day for multiple days, generally competitive at capacity factor > 50 %	Variable deployment of up to 24 hours per day for multiple days, generally competitive at capacity factor > 50 %, also limited by the amount of available feedstock [30]	Competitive at > 6 hours of storage, maximum storage approximately at 20 hours [30]	Cheapest at storage level of 0.5 hour, competitive up to 3 hours [30]	PHES are competitive across all durations of storage, particularly competitive > 6 hours [30]	Dispatchable technology with largest storage potential, which could allow for several weeks of continuous operation, however currently not competitive at any scale [30]	Competitive generation if operated closest to continuously, 24 hours [30]

	Hybrid concentrated solar biomass (HCSB) plants	Bioenergy	Concentrated Solar Power (CSP)	Battery	Pumped Hydro Energy Storage (PHES)	Hydrogen	Geothermal
Deployment potential in Australia	Australia has good biomass and solar resources and the hybrid technology could be deployed in many places [126]	Australia has good biomass resource availability, which is currently underutilised for bioenergy purposes [34]	Australia has good solar resources and siting is possible in many locations [157]	Batteries are already deployed in Australia and have no specific siting requirements	PHES is the most site specific technology due to its dependence on geology and head height characteristics, Snowy 2.0 is a planned for reservoir with 2,000 MW power capacity and 350,000 MWh of storage [30]	Hydrogen has no specific siting requirements	Australia does have some hot sedimentary aquifer resources, however small deployment potential, as Australia's geology does not have convective hydrothermal systems and can only use geothermal energy via conductive processes, which have low global experience [30]

One of the most important factors for local RE technology selection are the locally available resources. The various dispatchable RE technologies show different siting and deployment potential in NSW. While some technologies (like hydrogen and batteries) have no specific siting criteria and can be deployed almost everywhere [19], other technologies strongly depend on local resources availability. HCSB plants are highly reliant on local resources (research package II). In NSW, however, both supplying resources, biomass and solar, are highly abundant. This gives HCSB plants a good siting potential (research package I and II).

Another important performance indicator when comparing different RE technologies is their employment factor [jobs/MW_e]. As highlighted in research chapter III (section 4.3., p. 63), HCSB plants can create more local full-time jobs than some of the other RE technologies. While solar PV and wind power stations are generally operated with < 0.5 jobs/MW_e [158], in bioenergy related projects (like HCSB plants) require about 3 jobs/MW_e [159]. This is also significantly higher compared to PHES systems, with about 0.2 jobs/MW_e [160] and batteries, with 0.3 – 1.2[32] jobs/MW_e [160]. For geothermal, standalone CSP and hydrogen[33], these comparisons are difficult as there are no operating systems in Australia. The increased creation of job in bioenergy related technologies, such as HCSB plants, results from the increased effort for bioenergy harvesting, processing and transportation and can be seen as a significant socio-economic advantage.

Another important performance indicator for the selection of RE technologies is the levelised cost of energy ($LCoE$). The LCoE calculations considers fixed and variable operation and maintenance costs ($O\&M_f$ and $O\&M_v$), the installed cost (C) and financing (CRF), as well as the generated electricity (E) as described in Eq. (1):

$$LCoE = \frac{(\mathrm{CRF} + O\&M_f) \times C}{\mathrm{E}} + O\&M_v. \quad (1)$$

Here the CRF is the capital recovery factor, which depends on the weighted average cost of capital (WACC) and the lifetime of the plant (n) calculated using Eq. 2:

$$CRF = \frac{\mathrm{WACC} \times (1 + \mathrm{WACC})^n}{(1 + \mathrm{WACC})^n}. \quad (2)$$

Figure 44 compares the LCoE of the different dispatchable RE technologies using the dispatchable energy spreadsheet[34] [30] and HCSB plant cost estimates from research package III (section 4.3., p. 63). The LCoE comparison of different dispatchable renewable technologies is complex. This is because, as described above, dispatchable RE technologies are deployed with different

[32] For utility and distributed batteries.
[33] Estimates prognosticate that the hydrogen industry could generate about 7,600 jobs in Australia by 2050 [183]
[34] Using price data for 2017.

storage systems, thus storage capacities and at different scales. In order to compare the LCoE of different dispatchable RE technologies there are two options, to compare the LCOE i) at one specific deployment scale and storage capacity, and ii) of each technology at its individual optimal (most cost effective) deployment scale. Because our focus is the comparison of HCSB systems to other dispatchable renewable technologies, the first type of comparison is chosen. Figure 44 compares the LCoE of the different dispatchable RE technologies at 30 MW_e capacity and with 20 hours of dispatchable, renewable electricity supply. At this scale HCSB systems are among the cheapest dispatchable RE technologies, producing electricity at a cost of AU$ 109 – 159 /MWh. Bioenergy is slightly cheaper and can even be cost competitive with variable renewable technologies. Geothermal, CSP and PHES produce electricity at a similar cost than HCSB plants. In the LCoE comparison in Figure 44 hydrogen and batteries are currently not cost competitive to HCSB plants.

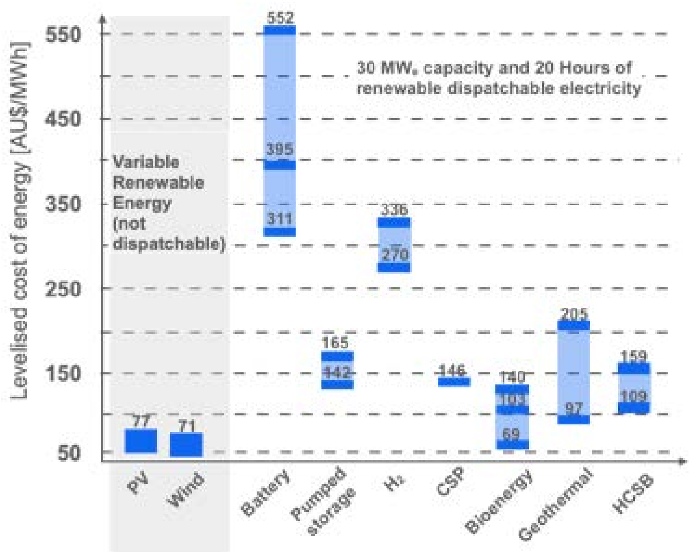


Figure 44: Levelised cost of energy (LCoE) produced in renewable technologies in 2017, comparing variable and dispatchable renewable energy (RE) generator at 30 MW_e and 20 hours of electricity generation per day. Cost model adopted from Lovegrove et al. [30].

To sum up, HCSB plants show very similar technical and operational characteristics compared to other dispatchable RE technologies. These performance similarities allow HCSB plants to be competitive to other dispatchable RE technologies and they can therefore be discussed alongside common RE technology in the context of the energy transition in NSW. The previous sections included a high-level comparison of different dispatchable renewable technologies. A detailed technology comparison is difficult and individual benefits and advantages of the different technologies need to be weighed against each other. The selection of a RE technology in a specific contexts needs to be selected on a case-by-case basis. A few additional comments on HCSB plants compared to other dispatchable RE technologies include:

- Batteries require minerals (such as cobalt), which are limited and their mining already has significant environmental and human impacts [161]. In contrast, HCSB plants use local biomass and solar resources for their operation. On the other hand, HCSB plants are by no means an alternative to batteries. In 2017, the biggest lithium ion battery in the world, the *Hornsdale Power Reserve* was commissioned in SA [162]. The 100 MW_e battery was a huge success and played a key role in stabilising the electricity grid during severe storms in 2020. Batteries are also needed for electric vehicles and household solar PV systems and are thereby globally deployed at high growth rates.

- In comparison to geothermal and PHES, HCSB plants have a greater siting potential. Solar and biomass resources are abundant and currently widely unused in the context of RE generation. In contrast geothermal resources are limited in NSW. On the other hand PHES has a good siting potential and the already mentioned *Snowy Hydro Scheme* [153] is a good example for a PHES in NSW.
- In comparison to hydrogen, HCSB plants are a technically and commercially mature (research chapter I, p. 53) technology. HCSB plants can be deployed without awaiting further research and development. In the future, hydrogen is likely to play an important role in the global energy supply system, with possibilities of integration with HCSB systems.

5.6. Temporal and policy context of work

The technical, economic and policy context for RE technology development and deployment has changed dramatically since previous investigations of HCSB plants (e.g. [16]) in Australia, prompting discussions of the temporal and policy context of this work. In recent years, Australia's energy transition away from fossil fuels towards a higher share of RE has been hampered by an unstable political climate and frequent changes in policy [163]. Political acceptance is an important factor for the financial feasibility of new RE power stations. In 2020 (the second year of this research project), still 94% of the energy consumption in Australia was derived from fossil fuels and the country had the largest per capita greenhouse gas emissions in the world [164]. Nevertheless, something has changed: while about a decade ago, the general social interest in energy transition was low and accompanied by fear of change, fear of higher energy prices and lack of interest in RE technologies [16], public voices against fossil fuel based energy generation are becoming louder and are being supported by large groups of the population [165]. Since mid-2018, parts of Australia's public have regularly participated in the international *School Strike for Climate*[35] [165]; and since mid-2019 people have been getting involved in the *Stop Adani* movement, with the goal to stop the development of a new coal mine in Queensland [166]. Importantly, these 'climate change movements' are supported by not only environmental non-governmental organisations and social groups, but are also becoming important to more (especially

[35] In August 2018, the 15-years old Greta Thunberg started the movement *School Strike for Climate* (*SS4C*) (also known as *Fridays for Future*) when protesting in front of the Swedish parliament for more actions on climate change. Since then the protests have spread around the world, also reaching Australia [165].

younger) people who fear the consequences of climate change for their future. On the other hand, *resource communities*[36] in regional Australia are still arguing against the energy transition, adding complexity to the debate [166]. Additionally, in some regions local communities show increasing opposition towards new solar farms because of fear of loss of prime agricultural land [167]. This doctoral project finds itself in a time when there is mounting hope for a positive change towards sustainable energy futures.

In the past decade, the RE share in Australia almost doubled, underlining that Australia's energy transition is indeed underway [20]. These developments have been supported by a number of policies, such as the *Renewable Energy Target* scheme [168], and Governmental initiatives, such as the *Australian Renewable Energy Agency* (ARENA) and the *Clean Energy Finance Corporation* (CEFC) [169], which encourages renewable electricity generation in Australia. These policies and initiatives can also be advantageous in the context of HCSB plant deployment.

This thesis opted for an applied research topic, the applicability of its results is inevitably contingent on the vagaries of politics, economics, and larger global trends. During the doctoral thesis many international crises affected and changed the likelihood of HCSB plant deployment in Australia. Certainly, these crises also have impacts on other RE projects (as well as the general economy) and HCSB plants, as a technology that is not yet deployed in Australia, are particularly affected. Two major events took place since the beginning of this doctoral research in early 2019, until its finalisation in mid-2022:

- In the first quarter of 2020, the COVID-19 pandemic hit the world, with significant impact on global trade and production. Many of the HCSB plant components likely need to be imported into Australia [43]. In the context of the COVID-19 pandemic this is especially problematic because equipment (such as the steam turbine) supply waiting times, as well as the costs for many raw materials (e.g. steel) increased [170], [171]. This makes HCSB plants, at least in the short term, more expensive and construction times longer.
- Additionally, in the first quarter of 2022, Russia invaded the Ukraine with dramatic impacts on world trade [172]. For example, Russia and the Ukraine are among the largest global exporters of major food crops (including wheat and corn) and additionally, Russia is one of the major fossil fuel exporters world-wide [172]. International sanctions to stop the Russian invasion led to global supply chain disruptions and increases in transport costs and production [172].

[36] *Resource communities* economically depend on fossil fuel industries (e.g., coal mining). Their financial situation, but also working personality (sense of self) is especially vulnerable during the energy transition.

As described above, there are several negative impacts connected to these international crises. Even though, in some countries, the Russian invasion of the Ukraine has also sparked discussions around energy self-sufficiency and reduction of the dependency on fossil fuels [172] – the overall effects of both international crises are negatively impacting on the likelihood of short-to-medium-term HCSB plant deployment in NSW. Especially the increased costs of raw materials and the extended waiting periods for global trade [170], [171], as exhibited by the two crises, pose major barriers to new RE projects[37] and cause increased economic risks.

To summarise, the timing of this works falls in a time in which, on the one hand, the energy transition is a widely accepted and necessary action and underway; on the other hand, the transition is being hampered by a slowdown in global trade and rising costs, under pressure from several global crises. HCSB plants have the potential to support the energy transition in various ways. Thermal energy and electricity generation are particularly important for the industrial sector of NSW, for which HCSB plants can operate as small scale (< 5 MW_e) industrial cogeneration plants. Small to medium (> 5 MW_e) HCSB plants can also operate for grid-connected electricity generation. In this context, the deployment of HCSB plants complies with key objectives of the current energy transition goals in NSW.

5.7. Next steps towards HCSB plant deployment in NSW

New technologies (such as HCSB plants) find themselves in the difficult situation of having to compete against existing technologies while their own industry is still underdeveloped. Generally, it can be assumed that one successful HCSB project in e.g. Australia, could support the deployment of other systems (since the technology would become better known and real performance data would become available). Once the solar thermal and bioenergy industries become more developed and advanced, deployment of HCSB plants will be better supported (self-reinforcing cycle).

As a first-of-its-kind system in Australia, HCSB plants are likely needing support to overcome the various barriers:

- Overcoming the barrier of capital investment could involve financial support from the Government or other institutions like the *Australian Renewable Energy Agency* (ARENA). In this regard, a concrete policy (including incentives and funding) that formulates dispatchable RE deployment targets could help to support HCSB deployment.

[37] Personal communication with Andreas Zourellis from *Aalborg CSP*.

- Overcoming the barrier of limited electricity market access is already partly diminished through the establishment of REZ. Detailed research and development activities that study HCSB plant deployment in the different REZ could further support their deployment.
- In the context of cogeneration for industrial heat and power supply, HCSB plants could be investigated in further case studies for a range of industries (a list of possible other industries can be found in section 5.3. (p. 79)). These case studies should also include detailed techno-economic assessments.
- For both HCSB options (grid and industry connected), future research should focus on the further understanding the social and policy aspects of HCSB plant deployment with the goal to understand other possible barriers of deployment.

All in all, the approach and selected methods of this doctoral thesis have a great applicability to other projects with a similar scope. While the investigation of HCSB technical design options, provided in the literature review of this thesis, can be used for other global studies, the HCSB market integration and the economic feasibility in case studies would need to be conducted for the specific local context. Equally relevant, however outside the scope of the current thesis (and therefore interesting for future work) is a detailed understanding of policies that can support and accelerate HCSB plant deployment. HCSB plants are facing the same problems as other dispatchable renewable technologies which are more expensive compared to variable RE technologies and compete for the same and limited grid access points. New policies that support small-to-medium scale RE generator and incentivise the ability of dispatchable RE generation, which offers additional services to the grid, can support future HCSB deployment in NSW.

6. Conclusion

This doctoral project investigated hybrid concentrated solar biomass (HCSB) plants as novel renewable energy (RE) technology for supporting the clean energy transition in New South Wales (NSW), Australia. The research design was comprised of a detailed literature review and four research packages, which were published as standalone journal publications. The specific focus of this thesis was the techno-economic feasibility assessment of HCSB plants, by investigating technical options, deployment potential and benefits of HCSB plant deployment in NSW. To sum up, this thesis has demonstrated that HCSB plants could play a potentially significant part in the clean energy transitions of NSW and Australia. Their specific potential resides in supporting the bioenergy and solar thermal industry and increasing the share of renewable, dispatchable electricity and industrial heat and power supply.

One important contribution of this thesis is the detailed understanding of local availability of biomass resources in NSW. In this context, high resolution (5 x 5 km) biomass resources maps for three important feedstock types (forestry waste, stubble and bagasse) were produced, which present the most up-to-date data for biomass resources on the Australian continent (section 4.1., p. 53). This assessment is particularly relevant and timely as bioenergy can be an important RE technology to overcome current challenges for the energy transition in NSW including contributing to the decarbonisation of the harder-to-abate sectors. Additionally, bioenergy is a dispatchable RE; and the assessment presented in this thesis showed that the biomass resources can supply substantive parts of the current electricity demand in Australia (section 4.1., p. 53). Furthermore, the dataset generated of prospective bioenergy sites has the potential to overcome some of the limitations of former bioenergy simulation in high-RE supply models and provides new insights in terms of how and where bioenergy projects can be commissioned (section 4.1., p. 53). These results underline the great potential of bioenergy in NSW and can be used as basis to inform policy goal setting and strategy supporting the bioenergy industry sector development.

Currently the Australian bioenergy industry is underdeveloped compared to that of other OECD countries. In this context, this thesis provides evidence on how the integration of solar thermal energy into bioenergy systems can help industry development by providing an option to reduce dependency on biomass resources and the transport of biomass to the bioenergy facilities with implications on social license, financial risk, and secure and ongoing RE generation.

Considering the novel HCSB technology, the technical option evaluation (section 2., p. 28) identified two technically and commercially mature HCSB design options ready for immediate deployment in NSW. These design options can operate as i) standalone, grid-connected renewable electricity generator and as ii) cogeneration system for local industries.

For grid connected HCSB plants (section 4.3., p. 63), this study found that:

- HCSB plants can generate electricity up to around 3% of NSW's electricity demand, with the potential to avoid over 6 $MtCO_2$-e/year,
- The Riverina region is the most prospective region for HCSB plant deployment in NSW, owing to sufficient solar resources of 1900–2200 kWh/m^2/year and rice straw resources of 27,000–255,000 kWh/m^2/year in proximity to up to 16 substations with new connection capacity,
- HCSB plant design is most cost-efficient with a solar tower system, low solar capacity factors and thermal energy storage with capacity of 3 hours,
- HCSB plants can reach a maximum net energy efficiency of 34%, comparable to the energy efficiency of standalone bioenergy plants,
- HCSB plants are economically viable for deployment with electricity prices of AU$ 120–350/MWh, assuming an IRR of 11%, and
- HCSB plants offer potential benefits to the environment and local communities including carbon emission mitigation, improved air quality and local job creation.

For industrial cogeneration (investigated in the context of energy generation for a major beef abattoir in NSW, section 4.4., p. 67) an organic Rankine cycle (ORC) and a hybrid combined cycle (HCC) HCSB system was evaluated. This study found that:

- The HCC HCSB system is more cost-effective and can operate at a lower levelised cost of energy (LCoE) than the ORC HCSB system,
- By incorporating this technology in all beef abattoirs in NSW, up to 1.3 $MtCO_2$-e can be avoided per year.

Despite these advantages, the techno-economic analysis showed that HCSB plants deployed at the case study abattoir are currently unlikely to be cost-competitive compared to other RE sources. Greater value for the HCSB plants can be achieved if policies and incentives recognise the advantages of i) low temperature heat recovery for industrial cogeneration in the context of energy efficiency ambitions, ii) energy self-sufficiency, and iii) carbon abatement. To support HCSB plant deployment in NSW further research projects could investigate HCSB plants in the context of different industries and focus on detailed discussions on the selection of plant components and simulation of the plant operation.

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8. Appendices

A.1. E. Middelhoff, B. Madden, M. Li, F. Ximenes, M. Lenzen, and N. Florin**,** "Bioenergy siting for low-carbon electricity supply in Australia," *Biomass & Bioenergy*, vol. 163, no. August 2022, p. 106496, doi: https://doi.org/10.1016/j.biombioe.2022.106496.

A.2. E. Middelhoff, B. Madden, F. Ximenes, C. Carney, and N. Florin, "Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia," *Applied Energy*, vol. 305, no. September 2021, p. 117942, 2022, doi: https://doi.org/10.1016/j.apenergy.2021.117942.

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A.4. E. Middelhoff, L. Andrade Furtado, J. Reis Parise, F. Ximenes, and N. Florin, "Hybrid concentrated solar biomass (HCSB) systems for cogeneration: Techno-economic analysis for beef abattoirs in New South Wales, Australia," *Energy Conversion and Management*, vol. 262, no. June 2022, p. 115620, doi: https://doi.org/10.1016/j.enconman.2022.115620.

A.5. List of bioenergy projects with temperature and scale range.

A.6. List of CSP projects with temperature and scale range.

8.A.1. Bioenergy siting for low-carbon electricity supply in Australia

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Bioenergy siting for low-carbon electricity supply in Australia

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A R T I C L E I N F O

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A B S T R A C T

In the context of renewable energy (RE) generation, biomass resources are different to other renewable resources because they can be stored and transported. These characteristics make bioenergy a dispatchable renewable energy source. While this property is recognised as being very important in supporting the global energy transition, the potential of bioenergy in renewable electricity generation systems is not well understood owing to coarse assumptions around the distribution and availability of the resource.

To address this limitation, this study derived a new database of prospective new bioenergy sites in Australia based on a geographic information system (GIS)- bioenergy siting algorithm. The optimised site selection relies on high-resolution biomass resource maps, resources transport distance and other key spatial constraints.

Specifically, we present biomass resources maps for bagasse, forestry and cropping residues at a spatial resolution of 5 × 5 km. Australia is on one of the top global producer of sugar cane and as such bagasse was included as feedstock for bioenergy generation. The study identified potential utilisation of 1.0, 16.6 and 28.7 million tonnes of bagasse, forestry and stubble residues respectively at over 223 prospective sites.

The new biomass site database is the most comprehensive and up-to-date compilation of prospective bioenergy sites in Australia. Moreover, by considering the real-world spatial constraints, this new data set allows for a reliable appraisal of potential biomass resource utilisation. While our study is focussed on Australia the approach is broadly applicable to other jurisdictions worldwide.

1. Introduction

Australia's energy transition is underpinned by a long-term ambition for achieving net-zero greenhouse gas (GHG) emissions, aiming to overcome energy system dependency on fossil fuels. This transition is in line with global agreements [1,2] and is recognized as a key strategy for avoiding the more severe impacts of rising temperatures on the Earth's climate system [3,4]. Similar to energy transitions in other parts of the world, Australia's energy transition is underway and has involved the uptake of variable renewable energy (RE) technologies such as solar photovoltaic (PV) and wind power plants [5]. In 2020, 24% of the total electricity generation in Australia was derived from renewable resources [6]. For an orderly and successful energy transition, not just in Australia but also globally, there is a need to increase the share of dispatchable RE, that can generate electricity in times of diminished solar and wind resources [7–10].

As dispatchable RE, bioenergy is expected to play a critical role in the success of the global energy transition [8,11,12]: Not only can bioenergy deliver diverse bioenergy products, including biofuels and industrial process heat, which are especially important for the harder-to-abate sectors [13]; bioenergy can also provide electricity on demand, which can be beneficial in times of diminished solar and wind resources [7–10]. While some countries already deploy bioenergy at high capacities [14], others are lagging behind in supporting the development of a bioenergy industry [14]. In Australia, for example, bioenergy and energy from waste are contributing around 1.4% of electricity output, which is low compared to around 2.4% in other OECD countries [14]. One of the reasons for an under-developed bioenergy sector in Australia is missing information on the actual bioenergy potential [15]. This has been recognized by the Australian Government and with the aim to promote the role of bioenergy in the energy transition a bioenergy roadmap was commissioned [15].

In order to promote the bioenergy industry sector, it is necessary to gain better understanding of its benefits and opportunities, e.g., in the future renewable electricity grid. Energy system models that are capable

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Abbreviations

ABBA	Australian biomass for bioenergy assessment
ACT	Australian Capital Territory
AD	Anaerobic digestion
AEMO	Australian energy market operator
ALUM	Australian land use and management
AREMI	Australian renewable energy mapping infrastructure
GHG	Greenhouse gas
GIS	Geographic information system
NEM	National electricity market
NSW	New South Wales
NT	Northern Territory
OCGT	Open cycle gas turbine
PV	Photovoltaic
QLD	Queensland
RE	Renewable energy
SA	South Australia
SA2/4	Statistical areas 2/4
TAS	Tasmania
VIC	Victoria
WA	Western Australia

of simulating a future high-RE[1] supply are very valuable in this context [16–24]. These high-RE supply models can be a tool to inform decisions around commissioning and integration of the future renewable portfolio considering different mature renewable technologies, including variable and dispatchable RE technologies. Many of these high-RE supply models investigate the renewable technology growth under specific economic assumptions (e.g. increasing carbon emission penalties [$/tCO$_2$-e]) or policy settings (e.g. RE deployment targets). As such also bioenergy deployment can be tested and projected in these models. In the past, high-RE supply model already showed the special role of dispatchable RE in the electricity market transition. One of the most important findings was that, although the installation of dispatchable REs is more expensive than variable REs, their deployment has a positive impact on reducing the total costs of the energy transition [8,25]. This can be explained by the fact that even though wind power plants and solar PV are the cheapest technologies per unit of installed capacity, large amounts of these variable RE need to be installed in different areas of the continent to secure electricity supply at all times (lulls in one part of the continent are settled with energy generation in other parts) [7,26]. High-renewable supply model simulations showed that the increase of dispatchable RE capacity, such as bioenergy can lead to lower overall cost of installed capacity. As example for this, Li et al. [8] found that the expansion of bioenergy of 5–15 times of the currently installed capacity can reduce the cost of the future renewable energy supply system by 11–40%.

Even though, these studies highlight the opportunities of increasing bioenergy in a high-renewable market, the actual simulation of bioenergy is often very simplified. High-renewable supply models are complex, because they need to consider several current and projected aspects of the energy market, such as energy demand changes, industrial growth etc. (e.g. Ref. [22]). Incorporating bioenergy adds further complexity: bioenergy can be generated from a wide range of different feedstocks (e.g. including waste residues), has diverse conversion pathways (e.g. including anaerobic digestion) and can generate different energy types (e.g. including biofuels). Biomass is also different from other renewable resources because it can be transported and stored and can thereby be used for energy generation at different times and places from where it was sourced. Because of the diverse characteristics, bioenergy simulation in high-RE supply models often relies on numerous assumptions and simplifications that are described below.

One simplification is the assumption of biomass resource availability [PJ/yr] at low spatial scale (e.g., the entire country or continent) from current or projected (based on policy growth targets) resources availabilities [27,28]. These low resolution bioenergy assumptions are often speculative as they do not consider plant siting, feedstock transport, or access to the energy markets (e.g. grid access). Connected to the consideration of low resolution biomass resources, former studies (summarized in Table 1) are also limited in their ability to indicate where (specific location) and at what scale [MW] bioenergy plants are likely to be deployed in future scenarios [29–31]. In the real world, and especially if biomass transport distances [km] are limited, the local biomass availability [tonnes/yr] is low. If bioenergy plants only use domestic and local resources, the typically low biomass concentration [tonnes/ha] and energy density [MJ/kg] (compared to e.g., coal) results in typically limited combustion plant generation capacities of <50 MW$_e$ [7,32]. These characteristics of bioenergy generation are barely considered in high-renewable supply model (Table 1).

The same limitations of bioenergy simulation in high-renewable supply model, that were summarized and described for the global context, can also be observed in the context of Australia. An overview of high-renewable supply models in Australia and their limitations is provided in Table 2. Those models relied on a number of simplifying assumptions: (i) Scenarios limit or aggregate the number of biomass feedstock types and biomass-to-electricity conversion technologies. For example, studies only consider agricultural [16,18] or forestry residues [16,34] for electricity generation in direct combustion plants. Other studies only consider biogas fired open cycle gas turbines (OCGT) [19,20,35]. (ii) Spatial bioenergy potential is estimated rather hypothetical and is not derived from biomass resources maps: The bioenergy potential is described at low spatial resolution. While some studies rely on bioenergy estimates on national scale (pre-assumed renewable percentages) [16,22,36], [16], others only consider generation at already operating bioenergy sites [24]. (iii) The bioenergy potential is only described for parts of the Australian continent, e.g. the Australian Energy Market Operator (AEMO) regions [34]; and Wright and Hearps [16] assume bioenergy generation at twelve pre-defined locations, completely independent of local biomass feedstock availably. (iv) Biomass resources transportation distance is not considered or limited.

To address these limitations, this study aims to present an approach to produce high-resolution biomass feedstock maps and a database of prospective new bioenergy sites. Both the maps and list of prospective bioenergy sites, can be used as input for high-RE supply models, with the overall goal of improving the simulation of bioenergy and achieving a better understand of the bioenergy generation potential. In order to demonstrate the approach and results within a real world context, this study focussed on the Australian continent. However, the methodology has simple data requirements, and can also be applied to other countries where data is available. Specifically, this study (i) provides estimates for three important biomass feedstock types (forestry and agricultural waste, including bagasse) by generating detailed (5 × 5 km) resources maps for the whole Australian continent. The study (ii) suggests a siting algorithm that assigns these resources to new prospective generator sites, by (iii) considering real-world spatial constraints, including but not limited to distance from transmission infrastructure and (iv) considering biomass feedstock transportation distances.

2. Material and methods

As mentioned above, this study demonstrates the approach of biomass mapping and bioenergy siting for the Australian continent (around 7.7 million km^2). The results are discussed individually for the

[1] This publication uses the term "high-renewable" referring to all projections with an increase of renewable energy supply compared to the current share, including 100% renewable energy supply simulations.

Table 1
Geographical scale of biomass resources assumptions and bioenergy plant siting of bioenergy simulation in high-renewable electricity supply models in the international context.

Country; study and simulated year	Biomass resources type	Geographical scale of biomass resources assumption	Geographical scale of bioenergy plant siting
UK; Jablonski et al. [27], 2000–2050	Domestic and imported resources of eight groups, including bio-fuels and solid and wet biomass	Average for the UK, three scenarios with increasing bioenergy production through i) provision of agricultural land for bioenergy crops, ii) subsidy to encourage bioenergy farming, and iii) improve woody and grassy bioenergy crops.	No specific sites
Mexico; Islas, Manzini & Masera [28], 2005–2030	Nine groups of biofuels and solid biomass, seven groups of energy generation technologies	Average for Mexico, moderate and high scenario for bioenergy use	No specific sites
Sweden; Börjesson Hagberg, Pettersson & Ahlgren [30], 2050	13 domestic types and three imported types, including fuels and solid biomass	Average for Sweden, domestic and imported resources supply	No specific sites
Review of eight high renewable scenarios for Germany; Szarka et al. [29], almost all focus on either the present or 2050 as projected year	Different approaches, one study focussing on biogas only, two studies only considering residues and waste for particularly sustainable bioenergy generation, the other focussing on a mix of solid and gaseous biomass fuels, some consider cogeneration or bio-fuels for transport	Averages for Germany, some only focussing on existing biomass resources and waste resources other assuming biomass-for-bioenergy increase in the future	None of the studies considered specific sites
Netherlands; Tsiropoulos et al. [31], 2030	Bioenergy and biochemicals, main focus on technology development based on learning and price cost reductions	Focussing on policy scenarios for bioenergy targets	No specific sites
Ireland, Chiodi et al. [33], 2030 and 2050	24 domestic types and four imported, including biofuels and agricultural and forestry residues and bioenergy crops	Average and growth estimates for Ireland	No specific sites

Table 2
Geographical scale of biomass resources assumptions and bioenergy plant siting of bioenergy simulation in high-renewable energy supply models for Australia.

Study and simulated year	Biomass resources type	Geographical scale of biomass resources assumption	Geographical scale of bioenergy plant siting
Farine et al. [17], Crawford et al. [18] for 2010, 2030 and 2050	Seven groups (forestry residues, stubble, bagasse, and different waste types)	42 AEMO regions of Eastern Australia (not including WA and NT)	No specific sites
Wright and Hearps [16] for energy supply in 2020	(Pelletised) stubble and crop waste	Australian continent (based on the assumption that 13–16% of Australia's straw residues would be used)	12 pre-defined sites (independent of biomass resources availability)
Ellison et al. [19,20,35] for 2010	Biogas from crop residues	Australian states and territories (not including WA and NT)	No specific sites
AEMO [34] for 2030 and 2050	Bagasse, wood and biogas	42 AEMO regions of Eastern Australia (not including WA and NT)	No specific sites
Teske et al. [22] for 2010–2050	No specification	Australian continent	No specific sites
Lu et al. [36], year not specified	Biogas	Australian state (not including WA and NT)	No specific sites
Blakers et al. [24], for 2017	Existing bioenergy sites	No potential new sites	Existing bioenergy sites
Clean Grid [34–24]	Seven groups (forestry residues, stubble, bagasse, and different waste types)	Whole continent in grid cells of 89 × 89 km	Existing bioenergy sites

different Australian states, which are shown in Fig. 1. Fig. 2 shows the approach taken for this study for the example of New South Wales (NSW), Australia's most populous state. The following sections discuss the approach of generating of i) biomass resources maps, ii) assessing spatial siting suitability, and iii) selecting prospective bioenergy sites.

2.1. Biomass resources maps

This study generates high-resolution biomass resources maps as a basis for finding potential bioenergy sites. The study differentiates three biomass feedstock categories:

(a) Bagasse, as remaining feedstock following the extraction of sugar from sugarcane;
(b) Forestry residues, summarizing woody biomass sources from forestry (harvest residues) or timber product residues or by-products from sawmills (offcuts, sawdust), as well as recycled wood from municipal waste, commercial waste (e.g. pallets) and residues from construction, demolition sources and from native and plantation forests; and
(c) Stubble residues, describing crop straw from standing stubble (of wheat, oats, barley, triticale, sorghum, canola, lupins, oil seeds and legumes).

These low-moisture feedstocks (moisture content ≤50%) can for example be used for steam generation from direct combustion and thermal conversion into electricity in Rankine cycle power plants. Due to the limited research scope, this study does not consider high-moisture feedstocks (e.g. animal waste and livestock residues), for anaerobic digestion (AD).

The biomass resources maps are generated in three steps: i) a dasymetric model combines raw biomass data and land-use data to generate high-resolution biomass resources maps; ii) a literature review lists all existing and currently existing bioenergy projects and their biomass use; and iii) a resources allocation algorithm summarizes resources to existing bioenergy projects and omits them from the biomass resources maps.

2.1.1. The dasymetric model

High resolution biomass resource maps were generated with consideration for underlying land use types by employing the

Fig. 1. Australian states and continent. Adopted from the Bureau of Statistics [37].

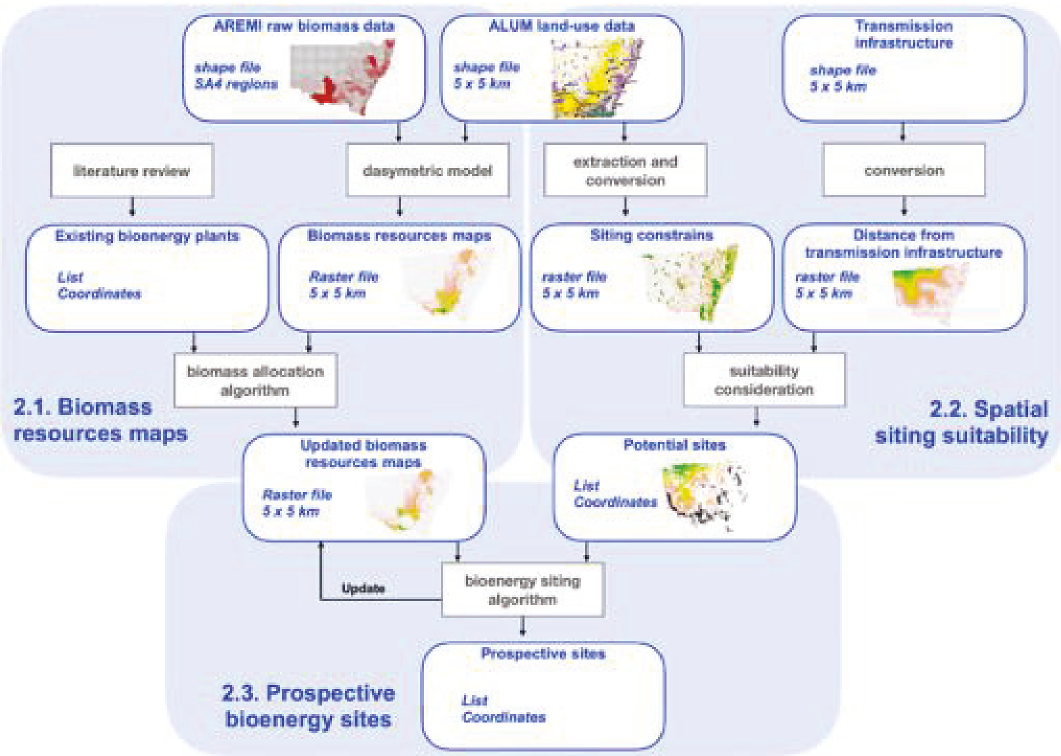

Fig. 2. Methodological approach of the study, shown for the state of New South Wales (NSW) as example.

dasymetric modelling approach found by Madden et al. [35]. This approach seeks to disaggregate low resolution data to a higher spatial resolution using available land use data and was first proposed by Mennis and Hultgren [33]. The dasymetric model used in this study was developed in R [34] utilizing the following data sets:

- Low-resolution biomass data for the jurisdictions across Australia was published recently as part of the Australian Biomass for Bioenergy Assessment (ABBA) initiative [38]. This data is centralised at the *NationalMap* [39] [2] and extracted for this study. Biomass quantities from the ABBA project data are available at different spatial scales depending on the biomass type. These spatial scales are part of the Australian Statistical Geography Standard [40]. The statistical area 2 (SA2) scale is equivalent roughly to the suburb scale, consisting of populations between 3000–25,000 people. The statistical area 4 (SA4) scale reflects labour markets and consist of populations between 300,000–500,000 people.
- Land use data was obtained from the Australian Land Use and Management (ALUM) classification system [41].

2.1.2. Resources allocation algorithm

The resources allocation algorithm was developed in R [36] with the goal of generating maps of potential biomass resources currently not utilised by existing bioenergy plants. A desktop review of Australian bioenergy data and reports (e.g. Refs. [27,33]) was first performed to identify existing bioenergy generation locations and reported facility-level feedstock volume. The resources allocation algorithm is then performed for all operational bioenergy plants identified through desktop analysis. To clarify the process, Fig. 3 shows the bagasse allocation for the Victoria cogeneration plant (listed in Ref. [42]), that uses 881,000 tonnes of bagasse per year. Using the resources allocation algorithm these resources are omitted from the resources maps. The algorithm is starting with a radius of 1 km and obtains all resources [tonnes/year] within this radius. If these obtained resources are not matching the reported resources of 881,000 tonnes per year, the allocation radius is incrementally increased by 5 km (the highest resolution this incremental update can be performed at). Once the obtained resources are matching the reported resource use of the site, the identified resources within this minimum allocation radius are omitted. For this example and shown in Fig. 3, the minimum allocation model was calculated to be 105 km.

2.2. Spatial siting suitability

Geographic information system (GIS)-based suitability analyses have been used to examine the regional potential of bioenergy from agricultural residues [43], and forestry resources [44–46] at various spatial scales. A common approach for these GIS-based studies is the incorporation of land attributes as inputs to determine the siting suitability. Typical land attributes include physical criteria such as distance to grid infrastructure and environmental criteria such as sensitive environments and habitats [47,48].

This study excluded regional and national protected areas, wetlands, river and water bodies from the maps as areas available for siting. The locations of these areas were obtained from land-use data of the ALUM classification data; land-use categories 1.1.0–1.3.0 and 6.1.0–6.6.0 were selected [41]. We followed a binary constraint map, whereby cells assigned values of 1 were not suitable for development, and cells assigned 0 were suitable. Here, cells are defined as 5 × 5 km grid squares following the spatial resolution of our analysis.

This study further chose distance from transmission infrastructure as a determining factor for biomass siting suitability. Transmission line data was obtained from Geoscience Australia [49]. For the purpose of this study, we generated raster files at 5 × 5 km spatial resolution representing the distance from the transmission infrastructure for each raster point.

2.3. Bioenergy siting algorithm

The database of prospective bioenergy sites is generated using a spatial optimisation model referred to as bioenergy siting algorithm. The algorithm underlies a GIS-based model, which was developed in R [50]. The biomass siting algorithm finds prospective bioenergy sites depending on biomass resources [tonnes/year] (section 2.1.) and spatial siting suitability criteria (section 2.2.). The algorithm was applied for individual state and territory jurisdictions, which assumes that resources in e.g. Queensland (QLD) will only be used for bioenergy generation within QLD. Due to its small size, the Australian Capital Territory (ACT) is combined with the State of New South Wales (NSW).

The bioenergy siting algorithm operates as follows:

- Step 1): The bioenergy siting algorithm generates a list of potential sites (open cycles in Fig. 4b), which fulfil two requirements: i) the binary constraint map (described in Section 2.2.) for the site is 0, indicating no siting constraints, and ii) the distance from the transmission infrastructure is $<$ 10 km.
- Step 2): The bioenergy siting algorithm than receives biomass resources [tonnes/year] within a 100 km catchment radius for each of these potential sites. (Choosing a catchment radius of 100 km is consistent with other studies, which chose a maximum transport distance for sustainable bioenergy generation of 50–150 km [32,44,51]). Fig. 4a is an example for a biomass resources map of stubble residues in NSW; the algorithm has been deployed for all residue types and all states of Australia individually.
- Step 3): The potential site with the highest biomass volumes is than selected as the first prospective site for bioenergy siting.
- Step 4): Biomass resources that are allocated to this prospective site are omitted from the biomass resource map so that they are not considered in successive iterations of the algorithm.
- Step 2, 3 and 4 are repeated to select prospective bioenergy sites until no more potential sites can be identified with minimum biomass feedstock availability of 10,000 tonnes/year. Choosing 10,000 tonnes/year as minimum threshold is following the assumption that the minimum size of a grid connected power plant in the National electricity market (NEM) is 5 MW_e [52]. A 5 MW_e bioenergy plant with 10,000 tonnes of feedstock would operate with a capacity factor of 12–48%. Assuming a biomass energy conversion potential of 0.53–1.49 MWh/tonne for bagasse, 1.17–1.67 MWh/tonne for woody feedstock, and 0.94–1.31 MWh/tonne for stubble [7,17,53–55]. Fig. 4c shows the prospective bioenergy sites from potential sites selected in step 1) which lay within <10 km from the transmission infrastructure. Fig. 4d shows the updated biomass resources map after resources are omitted for prospective bioenergy sites.
- Repeat from step 1): The bioenergy siting algorithm than repeats the previous step 1, now creating a list of potential sites within a distance from the transmission infrastructure of 10–20 km (Fig. 4e) (later within 20–30 km, and so on). For each of the lists with potential sites the algorithm is repeating step 2–4 by selecting new prospective bioenergy sites and omitting allocated resources until no more sites are identified with a minimum resource allocation of 10,000 tonnes (Fig. 4f).

3. Results

3.1. Biomass resources maps

3.1.1. Bagasse

Fig. 5a shows bagasse residues maps from the dasymetric model

[2] Formerly part of the Australian Renewable Energy Mapping Infrastructure (AREMI).

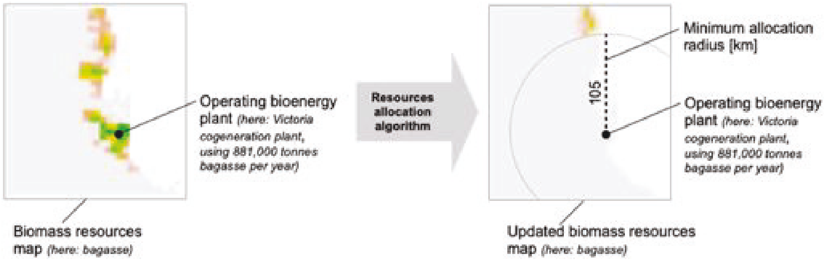

Fig. 3. Bagasse resources allocation for Victoria cogeneration plant and update of biomass resources map.

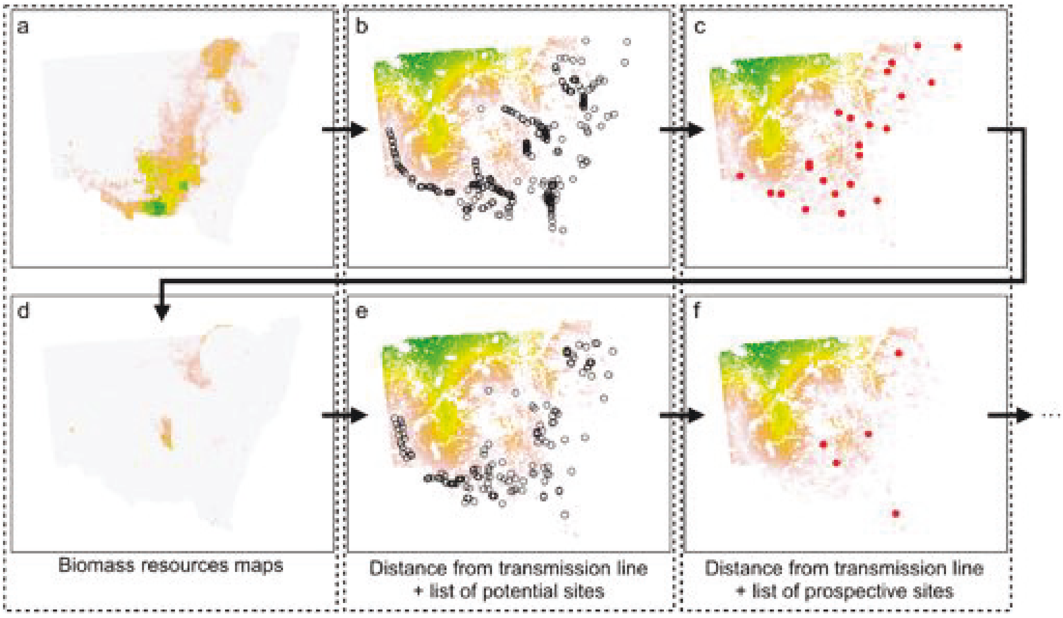

Fig. 4. Example for the approach of the 'bioenergy siting algorithm' for cereal straw in New South Wales: a) and d) coloured cells indicate availability of cereal straw in NSW, b) and e) coloured cells indicate distance from transmission infrastructure, open black circles show list of potential sites within 10 km (b) and 20 km (e) distance of the transmission line, c) and f) coloured cells indicate distance from transmission infrastructure, red circles show selected prospective sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(section 2.1.1.) at 5 × 5 km spatial resolution in QLD and NSW. In QLD, bagasse residues are clustered within four areas, around Hinchinbrook, Burdekin, Mackay and Bundaberg. This finding aligns with former detailed resources mapping e.g. by Jayarathna et al. [43]. Bagasse residues are also clustered at the north-eastern coast of NSW, around Byron Bay.

Fig. 5b shows the location of currently existing bagasse-fed bioenergy plants (black dots) in Australia. Table 3 shows the results of the desktop review (described in Section 2.1.2.). The review found 11 operating bagasse-fed plants in Australia, consuming over 4.5 million tonnes and 0.3 million tonnes of feedstock per year in QLD and NSW, respectively. In QLD and NSW, the minimum allocation radius (described in Section 2.1.2.) was modelled to be between 20 - 525 km and 10–130 km, respectively. Appendix Table 3 (A3) shows a complete list of bagasse-fed bioenergy plants, their exact locations and resources use, as well as the minimum allocation radius of bagasse resides for the operation of these existing plants.

Fig. 5b shows the remaining bagasse resides after bagasse volumes were allocated for the operation of existing plants and omitted from the resources maps. Most bagasse resources in QLD and NSW are currently used for operation of existing plants. In QLD, some unallocated bagasse resources are identified near Hinchinbrook and Bundaberg. In this spatial modelling approach these bagasse residues remain unused due to their lack of proximity to the existing bagasse-fed bioenergy facilities. In the north-eastern part of NSW with around 30,000 tonnes of bagasse only a small proportion of bagasse resources remain unutilized.

3.1.2. *Forestry residues*

Fig. 6a shows forestry residues maps from the dasymetric model (Section 2.1.1.) at 5 × 5 km spatial resolution in the states and territories of Australia. In QLD, forestry residues are distributed along the eastern coast of the state, with highest availabilities in the northern part around Hinchinbrook and in the southern part, in the North of Brisbane. In NSW, forestry residues are distributed along the eastern coast of the state, with higher availabilities in the North Coast between Coffs Harbour and Port Macquarie. This aligns with previous results published by Ximenes et al. [44]. In NSW, forestry residues are also abundant in the Central West, and in eastern parts of the Riverina and surrounding the Capital region, near ACT and Canberra. In Victoria (VIC) and Tasmania (TAS) resources are widely distributed across the states. In South Australia (SA) and Western Australia (WA), forestry residues are distributed in the southern parts of the states. In WA, forestry residues are located south of the state.

Fig. 6b shows the location of currently existing bioenergy plants

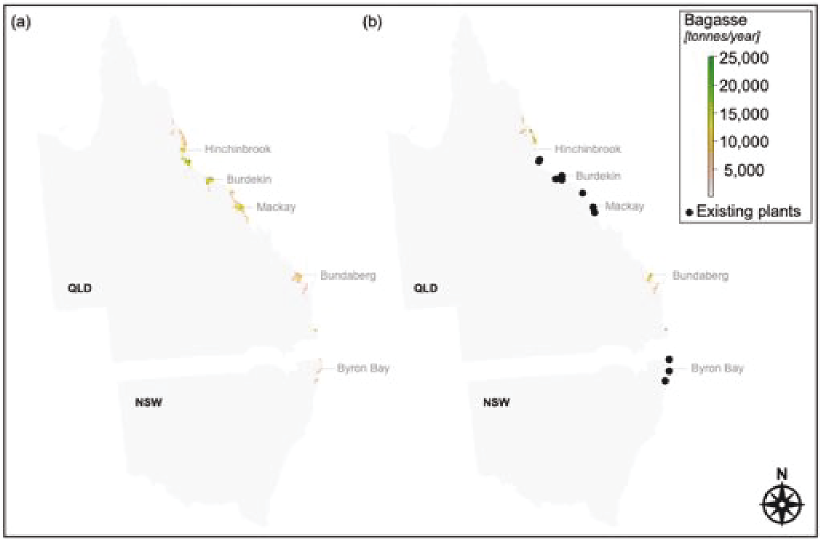

Fig. 5. Queensland (QLD) and New South Wales (NSW) showing (a) bagasse resources maps [tonnes/year] from the dasymetric model (Section 2.1.1.) and (b) locations of existing bagasse fed bioenergy plants (black points) and remaining bagasse resources [tonnes/year].

Table 3
Summarizing for each Australian state and each feedstock type: Number of operating bioenergy, used resources [tonnes/year], as well as number of prospective new sites, available resources and their minimal and maximal distance from transmission infrastructure.

	Number of operating bioenergy plants	Used resources [tonnes/year]	Number of prospective sites	Available resources [tonnes/year]	Distance from transmission lines [km]
Bagasse					
NSW	3	261,400	1	31,853	0.3
QLD	9	4,541,000	3	1,061,270	0.0–0.8
Forestry					
NSW	4	179,213	13	2,030,048	0.2–0.9
NT	–	–	1	367,000	0.0
QLD	1	900	6	745,055	0.0–0.8
SA	2	188,000	3	1,122,680	0.5–40.2
TAS	2	9400	4	5,529,649	0.1–0.7
VIC	4	13,900	14	4,045,344	0.3–40.7
WA	3	7009	9	2,737,107	0.0–111
Stubble					
NSW	–	–	46	10,324,224	0.0–140.2
QLD	–	–	16	915,307	0.0–130.9
SA	–	–	11	4,774,772	0.0–30.8
TAS	–	–	1	60,745	0.7
VIC	–	–	16	3,596,186	0.0–35.6
WA	–	–	79	8,980,602	0.0–230.3

(black dots) using forestry residues in Australia (described in Section 2.1.2). The review found 15 operating plants (in WA, VIC, NSW, SA and TAS), consuming approximately 400,000 tonnes of forestry resides per year (Table 3). Appendix Table 6 (A4) lists the locations of these existing plants and their use of forestry residues, as well as the minimum resources allocation radius of forestry residues for the operation of these plants. The minimum allocation radius for existing plants was <70 km in most states. Two plants in NSW and one plant in WA have a resources demand with modelled allocation radius of 90, 95 and 115 km, respectively.

Compared to bagasse and stubble, little is known about the current industrial use of forestry residues. There are many small boilers in operation, and in the case of sawmills for example a substantial proportion of residues is used in boilers used to generate steam to dry timber in kilns, however the numbers are not openly available (Pers. Comm. Ximenes, 2021). Thereby although the updated resources maps may not be particularly accurate, it is still the most detailed and up-to-date source we are aware of.

Another complicating factor when mapping forestry residues for Australia is that the different states of Australia used individual methods in reporting their forestry wastes to ABBA [38]. While some states took a very conservative approach such as e.g. NSW, where the forestry residue raw data is likely underestimating the actual availability – minimizing the risk of supply shortages, this is not guaranteed for all states. Furthermore this study decided not to consider biomass consumption for existing co-firing in coal power stations. Co-firing with biomass is suggested as an emission reducing method during continuous operation of coal fired stations; however high-renewable energy supply simulations (for which this data set is also generated for) usually assume coal phase-out in the next decades [56–58].

Nevertheless, we decided to obtain forestry residues for operating plants we found. Fig. 6b shows the remaining forestry residues after resources volumes were allocated for the operation of existing plants. The map shows that there are large amounts of residues available for new bioenergy generation capacity.

3.1.3. Stubble

Fig. 7 shows stubble residues maps from the dasymetric model (Section 2.1.1.) at 5 × 5 km spatial resolution in the states and territories of Australia. In NSW, stubble resources are located along the central part of the state, ranging from New England, the Mid-West to the Riverina-Murray region close to agricultural centres of Moree, Dubbo and Griffith. In WA, stubble resources are located in the Wheat Belt region in the southern part of the state. In SA, stubble resources are mainly located at the Yorke Peninsula and the southern part of the state. In VIC, stubble resources are located in the north-western parts of the state around the agricultural centre of Mildura. QLD has very limited stubble resources which are distributed around St. George and Emerald. In TAS, stubble resources are located in the northern parts of the state.

The desktop review (described in Section 2.1.2) found 8 plants which operate on crops or other agricultural residues. These plants are located in QLD, NSW, VIC and WA and are listed in Appendix Table 7 (A5). Bioenergy generation based on agricultural feedstock is divers. Some

Fig. 6. States and territories of Australia showing (a) forestry residues resources maps [tonnes/year] from the dasymetric model (Section 2.1.1.) and (b) locations of existing forestry-fed-bioenergy plants (black points) and remaining forestry residues [tonnes/year].

plants use oil crops for the generation of biodiesel or ethanol, but also residues, such as grape mark are common feedstocks. No plants were found to use stubble, as the remaining feedstock after crop harvest, for energy generation thereby no resources were omitted from the resources map of Fig. 7.

3.2. *Spatial siting suitability*

Fig. 8a shows the binary exclusion map according to the siting constraints (described in Section 2.2). A large portion of eastern NSW, northern QLD and large parts of WA, TAS, SA and VIC are deemed not-suitable for deployment. Fig. 8b presents a heat map that shows distances from the existing transmission infrastructure. The largest distances from the grid are in WA with distances over 700 km. For the eastern states and territories distances from the transmission infrastructure are <600 km.

3.3. *Prospective bioenergy sites*

3.3.1. *Bagasse*

Most bagasse resources in QLD and NSW are currently used for operation of existing plants. Fig. 9a shows prospective locations for new bagasse-fed bioenergy plants utilizing the remaining bagasse resources. Table 3 lists the three possible sites in QLD, consuming up to 1.1 million tonnes of bagasse and one site in NSW, consuming 0.03 million tonnes of bagasse per year. All prospective new sites lay within 1 km from the existing transmission line infrastructure. Appendix Table 8 (B6) shows a complete list of all prospective bioenergy sites, their location, resource

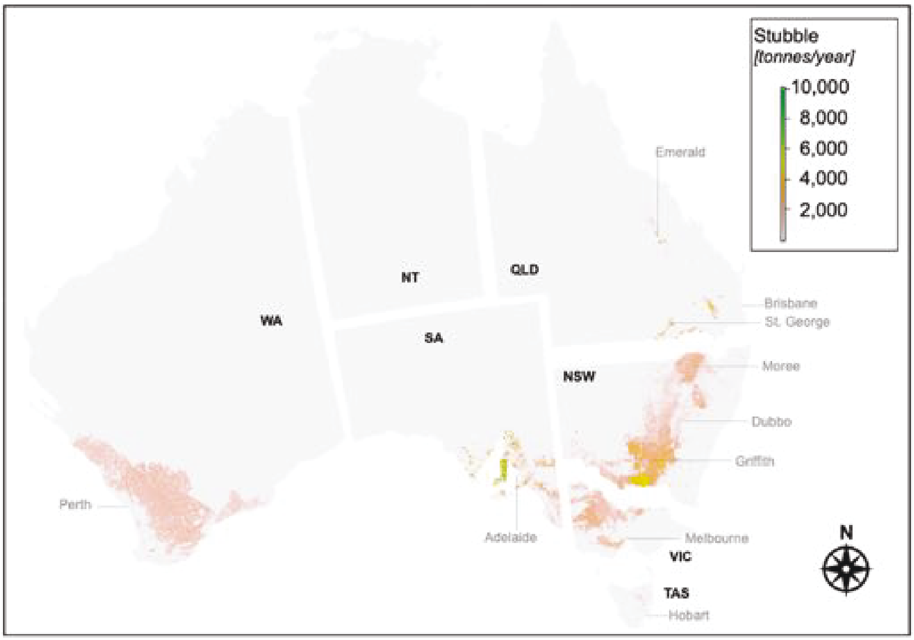

Fig. 7. States and territories of Australia showing stubble resources maps [tonnes/year] from the dasymetric model (Section 2.1.1.).

use and distance of transmission infrastructure.

An alternative to the use of remaining bagasse resources in new bioenergy plants is the extension of existing plants. This could be facilitated by expanding feedstock storage size or steam turbine capacities to increase operational time or power output, respectively. The option of extending the operation at existing plants may be especially interesting for the remaining bagasse resources in NSW owing to proximity to existing facilities. Remaining resources around Hinchinbrook and Bundaberg are far from the existing bioenergy sites (>200 km) and the transport over such long distances would need to be carefully considered to minimise costs and associated transport emissions.

3.3.2. *Forestry residues*

Fig. 10a shows the locations of prospective new bioenergy plants utilizing the remaining forestry residue resources. There are proposed new sites in all states and territories. Table 3 shows, that most new sites are suggested for TAS, VIC, WA and NSW, with over 5.5, 4.0, 2.7 and 2.0 million tonnes potential available forestry residues, respectively. While in TAS and NSW all 4 and 13 possible sites are located within 1 km of the existing transmission infrastructure, the maximum distance from transmission infrastructure for VIC and WA is over 40 and 110 km, respectively (Table 3). Prospective sites in SA (3), QLD (6), and NT (1) utilize 1.1 million, 0.7 million and 0.4 million tonnes of forestry residues, respectively (Table 3). The majority of possible sites are within 1 km of the existing grid infrastructure, except one site in SA which would require a transmission line extension of about 40 km. Appendix Table 7 (B7) shows a complete list of all prospective bioenergy sites, their location, resource use and distance of transmission infrastructure.

3.3.3. *Stubble residues*

Fig. 10b shows the locations of prospective new bioenergy plants utilizing stubble. Prospective sites in NSW and WA use the highest amounts of stubble with over 10.3 and 9 million tonnes of stubble per year potentially available at 46 and 79 sites, respectively. In NSW, 23 of the 46 sites are located within 1 km of the existing transmission infrastructure, while 21 sites are located within 100 km from the existing transmission infrastructure. 2 sites would require new transmission infrastructure >100 km and up to 140 km. In WA, 20 of the 46 sites are located within 1 km, while 41 are located within <100 km and 18 are located within <300 km of the existing infrastructure. 11 and 16 proposed sites were identified in SA and VIC with 4.8 and 3.6 million tonnes of stubble potentially available for electricity generation, respectively. In SA, 10 of the 11 sites are located within 1 km and 1 site 31 km of the existing infrastructure. In VIC, 9 of the 16 sites are located within 1 km and 7 between 5 and 35 km of the existing infrastructure. At 15 proposed sites in QLD 0.9 million tonnes of stubble could potentially be available for electricity generation, while 1 site in TAS could use 0.6 million tonnes of stubble. The site in TAS is located within 1 km of the existing transmission line. 4 of the 15 sites in QLD are located within 1 km of the existing transmission infrastructure. 9 of 15 sites in QLD are located within 100 km and 2 between 100 and 130 km of the existing transmission infrastructure. Appendix Table 10 (B8) shows a complete list of all prospective bioenergy sites, their location, resource use and distance of transmission infrastructure.

4. Discussion

The estimated energy contained in the biomass resources considered here (1676 PJ/year, derived from Table 4) is similar to estimates from other studies; e.g., Teske et al. assumed an energy potential of 1500 PJ/year [22]. The biomass resources availability translates to around 57.6 TWh/year – this is equivalent to around 28% of the Australian electricity demand (858 PJ/year) of 2019/20 [59]. These findings highlight the growth potential for the bioenergy sector in Australia, as currently bioenergy only accounts for around 4% and 1.4% of total energy and electricity supply respectively [14], leaving Australia in the bottom quartile of bioenergy deployment in comparison to other OECD countris. While a thorough analysis of emissions associated with the use of bioenergy resources was outside the scope of this study, the generation of 57.6 TWh of bio-electricity can avoid 35.7 million kg CO_2-e per year assuming current scope2[3] emissions of about 0.62 kg CO_2-e/MWh across the states of Australia [60]. The cost of electricity generation is difficult

[3] Scope 2 emissions are state-based, indirect emission factors from on-grid electricity [kg CO_2-e/MWh].

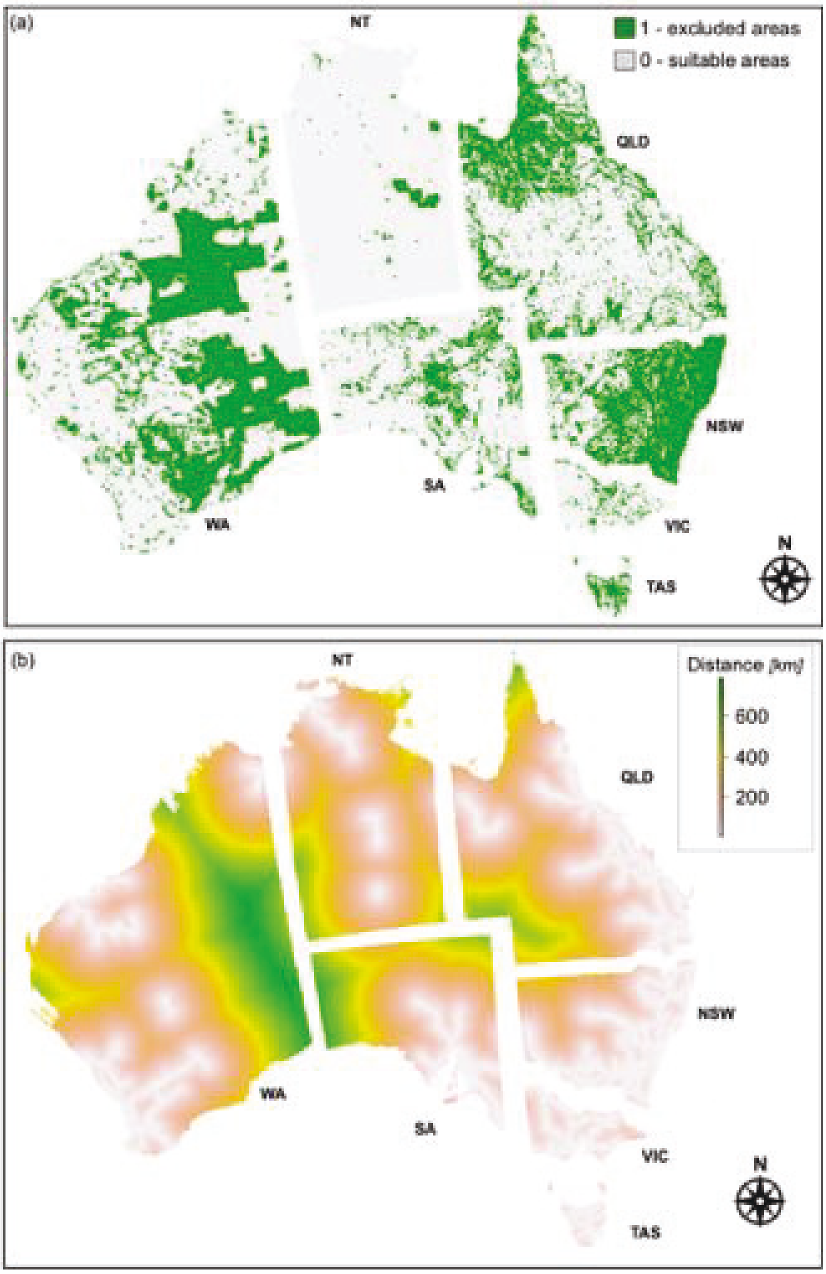

Fig. 8. (a) Green shading shows areas excluded (regional and national protected areas, wetlands, river and water bodies) for identifying possible new bioenergy sites in Australia at spatial resolution of 5 × 5 km. (b) Heat map showing distance from existing transmission infrastructure [km] in Australia at spatial resolution of 5 × 5 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

to estimate, because it is likely to decrease with a growing bioenergy industry. Assuming the current cost of electricity generation of about $ 96–125/MWh [7,61], the utilisation of all biomass resources in this study would conservatively translate to a cost of $ 5.5–7.3 billion per year.

The presented biomass maps are the most up to date bioenergy estimates for the Australian continent. This is because, compared to former assessments (e.g. Ref. [55]), this study uses the most up to date biomass resources raw data from the recently completed ABBA project [38] and furthermore consider already used resources at existing bioenergy sites. Additionally to this update, the approach and results of this study are relevant by.

i) Generating high-resolution biomass resources mapping: This study presented high-resolution (5 × 5 km) biomass resources maps for three biomass feedstock types for each of the Australian states. Previous biomass resources assessments focused only on specific regions of Australia, e.g. in 2011, Rodriguez et al. investigated the bioenergy potential in the wheat belt region [67], and in 2019 and 2022,

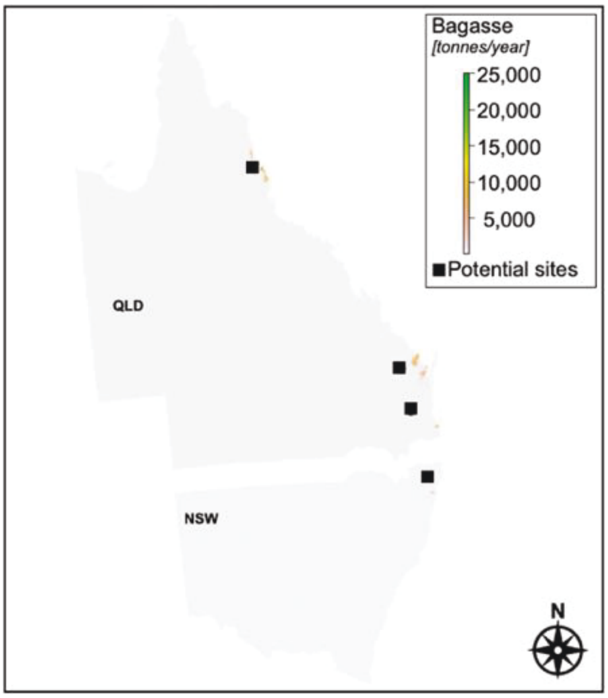

Fig. 9. Queensland (QLD) and New South Wales (NSW) remaining bagasse resources [tonnes/year] and locations for prospective bioenergy sites (black squares).

Jayarathna et al. investigated the bioenergy generation potential for QLD.

The differentiation of three important biomass feedstock types can help to support local industry development. For example, local communities can bring themselves into a pioneering position regarding technical know-how and targeted industrial development support for most efficient use of a certain feedstock type (e.g. stubble in the Riverina Murray region of NSW [68]).

ii) Determining prospect bioenergy sites: The study provided a list of prospective sites (defined coordinates) for bioenergy plants, which consider spatial constraints, and prioritise proximity to transmission network. This is in contrast to previous studies (Table 2) which focussed on resources use on the entire Australian continent [16,16,22,36], or only consider already existing bioenergy sites [24], without consideration of specific sites or siting constraints. This approach is not only valuable to setup or update Australian high-renewable supply models, but can also be beneficial to international studies, where bioenergy simulation in high-renewable energy supply model often suffers from the same simplifications (Table 1).

Using a list of prospective bioenergy sites has a number of advantages including the knowledge about the distance from transmission infrastructure. Grid connection can present an economic barrier for standalone renewable energy power plants. The limited size of bioenergy projects (usually <50 MW_e) makes major investment in network extensions or local network upgrades hard to justify relative to the total project value at this scale [69]. Estimates about increasing costs for plant siting further away from the transmission infrastructure are complex and depend on several local factors. The approach taken in this study provides a simple way to prioritise the most cost-efficient projects, which are the ones within 1 km of the existing grid infrastructure.

iii) Considering biomass feedstock transport distances: For each of the prospective bioenergy sites this study provides information on the available biomass resources [tonnes/year] in a maximum transport distance of 100 km. The limitation of the transport distance, and thus assumed use of local biomass feedstock, is especially relevant when considering carbon emissions associated with bioenergy generation. While it is assumed that the combustion of sustainable biomass resources is carbon neutral (because combustion related $CO_{2\text{-}e}$ emissions are reabsorbed by the plants during the next growth period), biomass feedstock harvest and transport generate emissions. These associated carbon emissions for harvest and transport are lowest, if the feedstock transport distance is limited; estimates for the three considered biomass feedstock types are summarized in Table 4. If all feedstocks considered in this study are used for bioenergy generation a maximum of 1.7 $MtCO_{2\text{-}e}$ would be produced due to harvest and transport.

The presented approach of high-resolution biomass resources mapping and determination of prospective bioenergy sites (including the consideration of biomass feedstock transport distances) in this study was demonstrated for the Australian continent. However the approach can also be applied to other countries. Applying this approach to other jurisdictions offers a solution to overcome speculative bioenergy assessments with the overarching goal of understanding the exact application potential of biomass and clarifying its important role in questions of future renewable energy supply.

4.1. Potential to update former high-renewable energy supply simulations

One of the main purposes of the biomass resources assessment in this study was the provision of a dataset that can enable a less uncertain assessment on the role of bioenergy in future high-RE supply simulations. As described in the introduction, former national and international high-RE supply models are often limited in their ability to represent the specific characteristics of biomass in bioenergy pathways. Some of these limitations are expected to be overcome by using the presented list of prospective bioenergy plants so that the biomass estimates in this study are less speculative compared to former high-RE supply simulations (Table 2).

The approach described here can be particular useful to derive estimates in simulation models that consider the relative share of energy sources supplying the electricity grid. An example of such a model is *Clean Grid*, developed in Australia [70]. In previous studies, and because of missing information on detailed biomass resources availability, *Clean Grid* only considered existing bioenergy sites in their simulations [71], or was able to map raw biomass resources in fixed grid squares of about 8000 km^2 [8]. The outputs of this study were used to update *Clean Grid* [72]. The simulation was improved by considering the appraisal of bioenergy resources as a list of precise coordinates for prospective bioenergy sites and computing the available resources within a defined collection radius (Fig. 11). With the complete list of prospective new bioenergy sites, *Clean Grid* now considers resources in a maximum transport distance of 100 km and an area of ~31,000 km^2. The simulation results are summarized and discussed by Li et al. [72]. The authors projected a bioenergy generation share of ~9–12% (at carbon prices above AU$ 30/tonne).

Compared to other high-RE supply models, *Clean Grid* does not simulate pre-selected plant sites and capacities, thus it optimises the specific capacity for each renewable technology and each grid cell over the entire Australian continent and over the course of one year of simulation. Because of this ability, the complete list of prospective new bioenergy sites, independently of the distance to the transmission infrastructure can be used as input into *Clean Grid*. *Clean Grid* contains information about the grid infrastructure and can expand the grid infrastructure during the simulation to cells that are not reached by the

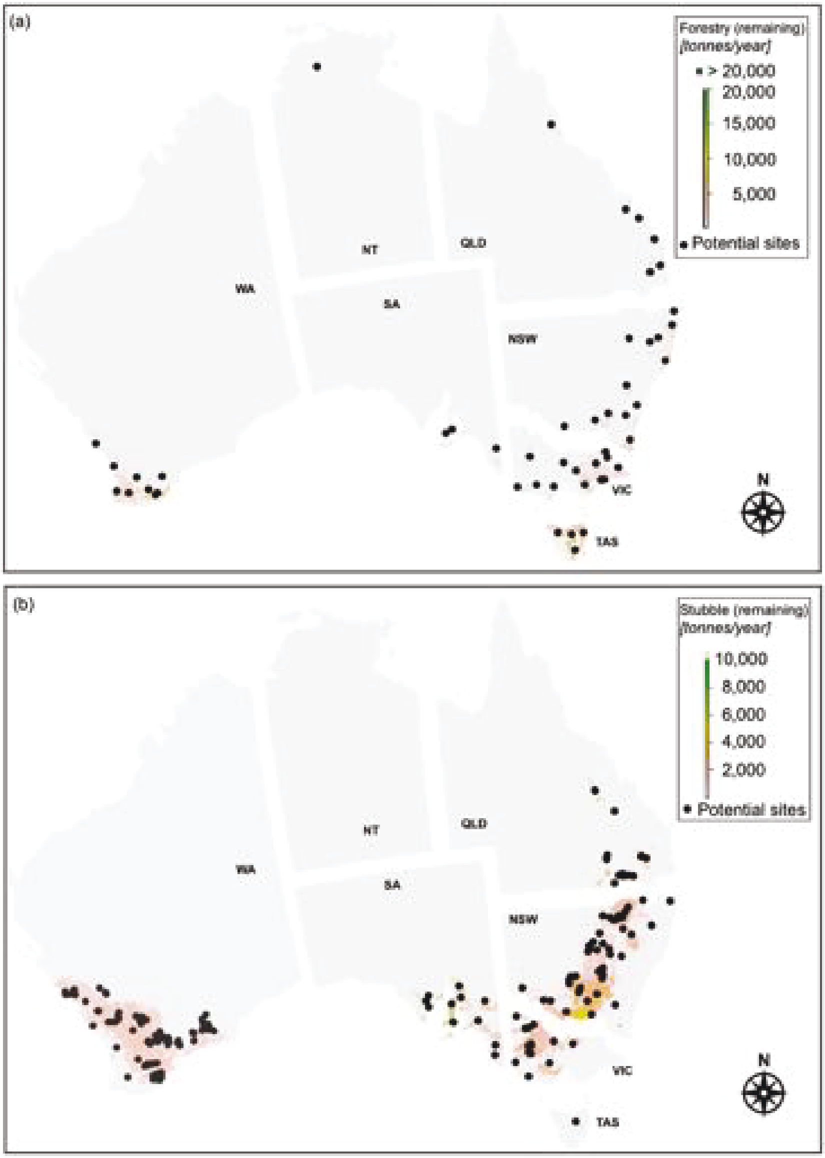

Fig. 10. States and territories of Australia showing prospective new bioenergy sites (black points), utilizing (a) remaining forestry residues [tonnes/year] and (b) stubble residues [tonnes/year].

grid, if beneficial. With this approach, *Clean Grid* can deploy bioenergy sites further away from the transmission infrastructure (which require expansion of the grid infrastructure) if the new transmission line extension is economically justified. Li et al. [72] found that transmission line extensions were justified to reach some of the prospective bioenergy sites. The study was the first one to specifically focus on bioenergy generation in 100% renewable electricity supply scenarios. The added level of detail in terms of bioenergy generation potential allowed for different bidding strategies of bioenergy plants to be investigated. Li et al. [72] highlighted the potential role of bioenergy as grid balancing technology with the potential to reduce the cost of the entire electricity supply system by 21–32%.

4.2. Focus of future work

Bioenergy is diverse in its biomass conversion pathways and final products. This study focussed on the investigation of biomass resources for grid connected thermal electricity. Depending on the local feedstock properties, and local energy demand (e.g. for industrial process demand) biomass resources could also be used for renewable heat generation, which is especially interesting in the context of harder-to-abate sectors [13].

Outside the scope of this study was the investigation of bioenergy generation from organic matter from animals, municipal waste, or manufactured food waste, as well as dedicated energy crops [73] and horticultural wastes. Other studies highlight that the utilisation of waste streams for bioenergy generation has great advantages (including the avoidance of disposing in landfill and burning without energy recovery), e.g. in Johnson et al. [32]. The approach taken in this study can be used to create high-resolution resources maps for other feedstocks, such as organic wastes [42]. High-moisture feedstocks like organic waste are suitable for anaerobic digestion [74]; the generated and cleaned biogas

Table 4
Calorific value, energy conversion factors and harvest and transport emission factors for bagasse, forestry and cropping.

	Calorific value [MJ/kg][a]	Energy conversion [MWh/tonne][1]	Harvest and transport (100 km) emissions [$tCO_{2\text{-}e}$/tonne]
Bagasse	17.5 [62] (8.8 [7,54] – 19.3 [18,63])	1.22 [18] (0.5 [7] – 1.5 [62])	32[b] [64–66]
Forestry residues	19.5 [63] (17.5 [7] – 22.3 [44,54])	1.4 [18] (1.1 [62] – 1.7 [7])	31 [51]
Stubble residues	17.3 [64] (14.8 [7,62] – 19 [18,63])	1.25 [18] (0.9 [62] – 1.3 [62])	41 [64–66]

[a] Values represent mean, min and max estimates.
[b] Not considering emissions from harvesting of bagasse, as the feedstock is commonly collected in the process of sugar production.

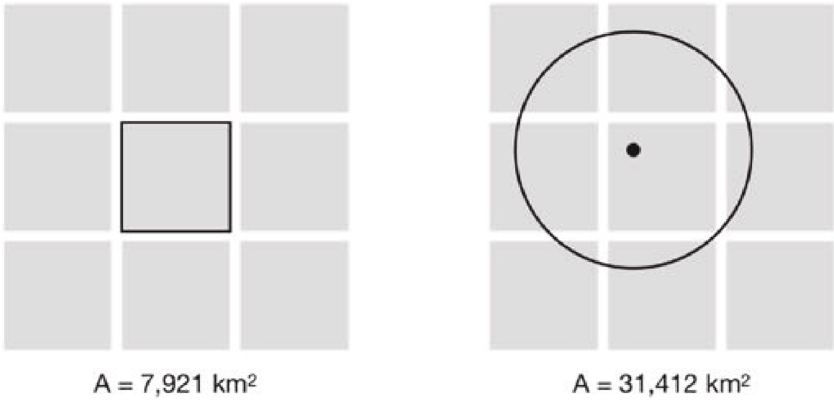

Fig. 11. Biomass resources consideration in Clean Grid: original approach (left) and updated approach (right). A = biomass resource catchment area.

can be included into the gas network for use in gas-fired OCGT e.g. Ref. [35]. The siting of anaerobic digestors should thereby consider distance from gas lines, rather than transmission infrastructure.

5. Conclusion

The presented high resolution biomass resources maps (5 × 5 km) for three important feedstock types (forestry waste, stubble and bagasse) are the most up to date biomass assessment for the Australian continent. Bioenergy from these feedstocks can produce additional 1676 PJ of energy per year. This energy generation potential can be important in the context of renewable energy provision in the harder-to-abate sectors, or in the context of dispatchable renewable electricity generation where the bioenergy resources can account for about 28% of Australia's current electricity demand. These results underline the great bioenergy potential of Australia, which is underutilised compared to other OECD countries.

The presented data set of prospective bioenergy sites has the potential to overcome some of the limitations of former bioenergy simulation in high-renewable energy (RE) supply models and provides new insights in terms of how and where bioenergy can be commissioned. The consideration of spatial constraints, distances to the transmission infrastructure, and maximum biomass transport distances for the identification of prospect bioenergy sites is an important approach that can also be applied to other jurisdictions. Using detailed bioenergy datasets can help to improve our understanding of the role of bioenergy in the global energy transition.

Funding

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Data availability

Data associated with this article can be sourced online and are available as supplementary data:-

ABBA biomass data for the different biomass resources types can be found here: https://www.nationalmap.gov.au,-

ALUM land-use data can be found here: http://www.agriculture.gov.au/abaras/aclump/land-use/land-use-mapping,-

Transmission line data can be found here: https://data.gov.au/dataset/ds-ga-1185c97c-c042-be90-e053-12a3070a969b/details?q=,-

List of existing bioenergy plants can be found in Appendix – A, Table 5 - 7,-

Biomass resources maps can be downloaded as supplementary data: *Middelhoff, Ella; Madden, Ben; Li, Mengyu; Ximenes, Fabiano; Lenzen, Manfred; Florin, Nick (2021), "Biomass resources maps", Mendeley Data, V1, doi: 10.17632/tmrv8m264b.1*,-

Transmission line data can be found here: https://data.gov.au/dataset/ds-ga-1185c97c-c042-be90-e053-12a3070a969b/details?q=. and-

a list of prospective bioenergy sites can be found in Appendix – B, Table 8 - 10.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2022.106496.

Appendix - A

Table 5
Existing bioenergy sites utilizing sugar cane residues: Location, size, feedstock usage and modelled minimum allocation radius. *calculated assuming a capacity factor of 50% [75] *and energy efficiency of* 1.22 MWh/*tonne.*

Name	Latitude	Longitude	State	Feedstock type	Size [MW_e] (export to grid [%])	Usage [tonnes/year]	Minimum allocation radius [km]
Macknade cogeneration plant	*−18.585*	*146.260*	QLD	Bagasse	8(4) [42]	415,000 [42]	20
Victoria cogeneration plant	*−18.650*	*146.200*	QLD	Bagasse	24(55) [42]	881,000 [42]	105
Invicta cogeneration plant	*−19.515*	*147.109*	QLD	Bagasse	50(71) [42]	805,000 [42]	35
Pioneer cogeneration plant	*−19.540*	*147.335*	QLD	Bagasse	68(74) [42]	538,000 [42]	160
Kalamia cogeneration pant	*−19.513*	*147.428*	QLD	Bagasse	9(22) [42]	416,000 [42]	230
Inkerman cogeneration plant	*−19.665*	*147.415*	QLD	Bagasse	10(16) [42]	448,000 [42]	240
Proserpine cogeneration plant	*−20.402*	*148.586*	QLD	Bagasse	17(33) [42]	498,000 [42]	160
Plane Creek cogeneration plant	*−21.426*	*149.213*	QLD	Bagasse	12(5) [42]	390,000 [42]	500
Racecourse cogeneration plant	*−21.158*	*149.139*	QLD	Bagasse	36(75)	150,000 [42]	525
Sarina Wilmar's biorefinery	*−21.429*	*149.220*	QLD	Molasses	NA	180,000 [42]	*Not considered*
Mackay biofuel pilot plant [42]	*−21.312*	*149.004*	QLD	Residues (incl. bagasse)	NA	NA	*Not considered*
Broadwater cogeneration plant	*−29.013*	*153.432*	NSW	Bagasse	38(NA) [75]	140,100 *	45
Condong cogeneration plant	*−28.312*	*153.435*	NSW	Bagasse	30(NA) [75]	105,100 *	130
Harwood cogeneration plant	*−29.424*	*153.249*	NSW	Bagasse	4.5(NA) [75]	16,200 *	10

Table 6
Existing bioenergy sites utilizing forestry residues: Location, size, feedstock usage and modelled minimum allocation radius. *calculated assuming a capacity factor of 60% and energy efficiency of 1.4 MWh/tonne [11].

Name	Latitude	Longitude	State	Feedstock type	Size [MW] (export to grid [%])	Usage [tonnes/year]	Minimum allocation radius [km]
Hills Transplants	*−41.166*	*146.323*	TAS	Tree residues	2.5(0) [42]	9400 *	10
Southwood Huon Valley	*−43.021*	*147.017*	TAS	Forest residues	30–50(100) [32]	300,000	*In development*
Nestle, Gympie	*−26.182*	*152.648*	QLD	Saw dust, coffee grounds	4(NA) [32]	800–1000	25
South East Fibre Export	*−37.118*	*149.941*	NSW	Sawmill residues	5(NA) [32]	NA	*In development*
Northern Cooperative Meat Company	*−28.850*	*153.034*	NSW	Timber waste	12(0) [76]	10,513 [76]	15
Vales Point B coal power station	*−33.162*	*151.541*	NSW	Sawmill residue and C&D waste	5(100) [57]	20,000 ***	65
Visy Tumut power station	*−35.278*	*148.139*	NSW	Pulp and paper	17(100) [57]	NA	*Not considered*
Family Fresh Farm	*−33.332*	*151.235*	NSW	Sawmill residues	NA	6000 ***	90
Broadwater cogeneration plant	*−29.013*	*153.432*	NSW	Forestry residues	38(NA) [75]	142,700 *	95
Kalannie mallee oil and biochar gas engine	*−30.363*	*117.120*	WA	Mallee	0.2(0) [77]	2409 [77]	115
Narrogin plant	*−32.936*	*117.173*	WA	Plantation wood and mallee	NA	20,000 [57]	*Not considered*
Muja coal power station	*−33.447*	*116.301*	WA	Wood waste	5(100) [57]	78,000 [57]	*Not considered*
Macco Feeds, Williams	*−33.018*	*116.905*	WA	Mallee woodchips	1.7(0) [78]	4000 [78]	25
Trandos Hydroponics biomass heating	*−31.671*	*115.803*	WA	Woodchips	4(0) [42]	600 [78] **	5
Manjimup biomass project	*−34.269*	*116.151*	WA	Saw mill waste	40(NA) [32]	380,000	*In development*
Reid Brothers Sawmillers	*−31.790*	*145.617*	VIC	Tree residues	1(0) [42]	3900 [42]	20
Beaufort Hospital	*−37.428*	*143.384*	VIC	Sawmill residues	0.1(0) [79]	400 [78] **	15
Gelliondale Nursery	*−38.598*	*146.670*	VIC	Wet sawdust	1.5(0) [42]	600 [78] **	5
Murphy Fresh Hydroponics	*−36.970*	*146.119*	VIC	Waste hardwood	6 (0) [78]	9000 [78] **	5
Mount Gambier Aquatic Centre	*−37.833*	*140.777*	SA	Wood	0.52(0) [80]	150,000 [80]	50
Mount Gambier, Carter Holt Sawmill	*−37.841*	*140.808*	SA	Wood waste	10(NA) [32]	38,000 *	50

assuming AU$ 50/tonne, * personal comment Ximenes, 2021.

Table 7
Existing bioenergy sites utilizing crop residues: Location, size, feedstock usage and minimum allocation radius.

Name	Latitude	Longitude	State	Feedstock type	Size [MW] (export to grid [%])	Usage [tonnes/year]	Minimum allocation radius [km]
Darling Downs grain-to-ethanol plant	*−27.150*	*151.245*	QLD	Sorghum grain	–	200,000 [42]	*Not considered*
	−26.190	*152.670*	QLD	Macadamia nut shells	1.4	5000 [42]	*Not considered*

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Table 7 (*continued*)

Name	Latitude	Longitude	State	Feedstock type	Size [MW] (export to grid [%])	Usage [tonnes/year]	Minimum allocation radius [km]
Suncoast Gold cogeneration facility							
BioWorks biodiesel	*−32.155*	*115.778*	WA	Mustard	4 ML/yr (0) [42]	NA	*Not considered*
Riverland biodiesel	*−32.643*	*115.835*	WA	Mustard, canola	20,000 L/yr (0) [42]	NA	*Not considered*
Canola to biodiesel	*−36.077*	*144.991*	VIC	Canola	1.5–2 ML/yr (0) [42]	NA	*Not considered*
Australian Tartaric Products (ATP)	*−34.550*	*142.330*	VIC	Grape waste	0.4 [78]	90,000 [78]	*Not considered*
Harvest biomass plant in Carwarp	*−34.545*	*142.232*	VIC	Almond and grape waste	35 (NA) [32]	NA	*Not considered*
Harvest plant in Robinvale	*−34.589*	*142.780*	VIC	Almond shell and hull	2.5 (NA) [32]	NA	*Not considered*
Energy from mustard and canola	*−36.379*	*141.240*	VIC	Canola, mustard	NA	NA	*Not considered*
Ethanol plant in Nowra	*−34.888*	*150.602*	NSW	Waste flour	300 ML/yr	NA	*Not considered*

Appendix - B

Table 8
Prospective new bioenergy sites utilizing sugar case residues: Location, size, feedstock usage (in 100 km radius) and distance from transmission infrastructure.

State	Latitude	Longitude	Available resources [tonnes/year]	Distance from transmission lines [km]
QLD	−16.980	145.374	540,068	0.8
QLD	−25.390	152.370	464,202	0.2
QLD	−27.106	152.911	57,000	0.0
NSW	−28.896	153.040	31,854	0.3

Table 9
Prospective bioenergy sites utilizing forestry residues: Location, size, feedstock usage (in 100 km radius) and distance from transmission infrastructure.

State	Latitude	Longitude	Available resources [tonnes/year]	Distance from transmission lines [km]
NSW	−34.980	148.169	447,125	0.7
NSW	−36.700	149.741	440,881	0.9
NSW	−31.918	152.406	323,281	0.2
NSW	−29.754	152.936	310,682	0.4
NSW	−33.361	149.602	209,227	0.4
NSW	−35.205	149.472	130,182	0.5
NSW	−30.781	151.368	50,087	0.5
NSW	−30.529	149.913	30,319	0.6
NSW	−30.517	151.946	24,110	0.3
NSW	−35.388	147.210	18,789	0.5
NSW	−35.617	144.935	15,941	0.5
NSW	−28.896	153.039	14,908	0.3
NSW	−34.596	150.316	14,516	0.4
QLD	−27.061	152.709	590,629	0.0
QLD	−17.927	145.522	49,341	0.0
QLD	−23.426	150.369	32,144	0.8
QLD	−24.026	151.291	30,906	0.1
QLD	−27.464	152.050	28,811	0.1
QLD	−25.389	152.365	13,410	0.2
NT	−13.778	131.893	367,000	0.0
SA	−36.559	140.622	1,018,286	0.9
SA	−35.098	137.699	64,758	0.5
SA	−35.130	137.259	39,636	40.2
TAS	−41.672	147.052	3,237,580	0.7
TAS	−42.750	147.011	1,352,510	0.1
TAS	−41.410	145.642	785,009	0.3
TAS	−41.628	148.016	154,549	0.3
VIC	−36.846	147.243	1,256,956	0.9
VIC	−37.823	142.521	851,105	0.4
VIC	−38.101	146.292	730,085	0.8
VIC	−38.025	143.855	408,352	1.0
VIC	−37.166	145.701	177,043	1.0
VIC	−36.100	142.315	154,269	0.3
VIC	−37.852	147.563	135,585	0.7
VIC	−37.822	141.108	55,607	0.4
VIC	−36.654	144.746	28,951	0.6
VIC	−36.161	148.016	10,309	0.5

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Table 9 (*continued*)

State	Latitude	Longitude	Available resources [tonnes/year]	Distance from transmission lines [km]
VIC	−37.812	147.679	30,178	10.7
VIC	−37.817	147.793	25,140	20.3
VIC	−36.525	148.104	14,771	30.6
VIC	−37.141	148.908	166,993	40.7
WA	−33.932	116.168	1,312,485	0.1
WA	−34.595	117.737	926,134	0.1
WA	−32.339	115.946	221,118	0.0
WA	−33.348	117.061	86,406	0.5
WA	−33.618	115.516	73,572	0.2
WA	−30.869	115.419	60,891	0.3
WA	−34.190	117.419	16,454	0.8
WA	−34.587	117.844	30,035	10.8
WA	−33.801	118.574	10,012	111.0

Table 10
List of prospective bioenergy sites utilizing stubble residues: Location, size, feedstock usage and modelled distance from transmission lines.

State	Latitude	Longitude	Available resources [tonnes/year]	Distance from transmission lines [km]
NSW	−35.005	146.745	2,708,614	0.2
NSW	−33.399	148.043	1,358,586	0.7
NSW	−29.536	149.841	1,255,596	0.8
NSW	−33.809	145.486	1,007,774	0.2
NSW	−35.538	145.108	916,024	0.6
NSW	−34.593	147.538	560,655	0.0
NSW	−31.807	147.656	517,998	0.8
NSW	−30.943	150.266	469,815	0.7
NSW	−34.699	143.449	266,125	0.3
NSW	−35.828	147.012	179,333	0.6
NSW	−32.160	148.641	114,635	0.3
NSW	−34.387	146.140	105,801	0.6
NSW	−28.838	151.092	82,510	0.5
NSW	−29.891	149.623	67,986	0.0
NSW	−33.858	141.986	59,378	0.6
NSW	−30.424	151.738	31,657	0.1
NSW	−31.559	147.144	28,122	0.8
NSW	−35.321	148.863	27,287	0.2
NSW	−32.994	148.066	25,731	0.6
NSW	−32.321	149.483	18,317	0.4
NSW	−34.830	143.978	16,700	0.8
NSW	−33.630	145.502	16,347	0.9
NSW	−28.896	153.039	13,389	0.3
NSW	−34.211	146.208	55,954	10.6
NSW	−29.843	149.521	24,074	10.3
NSW	−33.458	145.624	22,348	10.9
NSW	−33.080	147.954	19,926	10.5
NSW	−36.456	149.138	10,930	11.0
NSW	−29.314	150.002	22,654	20.4
NSW	−31.781	147.078	20,619	21.0
NSW	−29.840	149.418	16,028	20.2
NSW	−33.574	147.926	11,153	20.5
NSW	−33.161	147.736	50,508	30.1
NSW	−31.840	148.498	32,908	30.3
NSW	−31.347	147.420	25,679	30.1
NSW	−30.567	149.600	19,371	30.1
NSW	−29.793	149.316	15,001	30.7
NSW	−31.869	147.019	10,182	30.9
NSW	−29.970	149.206	16,993	40.5
NSW	−33.432	145.948	12,803	40.2
NSW	−31.464	148.096	18,115	50.0
NSW	−29.967	149.103	12,140	50.5
NSW	−30.005	148.894	21,061	70.9
NSW	−29.864	148.693	14,542	90.0
NSW	−30.825	147.868	11,727	100.6
NSW	−29.756	148.181	11,128	140.2
QLD	−27.092	150.995	352,467	0.5
QLD	−22.916	147.945	140,169	0.4
QLD	−28.345	150.411	113,194	0.0
QLD	−27.232	151.345	12,873	0.9
QLD	−28.293	150.055	32,254	30.7
QLD	−24.260	149.220	11,934	50.4
QLD	−26.993	148.630	10,513	50.5

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Table 10 (*continued*)

State	Latitude	Longitude	Available resources [tonnes/year]	Distance from transmission lines [km]
QLD	−28.330	149.697	34,805	60.1
QLD	−28.193	149.651	31,743	70.2
QLD	−27.171	148.573	19,291	71.0
QLD	−28.280	149.495	27,559	80.7
QLD	−27.261	148.569	12,861	80.5
QLD	−28.277	149.393	13,269	90.4
QLD	−28.764	149.070	28,988	110.8
QLD	−28.931	148.654	73,387	130.9
SA	−34.041	137.789	1,773,170	0.6
SA	−33.595	136.117	709,090	0.8
SA	−33.059	138.493	585,578	0.4
SA	−35.098	137.699	574,394	0.5
SA	−35.181	139.477	407,464	0.5
SA	−36.717	140.430	296,531	0.8
SA	−34.130	140.079	262,183	0.5
SA	−33.962	136.203	87,946	0.0
SA	−33.726	138.486	55,168	0.8
SA	−37.289	140.334	12,596	0.2
SA	−33.351	136.272	10,649	30.8
TAS	−41.672	147.052	60,745	0.7
VIC	−36.100	142.315	1,596,034	0.3
VIC	−36.115	144.138	566,067	0.3
VIC	−37.465	143.586	508,204	0.0
VIC	−35.022	142.295	421,880	0.3
VIC	−36.351	145.612	250,124	0.7
VIC	−36.725	142.284	63,991	0.1
VIC	−34.269	141.422	39,035	0.2
VIC	−34.922	142.690	35,342	0.8
VIC	−38.164	141.847	12,969	0.7
VIC	−36.184	142.248	12,243	5,8
VIC	−35.057	142.182	14,213	10,2
VIC	−36.179	142.194	11,053	10,8
VIC	−36.621	142.131	15,287	15,4
VIC	−37.138	140.993	21,580	20,8
VIC	−35.091	142.068	16,645	20,8
VIC	−35.750	141.923	10,519	35,6
WA	−31.680	117.622	1,409,407	0.5
WA	−33.209	117.278	1,087,124	0.4
WA	−30.825	116.398	1,006,302	0.8
WA	−32.349	118.814	963,560	0.0
WA	−29.394	115.554	663,767	0.3
WA	−34.492	117.684	504,898	0.9
WA	−31.406	118.621	476,370	0.6
WA	−28.756	114.855	320,996	0.9
WA	−30.078	116.010	233,469	0.9
WA	−32.210	116.303	195,063	0.7
WA	−33.669	117.516	114,325	0.1
WA	−32.509	118.246	67,699	0.3
WA	−33.875	116.247	40,332	0.2
WA	−30.866	116.524	40,227	1.0
WA	−28.885	115.122	35,240	0.9
WA	−32.243	119.157	26,196	0.0
WA	−28.724	114.639	24,031	0.2
WA	−31.498	118.239	22,140	0.1
WA	−28.997	116.606	18,828	0.4
WA	−30.712	115.443	11,250	0.7
WA	−30.949	116.776	76,414	10.1
WA	−31.329	118.506	37,935	10.2
WA	−33.662	117.621	34,152	10.0
WA	−32.414	118.886	33,083	10.8
WA	−28.640	114.630	27,295	10.9
WA	−34.536	117.818	26,940	10.5
WA	−31.410	118.228	17,302	10.4
WA	−32.537	118.334	12,508	10.1
WA	−30.105	116.093	10,829	10.2
WA	−30.903	116.893	49,258	20.3
WA	−32.502	118.898	39,357	21.0
WA	−33.603	117.699	28,469	20.6
WA	−31.289	118.376	24,787	20.1
WA	−29.319	116.848	18,619	20.1
WA	−32.406	119.138	15,442	20.5
WA	−34.308	117.773	14,738	20.6
WA	−32.662	118.329	14,585	20.1

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Table 10 (*continued*)

State	Latitude	Longitude	Available resources [tonnes/year]	Distance from transmission lines [km]
WA	−28.569	114.660	11,778	20.4
WA	−31.178	118.423	40,658	30.7
WA	−33.683	117.814	39,085	30.1
WA	−32.624	118.745	28,346	30.4
WA	−34.661	118.067	24,563	30.4
WA	−29.405	116.860	19,886	30.7
WA	−28.623	115.188	10,043	30.2
WA	−30.835	117.067	69,663	40.4
WA	−32.688	118.817	31,392	40.2
WA	−34.292	117.986	28,511	40.8
WA	−32.648	119.235	61,727	50.8
WA	−33.703	118.008	44,473	50.7
WA	−31.098	118.164	40,519	50.7
WA	−30.675	117.087	26,383	50.6
WA	−34.542	118.228	24,463	50.7
WA	−32.678	119.473	42,311	60.5
WA	−34.328	118.226	28,035	60.3
WA	−31.034	118.094	16,162	60.3
WA	−32.742	119.546	23,110	70.7
WA	−34.320	118.333	18,268	70.6
WA	−30.543	117.192	14,477	70.2
WA	−33.752	118.290	31,335	80.7
WA	−32.866	119.393	24,379	80.4
WA	−32.930	119.466	23,271	90.2
WA	−33.029	119.373	17,910	100.0
WA	−32.164	122.284	13,857	110.3
WA	−32.334	121.969	52,940	120.3
WA	−33.030	120.079	42,216	120.2
WA	−33.130	119.987	15,377	130.2
WA	−32.501	121.956	44,361	140.5
WA	−33.284	120.074	29,570	150.7
WA	−32.668	121.942	52,296	160.8
WA	−32.861	121.108	73,847	170.0
WA	−32.704	122.231	11,526	170.6
WA	−32.808	122.141	29,617	180.8
WA	−32.925	121.184	23,630	181.0
WA	−32.872	122.218	25,589	190.2
WA	−32.913	121.746	11,843	190.5
WA	−33.308	121.029	23,509	200.2
WA	−32.975	122.127	10,650	200.8
WA	−33.026	122.311	22,987	210.8
WA	−33.153	122.466	13,102	230.3

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8.A.2. Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia

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Assessing electricity generation potential and identifying possible locations for siting hybrid concentrated solar biomass (HCSB) plants in New South Wales (NSW), Australia

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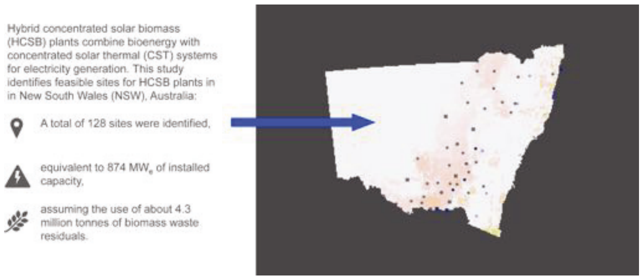
HIGHLIGHTS

- Geospatial modelling of deployment potential, considering substations and resources.
- Hybrid concentrated solar biomass (HCSB) plant deployment potential of 830 MW_e.
- Potential to abate about 6 billion kg $CO_{2\text{-}e}$/year in New South Wales (NSW)
- Straw residues are abundant and have the best overlay with solar resources.
- Highest quantities of cereal straw are located in the Riverina region of NSW.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to assess the deployment potential of hybrid concentrated solar biomass (HCSB) plants for dispatchable renewable electricity generation in New South Wales (NSW), Australia. We present an approach for identifying the most suitable locations for siting new plants. HCSB plants generate steam using a biomass boiler and a concentrated solar power (CSP) system and utilise a shared steam turbine for power generation. The total power generation opportunity was estimated based on available resources. This was achieved by mapping solid biomass (bagasse, stubble and forestry residues) and solar resources (direct normal irradiation) in proximity to zone substations with new grid connection capacity. The total installed capacity of HCSB plants at suitable grid connection locations was calculated to be 874 MW_e at a cost of about AU$ 6.3 billion. We also estimated the $CO_{2\text{-}e}$ emission abatement potential to be about 6 billion kg of $CO_{2\text{-}e}$ per year. The Riverina region was identified to be the most prospective region for HCSB plants in NSW owing to excellent biomass and solar resources and 25 suitable grid connection points. These findings underline NSW's excellent deployment potential for HCSB plants, a technology that can utilize the vast and currently under-exploited biomass residues and solar resources for dispatchable renewable electricity generation.

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Table 1
Overview about and specifications of former studies investigating the potential of hybrid concentrated solar biomass (HCSB) plants.

Study	Size region of interest, *region*	Biomass resource and spatial resolution	Biomass logistics	Direct normal irradiation threshold	HCSB plant design	Energy integration
Nixon et al. 2012 [32]	Five locations, *India*	Specific available feedstock for location	Up to 350 km	4–7 kWh/m^2/day	HCSB plants for tri-generation (2–10 MW$_e$)	Industrial integration (sites)
Peterseim et al. 2014 [23]	7.7 million km^2, *Australia*	Annual agricultural and forestry residues in larger regions	50 km around transmission lines	1995–2011, >18 MJ/m^2/day	Specific HCSB plant layout, 5–60 MW$_e$	Transmission lines 2011 with $\geq$ 66 kV capacity
Peterseim et al. 2014 [21]	7.7 million km^2, *Australia*	Agricultural regions	Not considered	1995–2011, >18 MJ/m^2/day	Unspecific HCSB plant design	Discussed but not specifically considered
Soria et al., 2015 [31]	70 km^2, *Bahia, Brazil*	Dedicated energy crops, constant concentration for region	50 km around substations	>2,100 kWh/m^2/year	Optimised HCSB plant layout (economic feasibility and emission abatement)	Substations in the grid
Hussain, Norton & Duffy 2015 [33]	10.2 million km^2, *Europe*	Not considered	Not considered	1,800–2,000 kWh/m^2/year	Unspecific HCSB plant design	Not considered
Thiam et al. 2017 [30]	196,722 km^2, *Sahel, Senegal*	Annual livestock residues and *Typha Australys* plants in nine regions	Not considered	>1,600 kWh/m^2/year	Unspecific HCSB plant design	Power lines with buffer of 80.5 km
This study	**801,150 km^2, *New South Wales (NSW), Australia***	**Three biomass feedstock types at 5 × 5 km**	**50 and 100 km radius around substations**	**>1,800 kWh/m^2/day**	**Optimised HCSB plant layout (maturity and efficiency), 5–50 MW$_e$**	**Substations with new connection capacity in the grid**

Fig. 1. New South Wales (NSW), Australia, *Australian Bureau of Statistics*, statistical areas level 4.

Table 2
HCSB plant energy efficiency for different plant sizes and full and part-load operation, adopted from Middelhoff et al. [18].

	Unit	5 MW$_e$	15 MW$_e$	30 MW$_e$	50 MW$_e$
Full load (100% from biomass):					
Net plant efficiency	%	21.2	27.1	32.2	33.7
Part load (80% from biomass, 20% CSP):					
Net plant efficiency	%	22.5	28.9	33.9	35.5

1. Introduction

In line with international efforts [1,2], Australia is on a track to phase out fossil fuels for energy generation – a major transition process considering the current high reliance on fossil fuels. Despite the recent growth in renewable generation capacity, only 6.4% of the total generated energy in 2018/19 was sourced from renewable resources [3]. Reaching a high level of renewable energy generation and achieving net-zero emissions by 2050 [4] will require significant investment in new renewable energy generation and storage technologies as emphasised in the recently published sixth assessment report from the Intergovernmental Panel on Climate Change [5].

Globally, in the context of the energy transition, several challenges are slowing the uptake of grid integrated renewable electricity generation technologies, including:

(i) *costs of continuous electricity supply*:

Variable renewable energy, generated from solar photovoltaic (PV) or wind power plants can be installed at a low levelized cost of electricity (for Australia of AU$ 40–60 /MWh [6]), which is cheaper than new installed fossil fuel power plants. Because variable renewable energy fluctuates owing to intermittencies of solar and wind resources, large amounts of these variable renewable energy need to be installed in different regions, so that lulls in one region are balanced with energy generation elsewhere [7,8]. Another option is the installation of dispatchable renewable energy with the potential to achieve higher cost efficiencies when considering a whole-of-system view [7,8]. Dispatchable renewable technologies, such as bioenergy and concentrated solar power (CSP) incorporate storages (e.g. for biomass feedstock or thermal energy) and can ensure energy supply at high capacity factors [9]. Nonetheless, dispatchable renewable energy remains more expensive than variable renewable energy [6,68]. In Australia for example, the deployment rates remain low in the absence of government incentives [7]. By comparison, in other Organisation for Economic Co-operation and Development (OECD) countries, bioenergy and energy from waste contribute around 2.4% of electricity output, compared to only 1.4% in Australia [10].

(ii) *upgrading transmission infrastructure to accommodate renewable generators:*

Historically, electricity markets (including the Australian national electricity market) were designed to transport electricity from large, decentralized power stations to the cities and centres of energy demand. With high construction and maintenance costs for electricity transmission infrastructure [11], and considering renewable projects are usually deployed at small- to medium- scales (e.g. 5–150 MW$_e$) (with exception of hydro dams, e.g. the Snowy 2.0 hydro dam [12]), it is often hard to justify investment in new transmission infrastructure. New

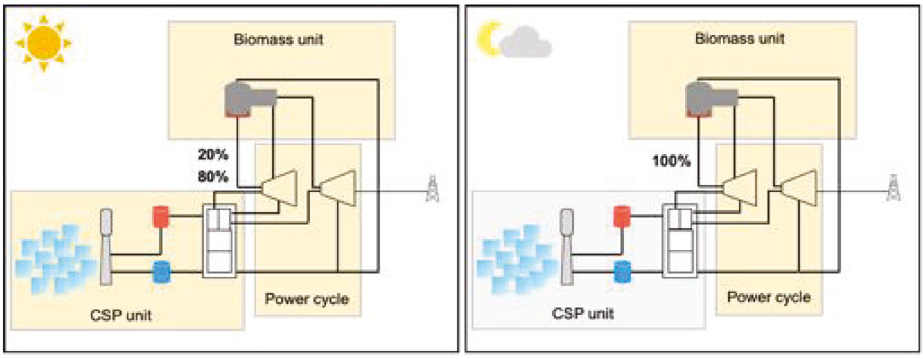

Fig. 2. Simplified process diagram for a hybrid concentrated solar biomass (HCSB) plant with 'fuel saving' operation mode and thermal storage.

Table 3
Three groups of investigated power generation scales and high and low voltage condition on substations with sufficient new connection capacity. Adopted from Lovegrove et al. [50].

Connection scale	Size [MW_e]	High voltage level [kV]	Low voltage level [kV]
Medium-scale Connection	30–50	132	66
Small-scale Connection	15–<30	132	11–33
Micro-scale Connection	5–<15	66	11–33

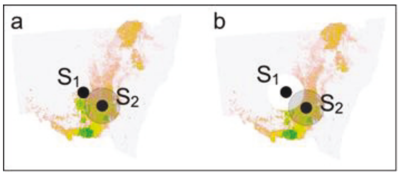

Fig. 3. Biomass resource allocation at substations in NSW. a) 'General suitability' resource allocation: Substation 2 (S2) independent from resource allocation to other substations (e.g. S1). b) 'Prioritized' resource allocation: S2 receives resources after resources were allocated to S1.

renewable plants need to be integrated into the existing network and feasible sites that allow grid access are limited. Furthermore, the siting of renewable technologies needs to fulfil several further requirements, including sufficient renewable resources availability.

This study investigates the energy generation and siting potential of hybrid concentrated solar biomass (HCSB) plants, a novel dispatchable renewable technology. For the purpose of this study we focus on the region of New South Wales (NSW), Australia. HCSB plants combine bioenergy with solar thermal energy, both feeding the same power generation cycle, as demonstrated in the 22.5 MW_e Termosolar Borges plant in Leida, Spain [13] or the 16.6 MW_{th} *Aalborg CSP* plant in Brønderslev, Denmark [14]. HCSB plants offer several general and specific (in the context of Australia) advantages over other dispatchable renewable technologies, including:

(i) The improvement of energy generation reliability and security, by using two independent renewable resources and integrating up to two different storages systems [15].
(ii) Lower biomass feedstock requirements [16], by offsetting energy generation through freely available solar energy. This enables a more diverse use of biomass resources for other industries (e.g. for bioplastics) and harder-to-abate sectors [17], and reduces the supply risk of biomass feedstock, which is increased by the frequency of droughts and bush fires in Australia [12,13]. It also minimizes traffic movements and associated emissions [18].
(iii) Accelerating CSP technology deployment and industry supply chain development [19], while bypassing deployment barriers of CSP. CSP plants are usually deployed at a scale > 50 MW_e and finding suitable sites at this scale is difficult. The shared use of equipment offers a way to minimize solar field and thermal energy storage system size while remaining economically feasible [20,21]. In the Australian context commercial CSP projects have failed to progress to the development stage, including recently the 250 MW_e Aurora plant in 2019 [22]. HCSB plant deployment scales of 5–50 MW_e could help fast-track CSP development with relatively low investment risk for demonstrating a first-of-a-kind successful project [19].
(iv) Expanding viable areas for siting of CSP integrated plants. While most operating CSP plants are located in areas with direct normal irradiation >2,000 $kWh/m^2/year$ [19], the Termosolar Borges HCSB plant operates in a region with direct normal irradiation around 1,800 $kWh/m^2/year$ [13] – this minimum threshhold for HCSB plant siting requirement [23] is easily exceeded in many areas of Australia. Thereby the siting potential of HCSB plants expands that of standalone CSP plants and moves energy generation from deserted areas closer to centres of energy demand.

For the investigation of energy generation potential of renewable technologies, geospatial modelling is a widely used method. Several studies have been presented for CSP [19,24,25] and biomass [26–29]. By contrasts, the number of studies investigating HCSB plants are limited. Table 1 summarises previous studies investigating HCSB plants in different parts of the world. These studies determine a direct normal irradiation threshold ranging between 1,600–1,800 $kWh/m^2/year$). The table also highlights several limitations that has informed the approach taken in this study:

(i) Biomass resource availability is assumed at high spatial resolution with high uncertainty and potential supply risks for actual deployment. Most studies assume biomass feedstock availability for large study regions as yearly averages [23,30].
(ii) Former studies assume simplified grid integration assumptions. Most studies which focus on grid integration, are considering points in direct proximity to the transmission infrastructure (e.g., [23]). Only one study [31], is considering substations for grid integration, however is not discussing the specific new connection capacity at the substation.
(iii) The energy generation potential of HCSB plants is either described at low spatial resolution (as total energy generation

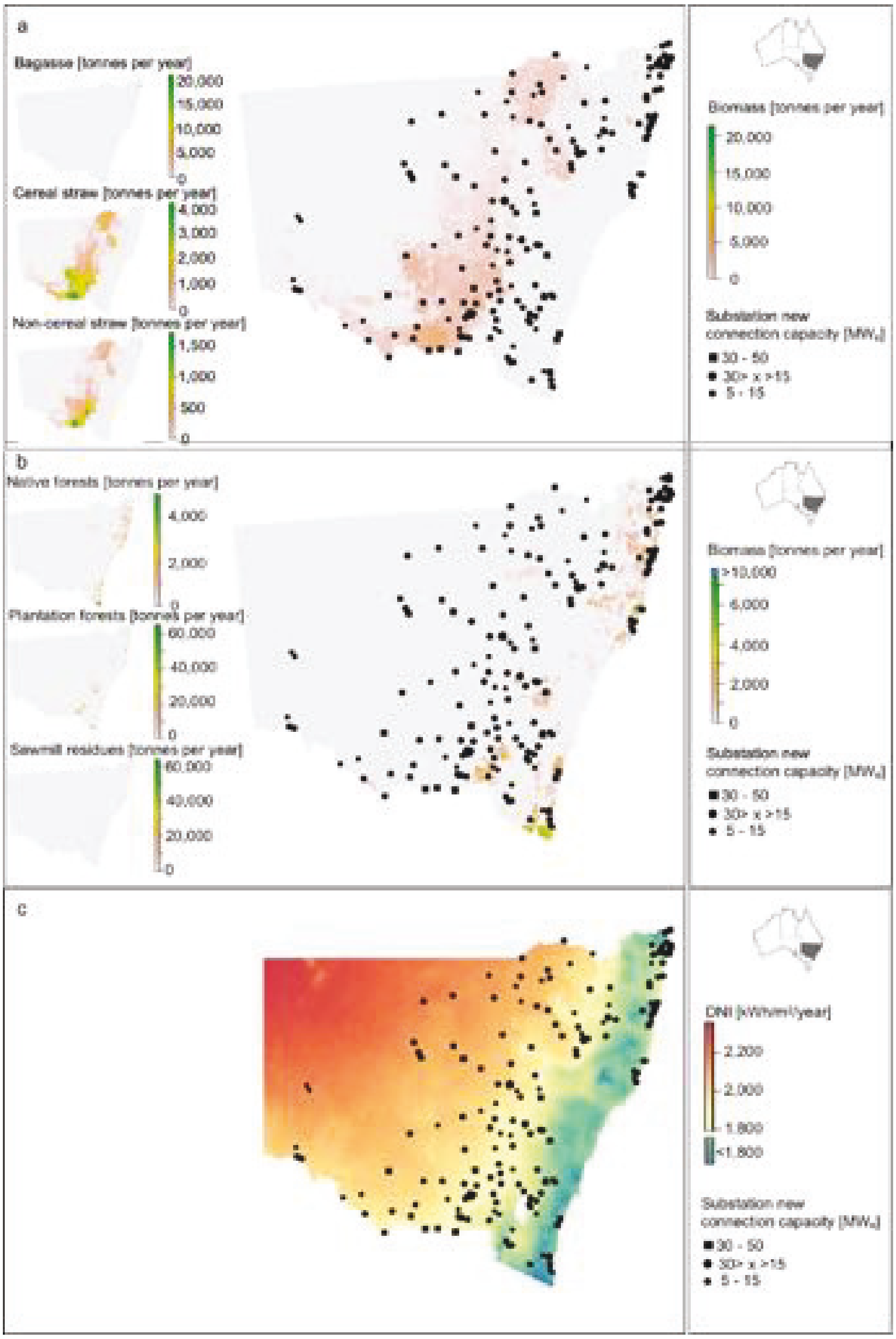

Fig. 4. Substation new connection capacity in NSW and a) agricultural residue availability [tonnes per year], b) forestry residue availability [tonnes per year] and c) direct normal irradiation [kWh/m^2/year].

[TWh/year] [23] or installed capacity [GW$_e$] [31] over the whole region) or at very high spatial resolution (e.g. for single locations [32]).

The approach taken in this study was informed by previous approaches (Table 1) by:

(i) Discussing HCSB plant deployment potential in the context of available biomass resources [tonnes/year] using up-to-date and

high resolution (5 × 5 km) resources maps for all major feedstock types in the region.
(ii) Considering realistic and up-to-date grid integration options by assessing plant siting at substations with new connection capacity [MW_e].
(iii) Giving a specific overview about HCSB industry potential in the case study region, assessing both total deployment potential (in installed capacity [MW_e] and installed cost [AU$]) and providing a list of specific prospective sites for future case studies.
(iv) Discussing HCSB plant advantages in the context of Australia's energy transition (carbon emission abatement potential [kg CO_{2-e}/year]), and specifically considering biomass feedstock transport (for 50 and 100 km).
(v) Discussing different HCSB plant design concepts and presenting technical considerations.

This case study is looking at HCSB technology deployment in the context of the Australian energy transition and for this purpose we have selected a specific technically mature design concept (discussed in detail below). Because realistic feasibility studies rely on local resources data, we have focussed our study on NSW, Australia's most populated state; however, the methodology, general insights and knowledge gaps which are addressed in the study are broadly relevant for other jurisdictions and the general insights of the study are applicable to other jurisdictions.

Table 4
Conversion rates (tonnes of feedstock to MWh electricity) for different feedstocks and power plant sizes.

	Unit	5 MW_e	15 MW_e	30 MW_e	50 MW_e
Full load (100% from biomass):					
Bagasse	*tonnes/hour*	4.86	11.41	19.43	30.78
	MWh/tonne	1.03	1.31	1.54	1.62
Stubble	*tonnes/hour*	4.91	11.54	19.65	31.11
	MWh/tonne	1.02	1.30	1.53	1.61
Forestry	*tonnes/hour*	4.36	10.24	17.43	27.60
	MWh/tonne	1.15	1.46	1.72	1.81
Part load (80% from biomass, 20% CSP):					
Bagasse	*tonnes/hour*	1.00	2.39	4.09	6.48
	MWh/tonne	5.00	6.28	7.33	7.72
Stubble	*tonnes/hour*	1.01	2.42	4.13	6.55
	MWh/tonne	4.95	6.12	7.26	7.63
Forestry	*tonnes/hour*	0.89	2.15	3.67	5.81
	MWh/tonne	5.62	6.98	8.17	8.61

Table 5
Specific plant investment for technology components of hybrid solar biomass plants. Adopted from Lovegrove et al. [7].

Specific plant cost	Cost estimates		Power size exponent (PSE)	Base size	
Thermal energy storage [$/$MWh_{th}$]	26,000	[$/$MWh_t$]	−0.1896	1,429	[MWh_t]
Solar field, tower and receiver [$/$MW_{th}$]	460,000	[$/$MW_t$]	−0.1896	600	[MWh_t]
Power block, heat exchanger and balance of plant [$/$MW_e$]	2,400,000	[$/$MW_e$]	−0.3145	100	[MW_e]
Biomass storage [$/MWh]	6.7	[$/$MWh_t$]	−0.3	15	[MWh_t]
Biomass boiler [$/$MW_e$]	1,641,526	[$/MWh]	0	44,384	[MWh]

2. Material and methods

2.1. Case study region

Australia's exceptional overlay of excellent natural resources for HCSB plant deployment has been previously recognised: Peterseim et al. [16] investigated the techno-economic aspects of HCSB plant deployment in the context of a modern waste to energy plant in Swanbank, Queensland, Australia. Several studies have also investigated the use of agricultural waste residues in the Riverina region of Australia [18,20]. Studies investigating the deployment potential of HCSB plants are important to highlight the opportunities for technology developers and energy policy makers.

To investigate the potential HCSB plant siting relative to population density and labour markets (and ultimately energy demand), this study compared the *Australian Bureau of Statistics* statistical area level 4 regions (Fig. 1) in NSW for HCSP plant deployment potential.

2.2. HCSB technology design options

Technical options to hybridize solar thermal- with bio-energy are diverse and have been reviewed by several authors, e.g. [34–36]. Different hybrid options can be categorised based on their underlaying energy generation pathways: Brayton cycle, solar thermal fuel production, and Rankine cycle options (for a detailed overview of different design points see Appendix Table 12). For this study, we decided to choose a technically mature plant layout suited to grid-connection, and that allows immediate deployment (without the need for further research and development).

Studies have investigated solar thermal integration for polygeneration systems, e.g., by the authors Vidal & Martín [37], and de la Fuente & Martin [38]. Solar thermal energy can also be used to aid biomass gasification processes [39–41]. The resulting syngas can be used for energy generation in several power cycles, including gas engines. While in theory gasification may offer higher thermal efficiencies, this option was not considered for this study noting technical complexity and the low commercial readiness [35].

Solar integration into gas and micro-gas turbines using the Brayton cycle for power generation have been investigated by a number of authors, including Ref. [35,42]. Gas turbines are only rarely operated with biogas and were not considered for this study. Micro-gas turbines, such as the *AORA tulip* system [42] are, due to its small size <1 MW_e, not considered to be a viable option for a grid-connected plant.

Solar thermal energy can be integrated into Rankine (e.g., [21,43])

Table 6
Assumptions for biomass feedstock emission intensity.

Biomass feedstock	Unit	Harvest	Transport (50 km)	Transport (100 km)	References
Straw	kg $CO_{2\text{-}e}$	9	16	32	[58,60,61]
Forestry	kg $CO_{2\text{-}e}$	17	7	14	[62]
Bagasse	kg $CO_{2\text{-}e}$	0	16	32	[58,60,61]

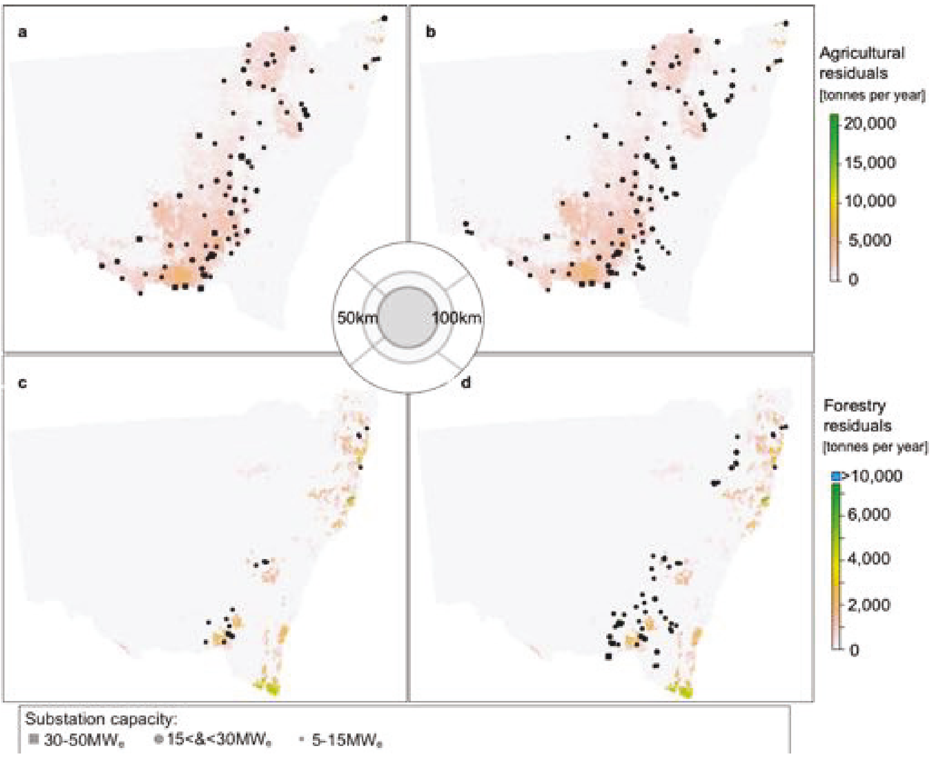

Fig. 5. Residual agricultural (a and b) and forestry (c and d) biomass resources [tonnes/year] in NSW and locations of substations with new connection capacity, which can be supplied by sufficient (to generate min. 5 MW_e) biomass resources in 50 km (a and c) and 100 km (b and d) resource collection radii and solar resources > 1,800 kWh/m^2/year.

Table 7
HCSB plant potential by substation size in 50 and 100 km feedstock collection radius.

Collection radius	Micro-scale options	Small-scale options	Medium-scale options
50 km	79	30	4
100 km	73	52	14

and Organic Rankine cycle (ORC) plants (e.g., [44–46]) as feed water heater (FWH) (e.g. [47]) or as steam generator for high- and low- temperature steam (e.g. [18,20]). These technologies have been demonstrated in several plants (e.g. [13,48]), thus have a high technical and commercial readiness. The first operational HCSB plant, the 22.5 MW_e *Termosolar Borges* project in Spain, uses parabolic trough collector that generate steam at around 663.15 K (390 °C), which is superheated by the biomass boiler to 793.15 K (520 °C) [13]. A more energy efficient option incorporates a solar tower with direct and high temperature of 723.15–813.15 K (450–540 °C) steam fed into the high pressure turbine of the plant [49].

This study focussed on Rankine cycle HCSB plants because of the high technical and commercial readiness. Rankine cycle HCSB plants can be designed with different solar feed-in points, different solar collector technologies, and different operational modes [35,20]. After Peterseim et al. [34], who compared the energy efficiency of different Rankine cycle HCSB plants, this study assumes a solar tower with a molten salt hybrid system that allows solar steam generation to be directly fed into the high-pressure turbine. Compared to other integration options this is the most efficient plant layout [34].

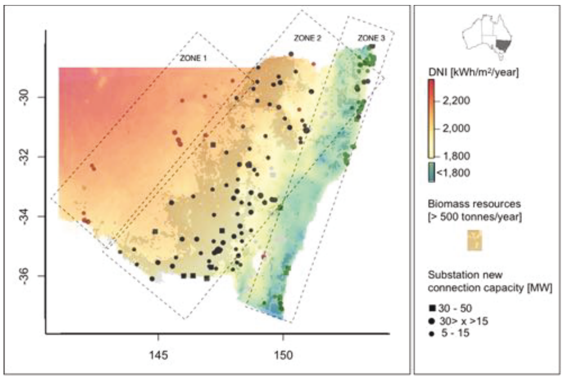

Fig. 6. Three zones of technology deployment: Zone 2 shows substations (in black) feasible for hybrid concentrated solar biomass (HCSB) plants deployment, with direct normal irradiation > 1,800 kWh/m^2/year and sufficient biomass resources collection in 50 km. Zone 1 maps substations (in red) with direct normal irradiation > 2,000 kWh/m^2/year, however with insufficient biomass resources, which are feasible for standalone CSP plants. Zone 3 maps substations (in green) with sufficient biomass resources, however insufficient solar resources, which are feasible for standalone biomass plants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

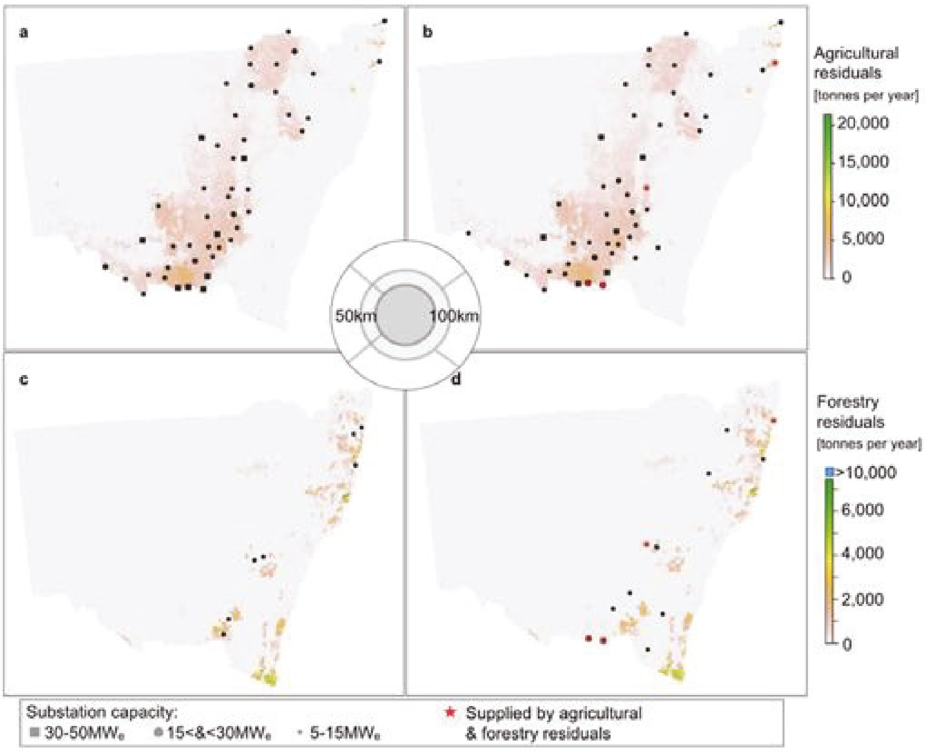

Fig. 7. Residual agricultural (a and b) and forestry (c and d) biomass resources [tonnes/year] in NSW and locations of substations with new connection capacity, which can be supplied by sufficient (to generate min. 5 MW_e) biomass resources collection in 50 km (a and c) and 100 km (b and d) radius and good solar resources (>1,800 kWh/m^2/year).

Table 8
Capacity at substations, biomass resources in 50 km from substations and direct normal irradiation at substations in the Australian Bureau of Statistics, Statistical Area Level 4 regions of NSW.

SA4 region	New connection capacity at substations [MW_e]	Number of substation with new connection capacity	Biomass resources in 50 km [t/a]	Direct normal irradiation [kWh/ m^2/year]	Capacity of HCSB plants [MW_e]	Capacity of HCSB plants [MW_e], agricultural residual fed	Capacity of HCSB plants [MW_e], forestry residual fed
Riverina	358	25	4,476,739	1,857 – 2,181	193.9	155.5	38.4
Murray	294	19	2,669,242	1,643 – 2,139	165.5	165.5	0.0
Central West	324	25	2,309,104	1,620 – 2,166	109.2	90.6	18.6
Richmond – Tweed	380	23	2,067,656	1,625 – 2,480	15	15	0.0
Coffs Harbour – Grafton	186	12	1,843,393	1,618 – 2,480	31.5	11.1	20.4
New England and North West	309	31	1,825,087	1,778 – 2,480	117.1	117.1	0.0
Capital Region	441	31	1,347,299	1,580 – 2,480	15	15	0.0
Far West and Orana	398.5	27	1,294,637	2,050 – 2,333	97.1	97.1	0.0
Mid North Coast	132	9	918,240	1,705 – 1,811	10.9	0.0	10.9
Newcastle and Lake Macquarie	15	1	172,229	1,787	0.0	0.0	0.0
Sydney - South West	10	1	152,381	2,013	0.0	0.0	0.0

2.3. HCSB plant design and operation

Middelhoff et al. [18] describe a Rankine cycle HCSB plant with solar tower system in detail and present energy efficiency estimates for different plant sizes, as shown in Table 2. Both the biomass boiler and the CSP field can produce high-pressure and high-temperature steam to feed the high-pressure turbine. This study assumes 'fuel saving' operation: The biomass boiler is accounting for most of the energy generation

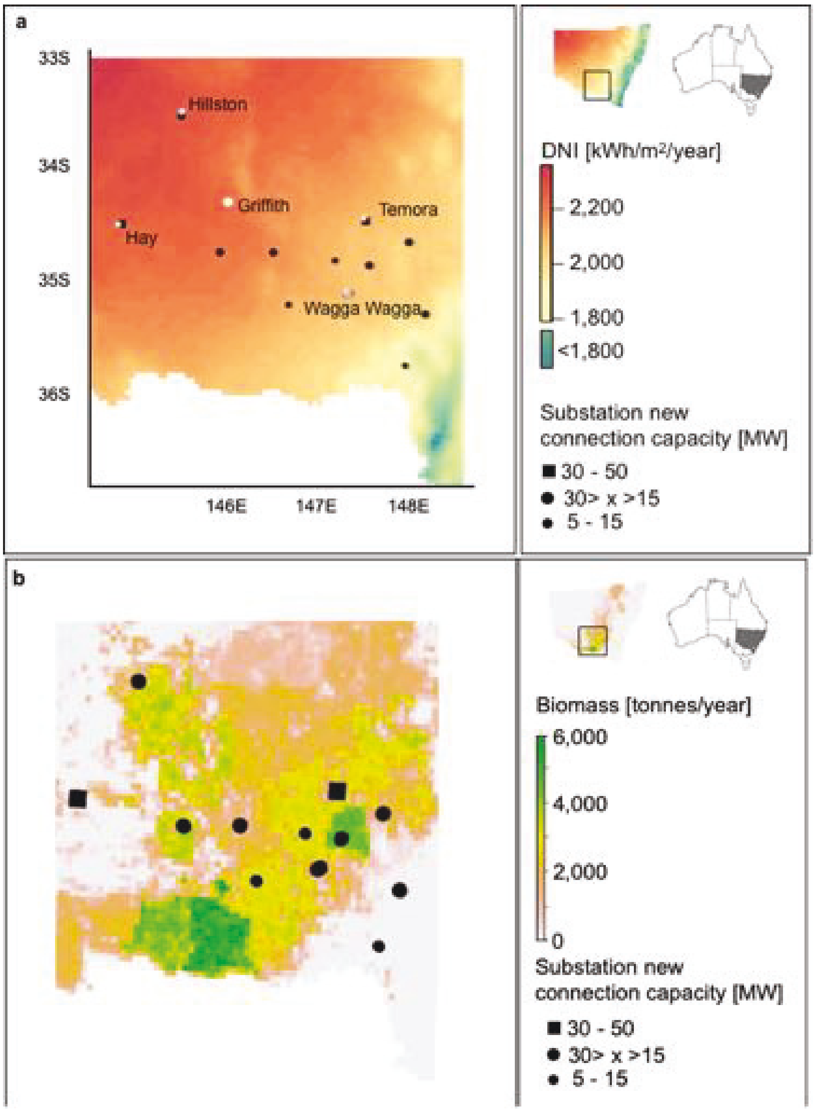

Fig. 8. Substation with new connection capacity in the Riverina, as well as a) direct normal irradiation [kWh/m^2/year] and b) agricultural biomass resources [tonnes/year].

Table 9
Investment for conventional biomass combustion plants and hybrid solar biomass plants per capacity.

Investment	5 MW	10 MW	15 MW	20 MW	25 MW	30 MW	50 MW
Conventional biomass combustion plant [m AU$/MW$_e$]	6.8	5.6	4.9	4.6	4.3	4.0	3.5
Solar biomass hybrid plant [m AU$/MW$_e$]	8.9–11.3	7.3–9.3	6.6–8.4	6.1–7.8	5.8–7.4	5.5–7.1 6	4.8–6.2

(full load operation). When solar thermal energy can be captured it is used to offset steam generation from the biomass boiler (Fig. 2). During these times, the biomass boiler is ramped down to up to 20% of its full-load operation (part load operation). Because the biomass boiler is not completely ramped down, in the case of diminished solar resource, it can be ramped up to its full capacity very quickly. We assume the integration of a thermal energy storage with the capacity to supply 3 h of operation. The thermal energy storage will maintain constant steam generation for relatively short periods of diminished solar resources e.g., due to fast passing clouds (per. Comm. Peterseim 2019).

Consistent with Peterseim et al. [49], this study assumes a capacity factor of 91.3%, and assumes a solar capacity factor of 18% (1,577 h per year), consistent with previous work [13,23].

2.4. Investigation of HCSB plant siting potential

Six steps were taken to investigate the HCSB plant siting potential:

Table 10
Substations with sufficient a) biomass and b) biomass and solar resources within 50 km collection radius: Number of substations served, total installed capacity, feedstock requirement, emission abatement potential and total installed cost (cost estimates are 11% accurate).

	a) Substations with sufficient biomass resources					b) Substations with sufficient biomass and solar resources				
	Number of substations	Total capacity [MW_e]	Feedstock requirement [tonnes/year]	Emission abatement potential [kg CO_2/year]	Total installed cost [AU $]	Number of substations	Total capacity [MW_e]	Feedstock requirement [tonnes/year]	Emission abatement potential [kg CO_2/year]	Total installed cost [m AU $]
Agriculture										
Bagasse	*3*	*42*	*199,391*	29.9 million	*207 million*	*2*	*26*	*132,386*	185.6 million	*200*
Cereal Straw	*46*	*632*	*3,012,566*	4,47 billion	*3.13 billion*	*46*	*672*	*3,321,906*	4.75 billion	*4,953*
Non-cereal Straw	*15*	*227*	*1,058,684*	1,61 billion	*1,09 billion*	*15*	*258*	*1,233,912*	1.83 billion	*1,809*
Forestry										
Wood, native forests	*9*	*98*	*495,947*	693.8 million	*534 million*	*3*	*29*	*160,973*	207.4 million	*251*
Wood, plantations	*6*	*62*	*318,133*	438.3 million	*345 million*	*4*	*53*	*268.315*	375.7 million	*372*
Sawmill residues	*7*	*66*	*246,086*	462.3 million	*567 million*	*6*	*76*	*496,800*	505.5 million	*589*

Table 11
Substations with sufficient a) biomass and b) biomass and solar resources within 100 km collection radius: Number of substations served, total installed capacity, feedstock requirement, emission abatement potential and total installed cost (cost estimates are 11% accurate). Note that in 100 km collection radius four substations can be fed by agricultural and forestry residues.

	a) Substations with sufficient biomass resources					b) Substations with sufficient biomass and solar resources				
	Number of substations	Total capacity [MW_e]	Feedstock requirement [tonnes/year]	Emission abatement potential [kg CO_2/year]	Total installed cost [AU $]	Number of substations	Total capacity [MW_e]	Feedstock requirement [tonnes/year]	Emission abatement potential [kg CO_2/year]	Total installed cost [AU $]
Agriculture										
Bagasse	*3*	*38*	*184,953*	234.0 million	195 million	*3*	*40*	*201,726*	284.3 million	304 million
Cereal Straw	*45*	*714*	*3,298,395*	5,06 billion	3.36 billion	*45*	*740*	*3,654,375*	5.23 billion	5.3 billion
Non-cereal Straw	*19*	*300*	*1,388,112*	2,13 billion	2.32 billion	*19*	*333*	*1,585,214*	2.36 billion	2.32 billion
Forestry										
Wood, native forests	*10*	*152*	*706,888*	1,07 billion	725 million	*6*	*77*	*415,644*	542.0 millon	592 million
Wood, plantations	*7*	*80*	*401,015*	569.4 million	426 million	*7*	*119*	*442,361*	658.6 million	708 million
Sawmill residues	*8*	*95*	*467,664*	668.9 million	498 million	*7*	*105*	*475,723*	746.7 million	768 million

(1) Identifying zone substations with new connection capacity in the electricity grid of NSW (described in Section 2.4.1).
(2) Identifying the annual average solar resource at the substations (described in Section 2.4.2).
(3) Identifying the annual average biomass feedstock availability at the substations (described in Section 2.4.3).
(4) Identifying HCSB plant siting suitability based on biomass energy efficiency estimates (described in Section 2.4.4).
(5) Identifying HCSB plant costs, based on scale of operation and economic assumptions (described in Section 2.4.5).
(6) Identifying HCSB plant emission abatement potential, based on transport emission assumptions (described in Section 2.4.6).

2.4.1. *Zone substations with new connection capacity*

This study assumes grid integration at zone substations with new connection capacity. These substations receive electricity from bulk supply substations and likely represent the lowest cost option for grid connection. Compared with connection to general transmission lines, connection to substations (preferably within 1 km from the substation) is assumed to limit the connection costs to below 10% of the total capital cost [50] (Pers. Com. McIntosh, 2020). Grid connection can present an economic barrier for small to medium (5–50 MW_e) standalone renewable energy power plants, because the otherwise major investment in network extensions or local network upgrades is hard to justify relative to the total project investment at this scale [50].

'Network Opportunity Maps', available from the *Australian Renewable Energy Mapping Infrastructure* portal [51], provide an indication of capacity and voltage levels of substations to accept new distributed power plants. These maps are updated yearly and are based on annual distribution and transmission planning reports from the different network providers in NSW [51]. Our study considered three size categories for connection at substations: Micro-scale (5 to <15 MW_e), small-scale (15 to <3 MW_e) and medium-scale (30 to 50 MW_e) – see Table 3, following the approach of Lovegrove et al. [50].

2.4.2. *Solar resources at substations*

The solar resource map was generated using hourly direct normal irradiation data for Australia, derived from 1995 to 2018 gridded (resolution of 5 × 5 km) solar exposure data [52]. The quality and accuracy of the hourly satellite derived data from the Australian *Bureau of Meteorology* has been previously evaluated by a number of authors; for example, Copper & Bruce [53] and Blanksby et al. [54] indicate a strong correlation between *Bureau of Meteorology*'s satellite derived direct normal irradiation data and the ground measurements for direct normal irradiation data products. This study relies on annual solar maps that do

Table 12
Overview about hybrid concentrated solar biomass (HCSB) plant technology design options and description of their technical and commercial maturity.

Energy generation	Concentrated solar collector	Technical and commercial maturity
Brayton cycle:		
High and low pressure air heater	High temperature solar air heaters, >500 °C	Low commercial maturity, pilot plants have been demonstrated in Europe e.g. [69,70], highest commercial readiness for biogas aided AORA tulip plants [42] operating micro-gas turbines, described by Lanchi et al. [71]
Hybridization via fuel:		
Solar gasification of biomass	E.g. high temperature packed-bed solar reactor	Low commercial and intermediate technical readiness, discussed by several authors e.g. Piatkowski et al. [40]
Rankine and Organic Rankine Cycle (ORC):		
Solar feedwater heater (FWH)	Solar feedwater heater (FWH)	High technical and commercial maturity, demonstrated in Liddell coal power plant solar FWH [72], and described by several studies, e.g. Amoresano et al. [47]
Solar high temperature feed-in	Solar high temperature feed-in	High technical and commercial maturity, demonstrated in Termosolar Borges plant [13] and Aalborg CSP plant [48], and described by several studies, e.g. Peterseim et al. [20] and Middelhoff et al. [18]
Hybrid solar receiver combustor (HSRC)	Hybrid solar receiver combustor (HSRC)	Low technical maturity, developed and discussed by Nathan, Battye & Ashman [73]

not account for the temporal availability of solar resources. Furthermore, it should be noted that local CSP output can only be broadly estimated with the direct normal irradiation data from the Australian *Bureau of Meteorology*. On-ground measurements are required to verify the actual CSP output - these would likely be undertaken during the early stages of a prospective project.

The direct normal irradiation level at substations was derived using raster packages in R [55] for resource mapping. A substation is suitable for HCSB plant connection if an average of 1,800 kWh/m^2/year was exceeded. This approach is consistent with previous studies, e.g.: Peterseim et al. [23] and Pérez and Torres [56].

2.4.3. Biomass resources in proximity to substations

This study has focussed on solid biomass waste residues (moisture content < 50%), which can be broadly grouped into agricultural wastes (bagasse, cereal and non-cereal straw) and forestry residues (harvest waste from plantations and native forests, and processing waste in sawmills). Up-to-date biomass resources maps for NSW were recently developed for the Australian biomass for bioenergy assessment project [11], which collated biomass data from jurisdictions across Australia into a national database. This data represents the most recent and accurate source of information on biomass volumes and spatial distribution in NSW. The data was made available through the NSW Department of Primary Industries.

Average annual quantities of different biomass resource types are provided for different forest management areas (forestry data) and Australian *Bureau of Statistics,* statistical area 2 (agricultural data) regions of NSW [11]. In this study we have used an even finer geographical distribution by overlaying the biomass resources in statistical area 2 raster format with NSW land use of the different biomass types (e.g. forestry and cropping), as per Madden et al. [57]. Through this refinement of biomass resources mapping, distribution is mapped at a scale of 5 km × 5 km.

The Australian biomass for bioenergy assessment defined a five-year average for estimating the yields of cereal straw (wheat, oats, barley, sorghum, maize, rice and triticale) and non-cereal straw (cotton, canola, peanuts, pulses and other oilseeds). Residues are estimated based on crop production totals, considering a species specific harvest index and a minimal cutting height of 0.125 m as described in Herr et al. [58]. For the purpose of soil protection and to minimise soil erosion from wind and water, a stubble retention rate of 1 and 1.5 tonnes/ha/year for southern and northern parts of the state respectively are assumed [58]. Residues derived from forest harvest activities (plantations and native forests) and sawmills were estimated for Australian biomass for bioenergy assessment based on production data supplied by forest growers, surveys of harvest contractors and wood-processing facilities [26].

This study used raster packages in R [55] for resource mapping. Biomass resources within 50 and 100 km collection radii around the substations were obtained from the resource maps. As a second step the model allocated different biomass types to each substation, prioritizing locations with greater connection capacity and within regions that had the highest direct normal irradiation. Fig. 3 outlines the approach. After resources were allocated to a substation, they were deleted from the raster files. It is important to note that the model optimizes the collection radius size. More resources might be available within the maximum radii than needed limited by the capacity at the substation. To avoid deletion of these unused resources, the collection radii were gradually decreased (from a defined maximum radius) until the resources collected matched the capacity at the substation.

2.4.4. Biomass energy efficiency

Annual power generation potential from biomass was calculated considering plant energy conversion efficiencies which are dependent on i) calorific value of different feedstock types and ii) plant size (in

Table 13
Energy content and energy efficiency of bagasse, straw and forestry residues used or measured for studies in Australia. (2-column fitting table).

Bagasse		Straw		Forestry residues		Source
Energy content [MJ/kg]	Energy efficiency [%]	Energy content [MJ/kg]	Energy efficiency [%]	Energy content [MJ/kg]	Energy efficiency [%]	
8.8	22	14.8	25	17.5	26	[7]
19	22	17.9	–	20.3	–	[74]
13.35–19.34	–	17.7–18.46	–	–	–	[75]:
–	–	–	–	18.6–22.3	–	*Softwood chips*
–	–	–	–	19.3	–	*Hardwood chips*
–	–	–	–	21	–	*Softwood native cypress*
–	–	–	–	19	–	*Softwood Pinus*
–	–	–	–	18.9	–	*Hardwood: Eucalyptus pilularis (blackbutt)*
17.7	27	15.7	27	19	28	[23]
17.9	–	17.8	–	19	–	[58]
–	–	–	–	18.6–21.5	–	[26]

accordance with e.g. Peterseim et al. [23] and Middelhoff et al. [18]). The calorific value for different feedstock types was determined based on a literature review (Appendix Table 13). This study assumed a calorific value for bagasse of 17.5 MJ/kg, for stubble we assumed 17.3 MJ/kg, and for forestry residues we used 19.5 MJ/kg. To incorporate the impacts of plant size on HCSB plant energy efficiency this study uses the estimates presented in Table 2. We considered bioenergy generation from bagasse, stubble and forestry residues in scales ranging from 5 to 50 MW_e (Fig. 4). This study further differentiates between full and part load operation (Table 4), as discussed in Section 2.3.

2.4.5. HCSB plant installed costs

Up-to-date CSP cost estimates were used from Lovegrove et al. in [19] and [7], and are summarised in Table 5; we note that as of 2020, there are no operating commercial CSP plants in Australia and the price assumptions are only considered accurate to an estimated ±20% [19]. Indirect costs (e.g. grid connection) of about 25% have been included 'pro-rata' into the physical subsystems. By contrast, the cost estimates for biomass boilers, which are a mature technology, are considered very reliable. Our estimates were verified through consultation with boiler suppliers (pers. comm. WTERT, 2019).

The installed costs of the different plant parts were grouped into: i) thermal energy storage; ii) solar tower and receiver with solar field, including molten salts and all pipework; iii) power block, balance of plant and heat exchanger; iv) biomass boiler; and v) biomass storage, and were calculated as:

$$\text{Cost} = \text{System Size}*\text{SIC}*\left(\frac{\text{System Size}}{\text{Base Size}}\right)^{\text{PSE}}$$

with SIC as the specific installed cost and PSE as power size exponent.

2.4.6. HCSB plant emission abatement potential

The combustion of sustainable biomass resources is considered carbon neutral, assuming that growing biomass removes at least as much CO_2 from the atmosphere as is released during combustion. However, greenhouse gas emissions ($CO_{2\text{-}e}$) due to feedstock harvest and transport are considered and are specific to the different feedstocks. The emissions for harvesting and transport of straw, forestry residues and bagasse are listed in Table 6. We do not consider the emissions from harvesting of bagasse, as the feedstock is commonly collected in the process of sugar production.

This emission intensity of power generation in HCSB plants is compared to scope 3 emissions (including extraction, production and transport, as well as emissions from burning the fuel) of power generation assets in NSW in the period 2018 and 2019, of 900 kg $CO_{2\text{-}e}$/MWh [59].

3. Results and discussion

3.1. Biomass and solar resources in proximity to substations

In 2020 there were 204 substations with new connection capacity in NSW, with a total capacity of around 2.8 GW_e. Of these, 22 substations have new connection capacity at medium-scale, 88 at small-scale, and 94 at micro-scale (Table 3). The substations are all located along the eastern and central parts of NSW (Fig. 4 a-c).

The location of agricultural waste residues (bagasse, cereal and non-cereal straw) is shown in Fig. 4 a. Sugar cane growing areas are located in the subtropical northern parts of the State, whereas cereal and non-cereal cropping areas are located all along the central southern and northern regions of the State. Fig. 4 b shows forestry residues from plantation, native forests and sawmills. These resources are located all along the coastal to central areas of NSW.

In Fig. 4 c the spatial distribution of the direct normal irradiation solar resource for NSW is shown. Australia has one of the best solar resources in the world and NSW's inner-western region can fulfil the minimum typical requirement of standalone CSP plants of > 2,000 kWh/m^2/year, and an even larger area is suitable for HCSB plant siting assuming a direct normal irradiation > 1,800 kWh/m^2/year is viable. The very good alignment between suitable substations and renewable resources is discussed below.

3.2. HCSB plant siting potential

The location of substations with sufficient biomass resources within 50 km and 100 km collection radii is shown in Fig. 5. There is sufficient biomass to supply 157 and 195 substations within 50 km and 100 km collection radii, respectively. Adding the condition of sufficient solar resource (>1,800 kWh/m^2/year) for HCSB plant deployment, 111 and 138 substations are suitable for deployment of the technology in 50 km and 100 km collection radii, respectively (Fig. 5). Increasing the maximum collection radius, increases the possible capacity for small and medium size substations (Table 7).

Considering the variation in resource distribution with better solar resources further inland and better biomass resources closer to the coast of NSW, the State can be geographically divided into three broad zones (Fig. 6):

- Zone 1: The western part of the State (in which 20% of all substations are located), with excellent solar resources (direct normal irradiation > 2,000 kWh/m^2/year) and insufficient biomass resources is more suitable for standalone CSP projects;
- Zone 2: The central part of the State (in which 60% of the substations are located), with good solar and biomass resources is best suited for HCSB plants; and
- Zone 3: The eastern part of the State (in which 20% of all substations are located), with good (primarily forestry) biomass resources but insufficient solar resource is more suitable for standalone biomass plants.

In NSW, HCSB plants have a higher siting potential than standalone CSP plants, as more substations are suitable for grid connection to HCSB plants (regions with direct normal irradiation > 1,800 kWh/m^2/year) compared to those available for standalone CSP plants (regions with direct normal irradiation > 2,000 kWh/m^2/year [19]).

Because HCSB plants are economically feasible at smaller scale (<50 MW_e), substations for HCSB plants are also ready for connection without requiring substantial update of the transmission infrastructure (Fig. 6, Zone 2). This contrasts with the substations available for standalone CSP plants. Substations in Zone 1 (Fig. 6) that are far from the main load and population centres can be categorized as fringe-of-grid locations in NSW [63]. These substations are unlikely to have the necessary infrastructure required to cope with the level of energy output and would need to be updated, thus increasing project costs.

3.3. Installed capacity of HCSB plants in NSW

Fig. 7 shows the location of substations which are suitable for the deployment of HCSB plants. Considering 50 km and 100 km collection radii respectively, we estimated that 786–874 MW_e of installed capacity of HCSB plants can be linked to substations with new connection capacity. (All substations identified as suitable for HCSB plants fulfil the requirement of sufficient solar and biomass resources described in Sections 2.4.2 and 2.4.3.) Increasing the maximum resource collection radius from 50 to 100 km increases the overall deployment potential of HCSB plants in NSW and could further allow a mix of agricultural and forestry resources to be utilized in four locations (Fig. 7 – star icon). The Energy Transition Commission [17] suggest that plants using feedstock with similar combustion properties is preferable in order to ensure optimal plant operating efficiencies. However, in regions with limited resources, combining resources might allow for larger plant capacities and increase the reliability of supply.

Neglecting the condition for sufficient solar resources, e.g. for the deployment of standalone bioenergy plants, 831–916 MW_e of installed capacity of biomass combustion plants can be linked to substations with new connection capacity. This highlights the abundance of biomass resources in NSW and the good potential for bioenergy generation.

Table 8 compares the HCSB plant deployment potential in Australian *Bureau of Statistics* statistical area 4 regions (Fig. 1) in NSW. The Riverina region shows the highest overall potential for HCSB plants with a possible 194 MW_e of installed capacity, comprised of agricultural and forestry residues within 50 km collection radius. Fig. 8 shows resources and substations in the Riverina in detail. The region has the highest cereal straw resources in NSW (>4 million tonnes within 50 km collection radius of substations) and direct normal irradiation between 1,857 and 2,181 kWh/m^2/year. Further regions that stand out for HCSB plant deployment in NSW are the Murray region and the New England and North West.

It is important to note that the Riverina region is currently being targeted for a number of large scale solar PV projects, such as the Griffith solar farm [64], which are also seeking grid connection through substations. Thus, the window of opportunity for cost-efficient new connection at substations in rural NSW may be shrinking. However, multiple large plants could justify investment in new infrastructure, where the costs could be shared across several projects. This approach could be supported by programs such as the NSW Government's Electricity Strategy [65], which includes a plan for three *Renewable Energy Zones* located in the Far West and Orana, New England and South West regions of NSW. From mid-2020 onwards, new grid infrastructure will be developed, which will allow new connection points to generators, such as HCSB plants.

3.4. Feedstock considerations

The number of substations which are supplied by different feedstock types within maximum 50 km and 100 km collection radii are listed in Table 8 and Table 9. Cereal and non-cereal straw have the best overlay with solar resources and network opportunities, also making up the predominant feedstock for HCSB plant deployment in the Riverina and Murray region in NSW.

In contrast to bagasse and forestry residues, which are common feedstocks for bioenergy projects [10], straw is an underutilized feedstock in Australia [58]. International examples show that stubble harvest for energy generation can effectively be encouraged by governmental incentives. For example, Bentsen et al. [66] describe how Denmark's biomass agreement from 1993 was followed by the increased use of straw for energy and peaked in 2010 at 1.6 million tonnes, around 25% of the total available straw in the country.

For this study, straw resources were calculated based on the assumption that 1 to 1.5 tonnes/ha of straw are left on the field for soil retention and structure [58]. Further engagement with local farmers may be required to validate this assumption and confirm resource availability. Further research could also determine the availability of other biomass residues (e.g. grape marc) and address potential local community concerns (e.g. around biomass feedstock transport routes).

While many studies confirm the general high potential of bioenergy in achieving climate goals [2], the lifecycle emissions of different feedstock in site-specific settings need to be carefully considered for achieving effective carbon mitigation [67]. While residues from agricultural harvest (e.g. straw) and processing (e.g. husk) are attractive options for bioenergy projects, implications for reductions in sequestered carbon associated with the harvest of agricultural residues need to be evaluated for different crops and land management systems [67]. Specifically, straw management systems which include ploughing and mulching can stabilize terrestrial carbon sequestration in soils and can reduce overall emissions from land management. Other practices, like on-field stubble burning, have adverse impacts on local communities and ecosystems as well as emitting carbon to the atmosphere. The potential positive environmental impacts of a bioenergy project relative to this management system is most significant.

3.5. Installed costs

HCSB plant cost estimates relative to scale, using price assumptions from Table 5, are listed in Table 9. If all substations with new connection capacity could be used for the deployment of HCSB plants, the total installed cost of these plants ranges between AU$ 5.8 billion (±11%) and AU$ 6.3 billion (±11%) for biomass resource supply within 50 km and 100 km collection radii. At this scale of deployment, HCSB plants have a total feedstock requirement of 3.9 million tonnes for 50 km collection radius and 4.3 million tonnes of feedstock for 100 km collection radius. The total installed cost and feedstock requirement by feedstock type are listed in Tables 10 and 11.

The study of Middelhoff et al. [18], is clarifying the economic feasibility of HCSB plants at these technology costs, including the calculation of the levelized cost of electricity and internal rate of return, and allows for cost comparison with other technologies.

3.6. Carbon abatement potential

If all substations with new connection capacity in NSW were used for HCSB plant deployment, 6.3 TWh or 7.0. TWh of electricity could be generated for biomass resource allocation within 50 km or 100 km collection radius respectively. This is equivalent to 2.3% and 3.0% of NSW electricity demand in 2019. In this context HCSB plants have the potential to abate approximately 5.6 billion kg of $CO_{2\text{-}e}$/year or 6.2 billion kg of $CO_{2\text{-}e}$/year, respectively using biomass supply within 50 km and 100 km collection radius. This is equivalent to between 3.4% and 3.7% of NSW's greenhouse gas emissions from power generation in 2019.

4. Conclusion

The hybrid concentrated solar biomass (HCSB) technology is a promising option for renewable and dispatchable electricity supply. In New South Wales (NSW), the technology can utilise the rich solar and biomass resources and contribute to concentrated solar power (CSP) and bioenergy industry development. This study found that HCSB plants provide an electricity generation opportunity equivalent to about 3% of NSW's electricity demand, with the potential to avoid over 6 billion kg of $CO_{2\text{-}e}$/year. The Riverina region was found to be the most prospective region for HCSB plant deployment in NSW. Because HCSB plants can generate dispatchable renewable electricity, they are increasingly important in supporting the energy transition — an opportunity that extends beyond this case study location. While this study focussed on electricity generation in HCSB plants, future work could investigate the combined heat and power generation potential from the technology, e.g. in the context of industry and commercial integration.

CRediT authorship contribution statement

Ella Middelhoff: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Ben Madden:** Resources, Software. **Fabiano Ximenes:** Writing – review & editing. **Catherine Carney:** Resources, Visualization. **Nick Florin:** Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A

Table 12 and Table 13

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8.A.3. Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia : Design and evaluation of techno-economic and environmental performance

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Hybrid concentrated solar biomass (HCSB) plant for electricity generation in Australia: Design and evaluation of techno-economic and environmental performance

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A B S T R A C T

Cost-efficient dispatchable renewable technologies are critical for enabling the energy transition towards 100% renewable generation. One promising example involves the integration of biomass boilers with concentrated solar power (CSP) referred to as hybrid concentrated solar biomass (HCSB) plants.

This study evaluates the technical feasibility of a potential plant design for a rice-straw-fed HCSB plant. A case study for the Riverina-Murray region of Australia, a prime area for deployment owing to abundant solar and biomass resources is presented.

Based on an assessment of different hybrid concepts, we investigate a solar-biomass hybridization with a concentrated solar tower system. With this hybrid concept, both the CSP and biomass boiler can raise steam to feed the high-pressure turbine enabling greater thermal efficiency. We evaluate HCSB plant performance at four scales: 5, 15, 30 and 50 MW_e. Depending on size, HCSB plants reach thermal efficiencies from 21 to 34%. Considering the economic feasibility, assuming an internal rate of return (IRR) of 11%, viable deployment requires an electricity price of AU$ 120–350/MWh.

The techno-economic assessment demonstrates advantages compared to standalone CSP plants and highlights the competitiveness of HCSB plants compared to other renewable technologies in Australia. The social and environmental impact assessment highlights additional benefits including local job creation and potential carbon emission mitigation.

1. Introduction

New South Wales (NSW)'s energy transition is underpinned by a long-term ambition of achieving net-zero greenhouse gas (GHG) emissions by 2050 [1]. This transition is in line with global agreements [2,3] and is recognised as a key strategy for avoiding the more severe impacts on the Earth's climate system [4,5]. Similar to energy transitions in other parts of the world, Australia's transition is underway and has involved the uptake of variable renewable energy (VRE) technologies, namely solar photovoltaic (PV) and wind power plants [6]. For an orderly and successful energy transition there is a need to increase the share of dispatchable renewable technologies, that can generate electricity in times of diminished solar and wind resources [7–10].

Many studies highlight the potential for bioenergy in supporting energy transitions by providing dispatchable electricity and mitigating emissions through displacement of fossil fuels (e.g. [8,11,12]). Recent economic assessments of future high-renewable energy generation scenarios for the Australian continent indicate that the expansion of bioenergy by 5 to 15 times compared to current supply could reduce the cost of a future 100% renewable energy generation system by 11–40% [8]. Considering that bioenergy deployment in Australia is currently lagging behind other jurisdictions there is clearly a major opportunity to support the development of a bioeconomy [13].

In NSW, existing bioenergy projects already utilize waste water and bagasse [14]. Currently, other residues (e.g. straw and husk and forestry residues) remain underutilized for energy generation [15]. One reason

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for this is, that the availability of agricultural and forestry residues is impacted by seasonal variations, which presents a challenge for projects that rely solely on that one feedstock. A promising option to overcome this problem is the hybridisation of bioenergy plants with solar thermal energy, so that solar resources account for energy generation during times of diminished biomass resources and vice versa.

The hybridization of bioenergy plants with concentrated solar power (CSP) systems is referred to as hybrid concentrated solar biomass (HCSB) plants. The hybrid concept has been demonstrated globally in a few examples, e.g. the 22.5 MW_e Termosolar Borges plant in Leida, Spain [16]. In such systems a CSP unit uses freely available solar resource for electricity generation during the day, while solid biomass feedstock can be used for energy generation in times of solar resource intermittencies (e.g. day-night cycles and changing weather conditions) (e.g. [17–19]). Heat generation from both systems is combined for electricity generation in the same power block (e.g. steam turbine). The flexible and continuous operation from two different resources can have a positive impact on the economic feasibility of bioenergy projects [20,21]. In NSW's future energy system, hybrid plants may be an alternative to expensive storage technologies for PV and wind power systems [7].

This study aims to understand the specific benefits and opportunities in deploying HCSB plants in the Australian context. Because realistic feasibility studies rely on local resource data, we have focussed our study on a specific region. We present a case study for the Riverina-Murray region in the central-southern part of NSW. Choosing a specific region gives the opportunity to evaluate the performance of HCSB plants in a real world context. The general insights of this study, especially the techno-economic methodology and plant design considerations are broadly applicable to other jurisdictions with implications for technology developers.

Earlier high-level studies (e.g. [22,23]), identified the Riverina-Murray as a highly suitable region for HCSB plant deployment. This study evaluates detailed resource availability and grid connection opportunities and discusses potential impacts for the local community and the environment. The Riverina-Murray region has significant solar resources (>2,000 kWh/m^2/year) suitable for CSP systems. Additionally, the region has abundant agricultural residues (mainly straw), which are currently underutilized in the context of bioenergy opportunities [24]. For this case study we consider rice straw as feedstock.

Rice is a commonly grown grain in the Riverina-Murray region. Standing stubble, which remains on field after crop harvest increases the risk of pathogen spread to new plants in the next growing period [25], such that current land management practices include on-field stubble burning (Fig. 1). On-field stubble burning has adverse impacts on local communities and ecosystems, but also creates unnecessary emissions (CO_2 and NO_X particles). Thus, utilisation in a local biomass or HCSB plant can offer an effective alternative.

1.1. Hybridization concepts of CSP and bioenergy

Different HCSB plant design concepts have been proposed in the literature (e.g. [17,26]) and few have been realised (e.g. Termosolar Borges plant in Leida, Spain [16]). HCSB plants have been analysed for different power cycle including Organic Rankine Cycle (ORC) [27], and micro-gas turbines [28]. However, this study focusses on HCSB Rankine cycle plants, as direct combustion for steam generation is a good option for the dry straw residues available in the Riverina-Murray region. With the goal to identify a highly efficient and mature plant design for this case study, this section provides a brief review of HCSB plant concepts and previous deployments. Table 1 gives an overview over the selection criteria which define efficiency and maturity in this study. We chose to organise the different HCSB concepts based on the CSP mirror technology and heat transfer fluids (HTF). Different configurations are listed in Table 1 and described in the following paragraphs.

Parabolic trough collector are most commonly deployed with thermal oil as HTF [29]. Thermal oil is limiting solar steam to a maximum temperature of about 400 °C, which is lower than typical steam temperatures which are reached in bioenergy plants, these level, depending on feedstock, between 450 and 520 °C [20,30]. Using thermal oil in an efficiently designed HCSB plant limits feed-in points into the Rankine cycle as solar integration for feedwater heating [31,32] and, for additional steam generation 'in-series' with the biomass boiler. 'In-series' generation, a solution that has also been chosen for the Termosolar Borges HCSB plant, defines the process that saturated steam that exits the solar system at a temperature of about 393 °C is superheated to temperatures between 450 and 520 °C by the biomass boiler before entering the high-pressure turbine [16].

Parabolic trough collectors as well as linear fresnel mirrors, can be deployed with DSG generation at maximal temperature of 450 °C. This steam parameter allows for solar feed-in 'in-parallel' operation to a biomass boiler. In this operational mode both technologies generate steam for the steam turbine in parallel. This concept was tested in the 'Scalable CSP Optimised Power Plant Engineered with Biomass Integrated Gasification' (SCOPEBIG) project, which has been launched in 2015 in Barun, India (mentioned by Soares [33]). In this 3 MW_e parabolic trough HCSB power plant, biomass combustion provides superheated steam for the high-pressure turbine, while CSP provides saturated steam via DSG for the low-pressure turbine.

CSP tower hybrids can use a range of different HTF e.g. molten salts and DSG [19]. The use of molten salts as HTF offers an easy and direct integration of molten salts storage without additional heat exchanger [30]. DSG and molten salts can be deployed at higher temperatures than thermal oil, with temperatures > 500 °C and pressure > 100 bar (Table 1), which results in higher cycle efficiency [30]. These steam parameters allow for solar feed-in 'in-parallel' operation to biomass boiler. Steam temperatures existing the CSP tower can be chosen

Fig. 1. On field burning of cereal straw on the East coast of Australia; photos taken by author in 2019.

Table 1
CSP technologies and most commonly used heat transfer fluids: comparison of efficiency and maturity.

	Unit	Molten salts	Thermal oil	DSG
Parabolic trough				
Efficiency:				
Optimal hybrid configurations	-	in-parallel	feedwater heating, in-series	in-parallel
Steam temperature	°C	530 [34] – 550 [35]	393 [36]	400–450 [36]
Peak net efficiency	%	32.2 [30]	29.5 [30]	30.3 [30]
Maturity:				
Global installed capacity	MW_e	~150 [29]	>5,000 [29]	>10 [29]
Largest plant (financially approved)	MW_e	64 [37]	250 [38,39]	5 [40]
Largest hybrid plant	MW_e	-	75 [41]	-
Number plants in Australia	MW_e	-	-	-
Linear Fresnel				
Efficiency:				
Optimal hybrid configurations	-	in-parallel	feedwater heating, in-series	in-parallel
Steam temperature	°C	510 [43]	393 [36]	450 [42]
Peak net efficiency	%	-	-	32.5 [30]
Maturity:				
Global installed capacity	MW_e	50 [43]	50 [44]	~250 [3]
Largest plant (financially approved)	MW_e	50 [43]	50 [44]	125 [45]
Largest hybrid plant	MW_e	-	-	-
Number plants in Australia	MW_e	-	-	2 [46]
Solar tower				
Efficiency:				
Optimal hybrid configurations	-	in-parallel	-	in-parallel
Steam temperature	°C	566 [17]	-	566 [18]
Peak net efficiency	%	32.8 [30]	-	33.0 [30]
Maturity:				
Global installed capacity	MW_e	>2,500 [29]	-	>2,500 [29]
Largest plant (financially approved)	MW_e	450 [47]	-	450 [48]
Largest hybrid plant	MW_e	-	-	-
Number plants in Australia	MW_e	1 [49]	-	1 [50]

according to the optimal combustion temperature for specific biomass feedstock types which determined to mitigate high temperature corrosion and ash melt.

2. Methods

2.1. Siting potential in the Riverina-Murray region of NSW

This section discusses the availability of rice straw residues and Direct Normal Irradiation (DNI) for HCSB plant operation in the Riverina-Murray region in NSW. Grid connection to the National Electricity Market (NEM) for HCSB plants is assumed at zone substations with new connection capacity, as these substations provide a cheap and ready access-points into the grid, while minimizing investment into poles and wires ([51,52]). Our approach follows the study of Middelhoff et al. [52], considering three main data sources of: i) Location of zone substations with new connection capacity, ii) spatial distribution of rice straw residues, and iii) DNI resources.

2.1.i) Zone substations with new connection capacity

'Network Opportunity Maps', available from the Australian Renewable Energy Mapping Infrastructure (AREMI) portal [53], indicate the capacity and voltage levels of zone substations allowing for new integrated distributed power plants. These maps are regularly updated based on annual distribution and transmission planning reports from the different network providers in NSW [53]. The study considered three size categories for connection at zone substations: Micro-scale (5 to < 15 MW_e), small-scale (15 to < 25 MW_e) and medium-scale (25 to 50 MW_e) [52].

2.1.ii) Straw residues

In the context of bioenergy generation, different feedstocks need to be appraised considering availability and site-specific carbon emission mitigation potential [54]. Potential carbon emissions associated with harvest of stubble from the field need to be considered carefully for different land management systems [54,55]. Common wheat straw management systems, which include ploughing and mulching can contribute to stabilise terrestrial carbon in soils and thus reduce overall emissions from land management [56,57].

Biomass resource maps for NSW were recently developed for the Australian Biomass for Bioenergy Assessment (ABBA) project [58]. This data represents the most recent and accurate source of information on biomass volumes and spatial availability in NSW. Rice straw quantities are estimated based on a five-year average of crop yields, considering a harvest index (HI) of 36%, moisture content after air drying of 12%, and a minimal cutting height of 12.5 cm as described by Herr et al. [15]. To maintain nutrients and vital elements in the soil, a stubble retention rate of 1 and 1.5 tonnes/ha for southern and northern parts of the state are assumed, respectively [15].

We present high-resolution rice straw resources maps, achieved by merging low-resolution biomass data from ABBA, with high-resolution land-use data in a dasymetric model, as proposed by Mennis & Hultgren [59]. Land use data is obtained from the Australian Land Use and Management (ALUM) classification system [60]. Raw biomass data is available at spatial scales of the Australian Statistical Geography Standard [61]. The annual estimated quantities of rice straw are provided for Statistical Area 2 (SA2) [61]. The SA2 scale is equivalent roughly to the suburb scale, consisting of populations between 3,000–25,000 people. The dasymetric model used in this study was developed and described in detail by Madden et al. [22], and disaggregates biomass data to a resolution of 5 × 5 km.

2.1.iii) Solar resources

The Australian Bureau of Meteorology (BoM) publishes hourly satellite derived DNI data for Australia, derived from gridded solar exposure data for 1995 to 2018 (resolution of 5 km by 5 km) [62]. The quality and accuracy of the data has been evaluated by a number of authors in previous studies (e.g. [63,64]) indicating a strong correlation between BoM's satellite derived DNI data and the ground measurements for DNI data products. This study uses the DNI average from 1995 to 2018, which does not consider temporal availability of solar resources. As such it should be noted that local CSP output can only be broadly estimated with the DNI data from the BoM. This means that ground measurements will be required to verify the actual CSP output and that would likely be undertaken during the early stages of a prospective project.

2.2. Technical performance

This study investigates an efficient HCSB plant design utilising mature technology. The plant is designed for 'fuel-saving' operation, implying that during the day if thermal energy from the CSP is supplied, the biomass boiler load is decreased to 20% of its full load capacity

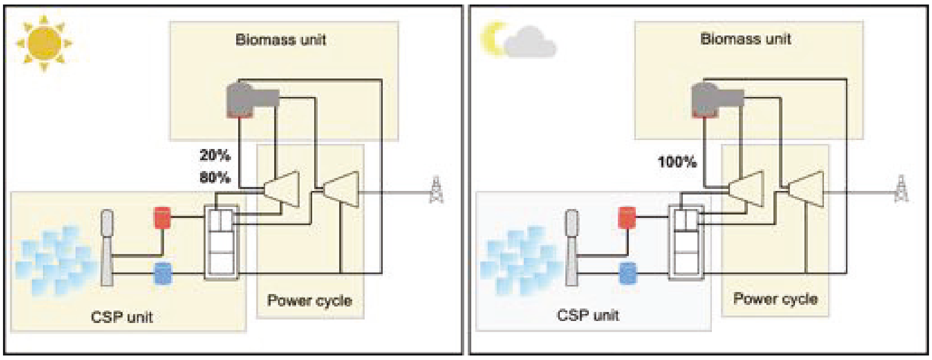

Fig. 2. Operational strategy of HCSB plant in 'fuel-saving' operation.

(Fig. 2). The CSP tower with a heliostat field and the biomass boiler work in parallel operation, which means that both the CSP tower and biomass boiler have the ability to feed steam into the steam turbine allowing continuous operation. This mode of operation allows the steam turbine to work at full capacity preventing reductions in its isentropic efficiency. Therefore, only the boiler performance is affected in off-design conditions, reducing the impacts on the plant's overall efficiency. Furthermore, operating the biomass boiler at a reduced load rather than completely turning off the steam generation, offers the option to ramp up the biomass boiler within about 30 min, rather than several hours from cold start (generally > 5 h) to full capacity, allowing a more stable electricity output.

Such low part-load operation is challenging and requires a special superheater design to manage a stable live steam production for the steam turbine: De-superheater spray system, including a reheat bypass and conditioning valves, is necessary to avoid large thermal stress in the tubes of the boiler heat exchangers [65], as well as to achieve the steam temperatures desired at the steam turbine inlet [66]. The biomass boiler accounts for full steam generation at night and in times of diminished solar resources.

We simulated the plant operations using a thermodynamic model. For modelling the CSP component we used the System Advisor Model (SAM) version 2018.11.11, which is a widely used program in academia and industry for the simulation of CSP plants [67]. The biomass combustion plant was modelled using a private industrial and research software developed by the company WTERT-Brasil, which is commonly used for commercial and academic feasibility studies of biomass plants [68–70]. Both models were integrated by matching the thermal energy input into the steam cycle for the CSP and biomass combustion units.

To match the new connection capacity at zone substations, as described in section 2.1.i), we modelled four HCSB plant sizes: 5, 15, 30 and 50 MW_e. Each HCSB plant size is modelled individually using different steam parameters, specific to the plant size and scale. A conventional biomass boiler, fuelled by rice straw, was modelled based on the steady state regime under design. In all calculations the total energy losses (i.e. thermal energy losses, unburnt fraction of fuel, leakages, tube fouling effects on heat transfer, lower heating value (LHV) variation) in the biomass boiler were conservatively considered to be between 2.5 and 3.0 % of the total amount of heat provided for steam generation from the combustion of biomass.

The main parameters for the HCSB steam cycle model are presented in Table 2. Parasitic losses of 10% were considered for HCSB plants of 5 and 15 MW_e, while 7.5% was assumed for larger HCSB plants of 30 and 50 MW_e. All scenarios consider generator efficiency of 97%, flue gas temperature at the outlet of the boiler of 125 °C and condensing pressure of 0.09 bar. For 30 MW_e and 50 MW_e plants, a single reheat cycle is applied at 22 and 25 bar, respectively, as well as losses due to the unburned fraction of the fuel of 1.0%. The ambient air temperature is assumed to be 25 °C. Due to the water scarcity in Australia this project considers an air-cooled condenser that minimises the total water consumption of the plant. Additional heat from the CSP technology can be stored as thermal energy storage (TES) using molten salts, with an assumed capacity of 3 h, the minimal possible size for TES (pers. Com. Peterseim, 2019).

The rice straw composition properties are presented in Table 3 based on results from combustion experiments by CSIRO [71]. Several studies confirm the feasibility of using rice straw as a fuel for electricity generation [72–74]. One of the main challenges related to the combustion of rice straw is the high ash content. The ash slagging and fouling may cause degradation in the boiler equipment, especially in the superheaters, as well as affecting the heat transfer to the steam cycle [75,76], reducing boiler performance. Furthermore, high levels of potassium and chlorine in this fuel may react with the silicate component of the ash leading to serious corrosion problems in the heat exchanges [72,77]. These specific problems experienced in straw-fired boilers can be managed with special equipment [78], such as appropriate cleaning systems, use of corrosion-resistant materials and technological improvements in the combustion process [79].

Table 2
Main parameters for the HCSB steam cycle.

	Unit	5 MW_e	15 MW_e	30 MW_e	50 MW_e
Feedwater temperature	°C	111.9	121.4	164	175.3
Reheating pressure	bar	–	–	22	25
Boiler efficiency	%	90.4	90.4	90.6	90.7
Live steam pressure	bar	22	62	95	110
Live steam temperature	°C	310	470	500	520
Nominal steam mass flow	kg/h	30,236	64,219	100,825	159,642

Table 3
Rice straw composition (air-dried basis).

	Unit	
Proximate analysis:		
Volatile	%	61.4
Moisture	%	8.4
Ash	%	17.7
Fixed Carbon	%	12.5
LHV	MJ/kg	13.49
Ultimate analysis:		
Carbon	%	34.0
Hydrogen	%	4.63
Oxygen	%	34.7
Nitrogen	%	0.5
Sulphur	%	0.05

2.3. Economic assessment

Up-to-date CSP cost estimates were available from Lovegrove et al. [7,80] and these are summarised in Table 4. As noted by Lovegrove [80] as of 2020, there are no large-scale commercial CSP plants in Australia, while commercial data for small-scale projects like the Sundrop farm in South Australia is not publicly available [50]; and thus, the price assumptions are only considered accurate to ±20% [80]. Indirect costs (e.g. grid connection) of about 25% have been included 'pro-rata' into the physical subsystems [7,80].

Cost assumptions for biomass boilers and the required flue gas cleaning equipment are considered very reliable given the maturity of this technology. All prices were obtained directly from suppliers and engineers.

Table 4 lists the installed cost (CAPEX) of the different plant parts is listed, grouped into: i) TES, ii) solar tower and receiver with solar field, including molten salts and all tubing, iii) power block, balance of plant (BoP) and heat exchanger), iv) biomass boiler and v) biomass storage. These costs were calculated using Eq. (1):

$$\text{Cost} = \text{System Size}*\text{SIC}*\left(\frac{\text{System Size}}{\text{Base Size}}\right)^{\text{PSE}} \tag{1}$$

where SIC is the specific installed cost and PSE is the power size exponent.

The economic feasibility assessment considers the levelized cost of energy (LCoE) and internal rate of return (IRR), which was calculated using Eq. (2):

$$\text{LCoE} = \frac{(\text{CRF} + \text{OM})Cost}{\text{E}} + \frac{\text{bio}}{\text{e}} \tag{2}$$

where E is the generated electricity per year, O&M is the fixed operation and maintenance cost expressed as a fraction for installed cost per year, bio is the cost unit of fuel input, e is the conversion efficiency between energy input and output and CRF is the capital recovery factor, which depends on the weighted average cost of capital (WACC) and the lifetime of the plant (n) calculated using Eq. (3):

$$\text{CRF} = \frac{\text{WACC}(1 + \text{WACC})^n}{(1 + \text{WACC})^n} \tag{3}$$

In Table 5 the Australian market assumptions used for this study are listed. The feedstock price is provided as a range considering this is highly variable and depends on costs associated with cereal straw harvest method, potential nutrient replacement costs, and costs associated with transport and handling.

Table 4
HCSB plant cost assumptions, adopted from Lovegrove et al, comparing components of the plant including thermal storage (TES), power block (PB), heat exchanger (HE) and balance of plant (BoP).

CAPEX	Specific installed cost (SIC)	Unit	Power size exponent (PSE)	Base size	Unit
TES	26,000	AU$ /MWh_{th}	−0.1896	1,429	MWh_{th}
Tower, solar field and receiver	460,000	AU$ /MWh_{th}	−0.1896	600	MWh_{th}
PB, HE and BoP	2,400,000	AU$ /MW_e	−0.3145	100	MW_e
Biomass boiler	1,641,526	AU$ /MW_e	−0.3	15	MW_e
Biomass storage	6.7	AU$ /MWh	0	44,384	MWh

Table 5
Australian financial and tax assumptions.

OPEX	Unit	Specific installed cost (SIC)	Source
Biomass boiler O&M	%	3.8	[2]
CSP and conversion O&M	%	2	[2]
Plant lifetime	*years*	30	[2]
Depreciation period	*years*	20	[60]
Federal income tax rate	%	30	[60]
Loan fraction of total	%	60	[60]
Loan period	%	15	[60]
Loan interest rate	%	7.78	[60]
Feedstock price	AU$ /tonne	40–90	[59]

2.4. Impact assessment

The impact assessment investigates the number of truck journeys for feedstock transport, emission abatement potential and plant footprint of the proposed HCSB plant. The plant footprint was estimated using SAM. The number of trucks journeys for feedstock transport considers round bales (1 m × 1 m × 1.2 m), weighing on average 0.6 tonnes and with a bulk density of 0.5 tonnes/m^3, as well as a 8.4 m long truck with maximum load of 26.4 tonnes. It is thereby assumed that one truck journey could transport 40 straw bales or about 24 tonnes of feedstock [15].

This study estimates the carbon emission abatement potential of HCSB plants, compared to the current emission intensity of energy generation in the NEM. A comprehensive analysis of the global warming potential (GWP) of different rice straw management options would consider multiple factors that are outside the scope of this study. For example, this comparison might compare rice straw on-field burning with the alternative use for bioenergy generation. On-field burning of rice straw is an incomplete combustion process, which releases hazardous pollutants and can lead to Atmospheric Brown Clouds (ABC) and poor air quality [81]. International examples which compare the management systems of on-field burning and bioenergy generation in Asia, found that rice straw removal for bioenergy purposes had lower GWP compared to on-field burning [81].

Carbon dioxide (CO_2) emissions from biomass combustion is generally not considered when calculating emission abatement potential, because they are reabsorbed during the next growing cycle of the rice crop with zero net emissions [81]. Utilizing rice straw as feedstock for energy generation produces additional emissions connected to straw harvest. In the transport sector, several authors have assessed efficient ways of controlling particulates and reducing the emission of pollutants from fossil fuels, including the soot combustion performance [82] and NO conversion efficiency [83]. We consider additional CO_2 emissions for feedstock harvest and transport of rice straw. The emissions for harvest and transport of straw were estimated to be 9 kg $CO_{2\text{-e}}$/tonne for harvest and 32 kg $CO_{2\text{-e}}$/tonne for transport within 100 km [15].

3. Results

3.1. Siting potential of rice-straw-fed HCSB plants in the Riverina-Murray region of NSW

Fig. 3 shows DNI and rice straw residue quantities, as well as locations of substations with new connection capacity in the central-southern part of NSW. In the Riverina-Murray DNI ranges from 1900 to 2200 kWh/m^2/year. Rice straw residues are especially abundant in the north-eastern parts of the Riverina and wide areas in the Murray. A total of sixteen substations with new connection capacity are located in the Riverina-Murray, four with new connection capacity of 25–30 MW_e, five between15 and 25 MW_e and seven between 5 and 15 MW_e.

DNI and rice straw resources in a 100 km catchment radius around the substations are listed in Table 6. >100,000 tonnes/year of rice straw are available within a 100 km radius of most substations in the Riverina-

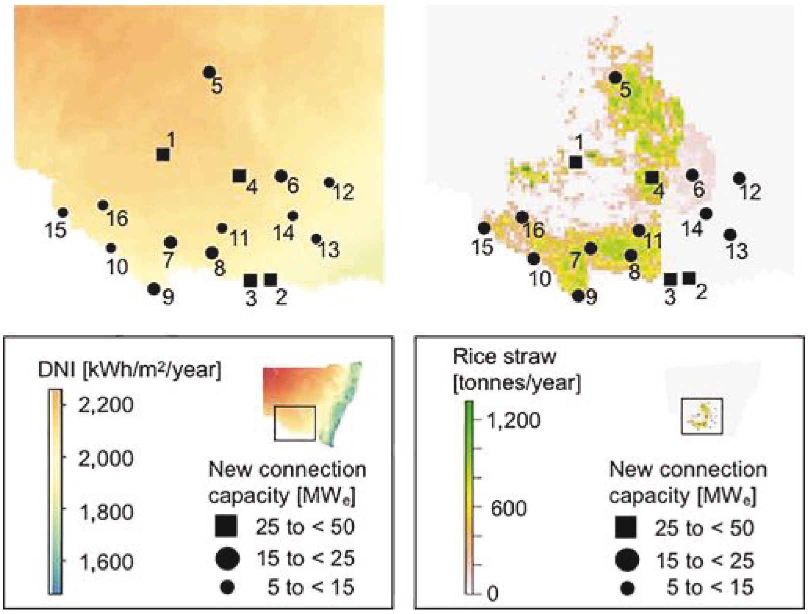

Fig. 3. 16 Substations with new connection capacity in the Riverina-Murray as well as DNI [kWh/m^2/year], and rice straw [tonnes/year]. The numbering of substations referees to number of substation in Table 6.

Table 6
Zone substations with new connection capacity in the Riverina-Murray and DNI [kWh/m^2/year], as well as rice straw residues [tonnes/year] cereal in 100 km radius.

No	Substation name	New connection capacity [MW_e]	DNI [kWh/ m^2/year]	Rice straw in 100 km radius [tonnes/year]
1	HAT Hay	30	2,151	140,147
2	MWA Mulwala	30	1,992	119,861
3	CRA Corowa	30	1,991	77,534
4	CLY Coleambally	25	2,127	255,930
5	HIL Hillston	16	2,181	184,129
6	NDA Narrandera	15	2,095	167,363
7	DEN Deniliquin	15	2,085	253,974
8	FIN Finley	15	2,071	228,038
9	MOA Moama	15	1,992	175,670
10	BAR Barham	10	2,047	165,179
11	JER Jerilderie	10	2,089	232,356
12	CLN Coolamon	8	2,028	27,869
13	HEN Henty	5	1,990	15,434
14	LOC Lockhart	5	2,039	102,352
15	KOR Koraleigh	5	2,089	78,192
16	MOU Moulamein	5	2,108	147,889

Murray. The highest rice straw abundance is the in the catchment around the Coleambally substation with over 250,000 tonnes/year. While globally most standalone CSP projects are located in areas with DNI > 2000 kWh/m^2/year, HCSB plants can be sited in locations with DNI > 1700 to 1800 kWh/m^2/year [23,84]—a threshold that is exceeded for all substations in the Riverina-Murray.

3.2. Technical performance

A Rankine cycle, powered by rice straw and solar energy, was developed for four different plant sizes scenarios of 5, 15, 30 and 50 MW_e. The plant layout for a 30 MW_e HCSB plant (gross generation of 32.4 MW_e) is shown in Fig. 4. In the CSP cycle, molten salts (60% $NaNO_3$, 40% KNO_3) enter the receiver at 290 °C and leave the receiver at 570 °C. The boiler produces steam at 95 bar/500 °C that feeds the high pressure steam turbine (HPT). A reheating cycle at 22 bar is installed to ensure operation at higher temperatures and pressures without having excessive moisture at the condensing steam turbine (CDT) outlet. Steam extractions are necessary for the deaerator (DEA) as well as to preheat the boiler feed water at the feedwater heater (FWH), thus increasing the steam cycle efficiency.

The immediate new connection capacity at substations in the Riverina-Murray offers access for micro (5 MW_e) to medium (~30 MW_e) sized HCSB plants. As described before we examined four HCSB plant scenarios, varying the power generation range (net) from 5 to 50 MW_e. Results for full-load (e.g. during night time) biomass operation, in which the biomass boiler accounts for 100% of the energy generation are presented in Table 7, while results for part-load operation where biomass boiler accounts for 20% and CSP accounts for 80% of the energy generation are presented in Table 8. As discussed above, the efficiency of HCSB plants increases for larger units thus less feedstock is required per generated kWh of electricity with an increase in plant size.

All scenarios consider a total of 7300 h of power generation (capacity factor of 83%), aligned with a previous study by Peterseim et al. [21], considering the need for shut down periods for plant maintenance. HCSB plants have two independent resource storage systems, a TES and the biomass feedstock storage. Both storage systems can be sized flexibly, which impacts on the proportion of energy generation from biomass or solar.

The solar share of electricity generation in HCSB plants can be optimized through TES sizing, and through the size of the solar field. Fig. 5 shows how increasing the SM and TES capacity increases the capacity factor of the CSP unit in HCSB plants. The solar field sizing is described using a solar multiple (SM) value, which represents the actual size of the solar field relative to what would be required to reach full capacity for a given DNI design point. The DNI design point depends on the local solar irradiation and is set to 850 W/m^2 as typical solar energy

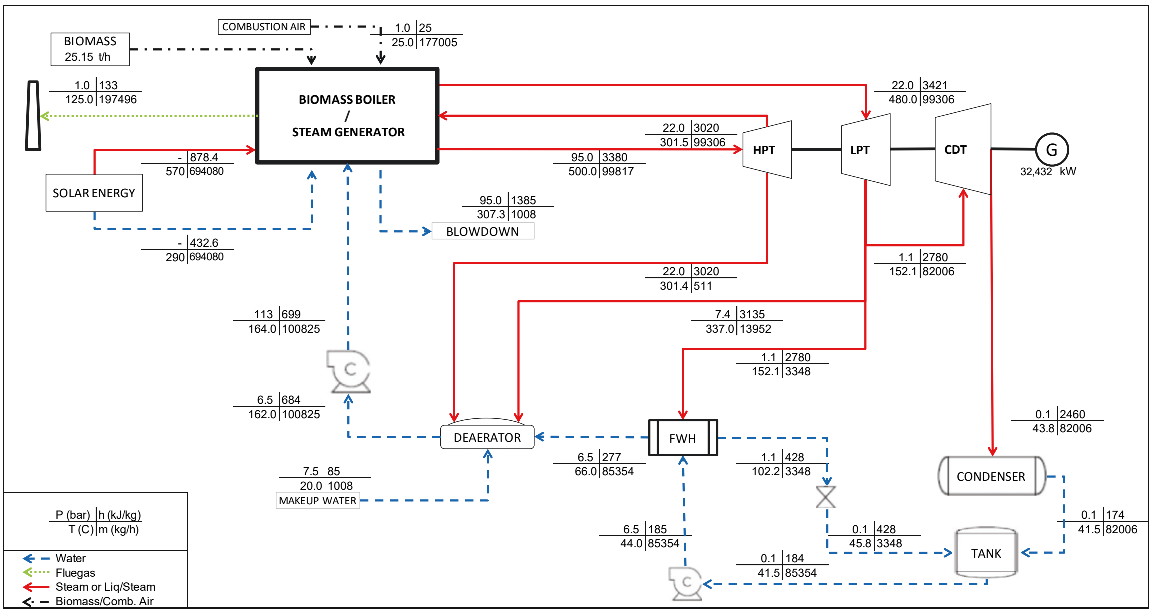

Fig. 4. Mass and energy balance of a 30MW$_e$ HCSB plant.

Table 7
HCSB plant results for full load operation (100% biomass aided energy generation).

	Unit	5 MW$_e$	15 MW$_e$	30 MW$_e$	50 MW$_e$
Biomass consumption	*tonnes/h*	6.3	14.8	25.2	39.9
Conversion rate	*MWh$_{el}$/t*	0.8	1.0	1.2	1.3
Biomass thermal energy	*MWt*	23.6	55.3	93.3	148.2
Power generated - gross	*MW$_e$*	5.6	16.7	32.4	54.1
Power generated - net	*MW$_e$*	5.0	15.0	30.0	50.0
Plant efficiency - gross	*%*	23.5	30.1	34.8	36.5
Plant efficiency - net	*%*	21.2	27.1	32.2	33.7

Table 8
HCSB plant results for part-load operation (80% CSP/20% biomass aided energy generation).

	Unit	5 MW$_e$	15 MW$_e$	30 MW$_e$	50 MW$_e$
Biomass consumption	*tonnes/h*	1.3	3.1	5.3	8.4
Conversion rate	*MWh$_{el}$/t*	3.8	4.8	5.7	6.0
Biomass thermal energy	*MWt*	5.0	11.7	19.8	31.5
CSP thermal energy	*MWt*	17.2	40.3	68.8	109.3
Power generated - gross	*MW$_e$*	5.6	16.7	32.4	54.1
Power generated - net	*MW$_e$*	5.0	15.0	30.0	50.0
Plant efficiency - gross	*%*	25.0	32.1	36.6	38.4
Plant efficiency - net	*%*	22.5	28.9	33.9	35.5
CSP capacity factor	*%*	19.5	22.2	23.3	24.2
Heliostat reflective area	*m^2*	40,281	88,069	148,562	228,978

received around noon on typical days in the end of December in the Riverina-Murray region.

In Fig. 6 the impact of increasing TES sizes (as described above 3 h of thermal storage capacity is the minimal possible size) and SM in terms of emissions, capital costs and LCoE is demonstrated. These results show that increasing the solar capacity factor of the HCSB plant reduces the need for biomass and hence decreases associated annual emissions for biomass harvest and transport. Choosing a larger CSP unit is also favourable if biomass availability is limited. However, increasing the solar capacity factor increases the plant costs, as both plant components

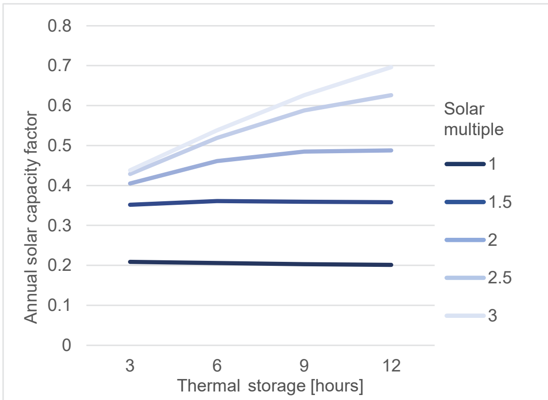

Fig. 5. Solar capacity factor in dependence of thermal storages size and solar multiple for a 15 MW$_e$ HCSB plant.

are more expensive than the biomass storage.

There are large quantities of rice straw feedstock (>100,000 tonnes/year) available in the vicinity of substations in the Riverina-Murray (Fig. 3). As such, for our analysis we have selected a design to maximise economic performance (minimising the LCoE), which means selecting a small solar field and limiting the TES to 3 h. The TES will be important during the biomass boiler ramp-up time of about 30 min (hot ramp up), where TES is utilised for steam generation allowing continued operation of the plant at night, when the electricity prices are the highest (similar approach chosen by e.g. [21,42,85]).

3.3. Economic assessment

The economic data for different HCSB size scenarios is presented in Table 9. The total plant investment varies between AU$ 49.5–68.5 million and AU$ 241.4–333.0 million for the smallest and largest plant scenario and this corresponds to an investment of AU$ 9.9–13.7 million/

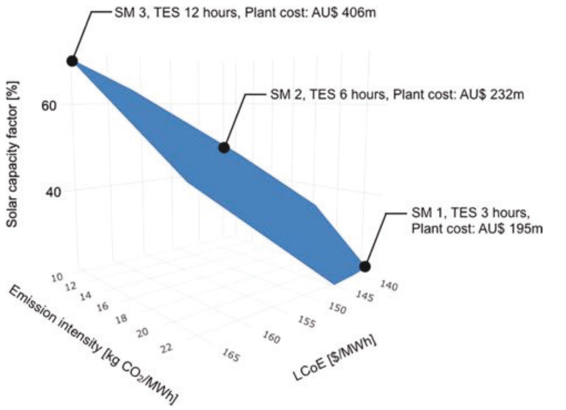

Fig. 6. 30 MW_e HCSB plant with increasing solar multiple (SM) and solar thermal storage (TES) capacity: Impact on solar capacity, emission intensity, capital cost and LCoE.

MW_e and 4.8–6.7 million/MW_e, respectively. Solar field, tower, receiver and thermal storage account for about 25% of the total plant investment, while the cost for the biomass boiler is 20% of the total plant. The biggest investment is the power block unit which accounts for >50% of the total investment.

In order to achieve the minimum required IRR of 11% (in accordance with Peterseim et al. [21]), while assuming a water price of AU$ 1.8/m^3 and biomass feedstock price of 40, 70 or 90 AU$ /tonne, the required annual electricity price of the different system sizes ranges between AU$ 235–350/MWh and AU$ 120–180/MWh for the smallest and largest plant scenario, respectively (Table 10). The LCoE levels vary from AU$ 96–154 /MWh for the largest HCSB plant to AU$ 187–293/MWh for the smallest HCSB plant size (Table 10).

3.4. Impact assessment

HCSB plants between 5 and 50 MW_e require a minimum of 36,500 tonnes and up to about 225,000 tonnes of rice straw per year (Table 11). Considering a maximum of 40 tonnes of feedstock per truck journey, between 914 and 5,617 round trips are required, emitting between 25.2 and 41.0 tonnes $CO_{2\text{-}e}$/MWh (including emissions for harvest). Plant footprint was obtained directly from simulation results using SAM. The solar field with single heliostats of 12 m × 12 m and other plant components require between 36 and 150 ha.

4. Discussion

This section discusses the techno-economic performance of HCSB plants compared to other renewable electricity generators; we consider the potential advantages compared to CSP or bioenergy plant, including reduced resource supply risks; and, possible benefits for local communities.

4.1. Techno-economic evaluation of HCSB plants

Australia's energy transition is characterized by significant uptake of VRE [6] and it is within this context that the uptake of dispatchable renewable energy capacity is important for generating electricity in times of diminished solar and wind resources [7–10]. Dispatchable electricity is more expensive than VRE [7]. Power purchase agreements (PPA) for VRE generators (such as solar PV and wind power plants) are typically fixed at AU$ 50–80 /MWh in NSW (pers. Com. Briggs, 2020). This price is significantly lower than what is estimated for HCSB plant operation, for which required prices are ranging between AU$ 120–350/MWh (Table 10). Considering the important role of dispatchable renewable energy is supporting the energy transition, the relatively high cost of HCSB plants compared to VRE highlights a need for policy incentives to support the deployment.

As the need for dispatchable electricity in the NEM increases, it can be expected that the additional value will justify the additional costs of dispatchable energy. A broad comparison of HCSB plants with other dispatchable renewable technologies is complex because different dispatchable technologies vary in terms of their deployment scale and hours of dispatchability. Two dispatchable technologies already deployed in Australia are batteries and pumped hydro power plants. Hydro power plants are usually deployed at much larger scales (>200 MW_e) [7] than the discussed HCSB plants and provide bulk storage. Batteries usually have capacity for large outputs limited to relatively short durations of 2–4 h of electricity supply [7,86], that is significantly shorter than considered for HCSB plants. The detailed comparison of different dispatchable technologies with HCSB is due to its complexity not part of this paper, however the required electricity price can be compared:

PV with battery or pumped hydro require PPAs as low as AU$

Table 10
PPA and LCoE for HCSB plants in four scenarios of 5, 15, 30 and 50 MW_e and for feedstock price between AU$ 40 per tonne and AU$ 90 per tonne.

	Unit	5 MW_e	15 MW_e	30 MW_e	50 MW_e
Feedstock price: 40 AU $ / tonne					
Required price	*AU$ /MWh*	235–290	170–210	135–170	120–150
LCoE	*AU$ /MWh*	187–243	134–173	109–139	96–123
Feedstock price: 70 AU $ / tonne					
Required price	*AU$ /MWh*	265–320	190–205	155–185	135–165
LCoE	*AU$ /MWh*	217–273	157–196	128–159	115–141
Feedstock price: 90 AU $ / tonne					
Required price	*AU$ /MWh*	285–350	205–250	170–200	150–180
LCoE	*AU$ /MWh*	237–293	173–212	141–172	127–154

Table 11
Impact assessment of HCSB plants in four scenarios of 5, 15, 30 and 50 MW_e.

	Unit	5 MW_e	15 MW_e	30 MW_e	50 MW_e
Rice straw	*tonnes/year*	36,550	85,146	143,059	224,669
Truck journeys	*number/year*	914	2,129	3,576	5,617
Emissions intensity	*kg $CO_{2\text{-}e}$/MWh*	41.0	31.8	26.8	25.2
Footprint	*ha*	36	68	106	150

Table 9
Economic performance summary of HCSB plants in four scenrios of 5, 15, 30 and 50 MWe, comparing investment in different plant components, including the power block (PB), heat exchanger (HE), balance of plant (BoP) and thermal storage (TES).

	Unit	5 MW_e	15 MW_e	30 MW_e	50 MW_e
Total plant investment	*million AU$*	49.5–68.5	104.1–143.7	166.8–229.8	241.4–333.0
PB, HE, HTHE and BoP	*million AU$*	26.8–40.2	55.5–83.3	88.4–132.5	126.3–189.5
Tower, solar field and receiver	*million AU$*	9.0–13.6	19.5–29.2	31.4–47.1	47.7–71.5
TES	*million AU$*	2.1–3.1	4.1–6.1	6.3–9.5	9.2–13.7
Biomass boiler	*million AU$*	11.4	24.6	40	57.2
Biomass storage	*million AU$*	0.19	0.40	0.66	1.0

50–100/MWh [87]. At these costs (different to the comparison with much cheaper VRE generators) HCSB plants become a cost-competitive technology. An important factor for the competitiveness of HCSB plants with other dispatchable renewable energies is the biomass feedstock price, which has significant impact on the required electricity prices. This study found that a feedstock price increase of 10% can lead to an increase of the required electricity price of about 2.6%. In line with assumptions from Herr et al. [15], this study assumes a straw price of AU $ 40–90/tonne. Rice straw is a comparably expensive biomass feedstock. Utilization of low or no cost feedstock (e.g. wastes), HCSB plant deployment could be even more competitive with other dispatchable technology. This finding is important when considering different feedstock types for eventual HCSB plant deployment in other parts of Australia.

Currently, the operation of HCSB plants as a 'free bidder' in the Australian energy market is attractive as peaking generator producing renewable power for the high-price periods and as provider of 'cap' products that limit exposure of retailers to price periods > AU$ 200–300/MWh. Fig. 7 shows the spot price in a typical summer and winter week in 2019 in the NEM. During summer, between 2 and 9 p.m. the average electricity price exceeds AU$ 200/MWh. At these times the HCSB plant could sell electricity to the NEM. However, this operation strategy would implement a dramatically lower capacity factor impacting the IRR and thereby the economic feasibility of the project. The operation strategy as 'free bidder' can be made more attractive if the cogeneration of heat was considered. Producing and selling thermal energy to a local industry or commercial building in times when electricity prices are too low for HCSB plant NEM bidding, will make the operation more profitable.

4.2. Comparison of HCSB and standalone CSP plants

The following paragraphs will elaborate the potential importance of HCSB plant deployment in the context of Australia's CSP industry development and will present a number of techno-economic advantages over standalone plants.

Several studies and reports describe Australia's significant CSP deployment potential [51,89]; however historically, commercial CSP

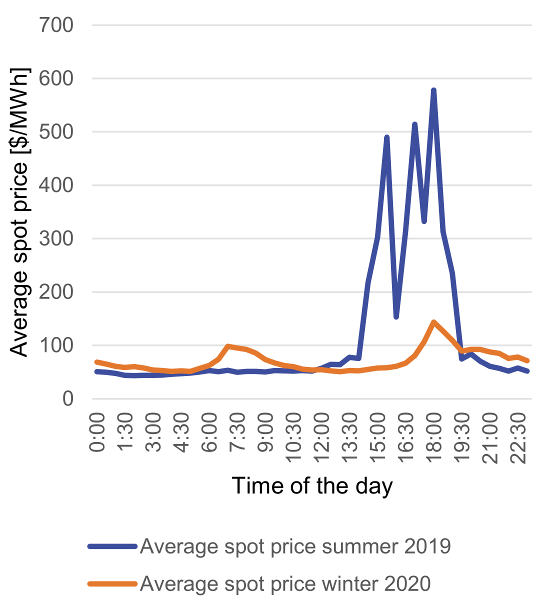

Fig. 7. Average spot price [$/MWh] in summer and winter (period 2019–2020) in the Australia energy market, adopted from AEMC [88].

proposals have failed to secure investment. For example, recently the AU $ 650 million Aurora Solar Energy Project outside Port Augusta, South Australia failed to reach financial closure [90]. This suggests that the proposed project at the proposed scale was not financially viable and highlights a lack of investor confidence in supporting CSP in Australia. Reflecting on the record of failed projects, a key recommendation of the Australian CSP Roadmap was for the development of small to mid-size (<50 MW_e) solar thermal systems to demonstrate the technology [91].

Owing to the smaller solar field and TES unit, HCSB plants become economic at smaller scales compared to standalone CSP plants. This economic benefit becomes apparent when comparing HCSB plants with standalone CSP plants assuming the same annual power generation. The equivalent to about 220,000 MWh/year (the same as the 30 MW_e HCSB plant in this publication) would require a 43 MW_e (gross) stand-alone CSP plant with 12 h of TES and SM of 2.5. We estimate that a plant of such size would require a capital investment of AU$ 303 million. This represents a considerably larger investment than AU$ 167–230 million that as estimated for a HCSB system. The required electricity price for the standalone CSP plant, considering the economic model used in this study would be AU$ 220/MWh – which is higher than the required electricity price for 30 MW_e HCSB plants of AU$/ 135–200 AU$/MWh.

As well as lower capital costs, the solar field has a much smaller footprint compared to conventional plants. The solar field for the above described standalone plant is about 75% larger than for the HCSB plant and requires about 320 ha of land. At this size, and despite its excellent solar resources, the Riverina-Murray would likely be unsuitable for standalone CSP plant siting owing to land use competition with traditional agriculture [92].

4.3. Lessening resource supply risk

Agricultural residues such as rice straw, which is an annual crop, carries a potential supply risk for bioenergy projects. This has been described as one of the reasons why straw is currently unutilized for bioenergy purposes [93]. Annual straw yields are highly impacted by seasonal variation as well as extreme weather events. The availability of harvestable stubble in NSW over the last 30 years is shown in Fig. 8. In times of drought (e.g. 2003 and 2004, as well as 2015) the stubble amount decrease dramatically. Hybrid plants reduce resource supply risks. Electricity generation from solar resources continues in times of diminished biomass supply and vice versa.

Additionally, to the hybridization with solar thermal energy, rice straw feedstock can also be subsidised with other waste residues with similar combustion properties. Straw from other cereal crops and forestry as well as winery residues, are abundant in the Riverina-Murray region. Another potential exists for growing of dedicated biomass woody crops in marginal, unproductive parts of the landscape as an additional feedstock type. Woody crops are less affected by seasonal variations than annual crops, whilst also achieving carbon sequestration outcomes. These waste residues and alternative feedstocks could be co-fired with rice straw to increase the amount of available biomass feedstock and reduce supply risks. The accrued carbon credits would have a positive impact on the LCoE of HCSB plant operation.

4.4. Potential benefits for the local community

Social license to operate (SLO) is an important matter for the success of any new electricity generation project [96–98]. There is often tension between the accepted broader benefits of renewable energy generation for society and the concerns from local communities around the impacts of new energy generation technologies, including noise and visual changes, that can influence community acceptance [99]. This study does not contain a SLO analysis, however highlights a number of potential benefits associated with the operation of a HCSB plant in the Riverina-Murray region. These include, but are not limited to:

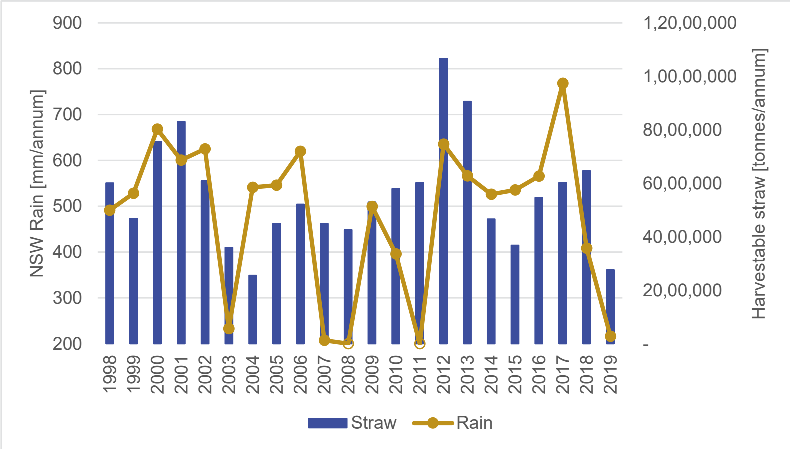

Fig. 8. Harvestable straw [tonnes/year] (from [94], using grain to straw conversion suggested by [15]) and rain [mm/year] (from [95]) in NSW from 1998 to 2019.

- The finding of some local studies (e.g. [100–102]) that energy generation from energy crops or forestry products may have lower community acceptance than for residual feedstocks like straw. Additionally, the use of rice straw for energy generation, as an alternative to current questionable and hazardous practice of on-field stubble burning (Fig. 1), would have a positive impact on the local air quality.
- HCSB plants likely create more local long-term job opportunities compared to other renewable energy options. Compared to PV plants, which are operated with<0.5 jobs / MW_e, bioenergy projects generally create about 3 jobs / MW_e [103–105]. This is a significant socio-economic advantage and locals can potentially be employed for feedstock supply, handling and operation of the plant. However, it needs to be noted that the deployment of HCSB plants in Australia faces the same difficulties that may be expected for standalone CSP plants. This includes limited industry capacity for supplying the substantial parts of the CSP unit including mirrors and HTF [80]. The deployment of FOAK HCSB plant in Australia would likely draw on international experience in CSP to support construction, installation and commissioning as well as for training and developing the capabilities of local workers.
- Offsetting biomass feedstock with solar energy reduces the overall biomass feedstock transport need and associated emissions (Table 11). Fewer truck movements is an important consideration for the Riverina-Murray region. As a top producer of agricultural goods in Australia, the Riverina-Murray region records heavy traffic movements, as products are mainly transported on the roads [92]. Local stakeholders have indicated that increased truck movements associated with biomass movements is a concern.

5. Conclusion

This paper describes the technical design of an HCSB plant and presents a broad evaluation of the techno-economic and environmental performance for the Australian context. The main research findings are summarised:

- Good siting potential of HCSB plants in the Riverina-Murray region of NSW, owing to sufficient DNI of 1900–2200 kWh/m^2/year and rice straw resources of 27,000–255,000 kWh/m^2/year at up to 16 substations with new connection capacity;
- HCSB plant design for cost-efficiency with a CSP tower system, low solar capacity factor and TES of 3 h;
- Maximum net energy efficiency of 34%, comparable to the energy efficiency of standalone bioenergy plants;
- Economically viable deployment with an electricity price of AU$ 120–350/MWh, assuming an IRR of 11%;
- Potential benefits to the environment and local community including carbon emission mitigation, improved air quality and local job creation.

6. Data availability

- Zone substation data is available over the AREMI website and can be downloaded: https://nationalmap.gov.au/renewables/.
- Rice straw data is available from the Department of Primary Industries for SA 2 regions in NSW, for detailed data at spatial scale of 25 qm (used in this study), data can be requested from the corresponding author of this paper.
- Solar resources data needs to be purchased from the Bureau of Meteorology: http://www.bom.gov.au/climate/how/newproducts/IDCJAD0111.shtml
- SAM is a openly available thermodynamic modelling software that can be downloaded here: https://sam.nrel.gov/
- The bioenergy plant was modelled using a private industrial software that is not available for download or use by external researcher.

CRediT authorship contribution statement

Ella Middelhoff: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing - original draft. **Leandro Andrade Furtado:** Formal analysis, Investigation, Software, Writing - original draft. **Juergen H. Peterseim:** Supervision, Validation, Writing - review & editing. **Ben Madden:** Resources. **Fabiano Ximenes:** Resources, Supervision, Writing - review & editing. **Nick Florin:** Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

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

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8.A.4. Hybrid concentrated solar biomass (HCSB) systems for cogeneration: Techno-economic analysis for beef abattoirs in New South Wales, Australia

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Hybrid concentrated solar biomass (HCSB) systems for cogeneration: Techno-economic analysis for beef abattoirs in New South Wales, Australia

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ABSTRACT

The clean energy transition and commitments to achieve net-zero greenhouse gas emissions by mid-century are most challenging for energy-intensive industries, like meat processing, that have traditionally relied on fossil fuels for heat and power. This study examines technical design options of combined heat and power (CHP) systems for beef abattoirs. Specifically, we investigate the technical and economic viability of a novel hybrid concentrated solar biomass (HCSB) system for a major beef abattoir in Australia. Two prospective design options are presented: The first considers an organic Rankine cycle (ORC) system integrated to a concentrated solar power (CSP) plant and an existing biomass boiler. The second option consists of a hybrid combined cycle (HCC) system fed by an existing biomass boiler, a solar thermal system and biogas, from anaerobic digestion (AD) of liquid waste streams of the abattoir. The two design options are simulated, considering operational modes and energy demand of the abattoir. Costs of energy generation [AU$/MWh] and emission abatement potential [$tCO_{2\text{-}e}$], for different solar field sizes [ha], are discussed for both cases. The simple retrofit ORC HCSB solution is characterized by easy integration, but can only cover a fraction of the required electricity. The more sophisticated HCC HCSB system presents a more economical solution, as it can provide 100% renewable heat at a cost of 66.0 AU$/$MWh_{th}$; and up to 65% of electricity at a cost of 151.7 AU$/$MWh_{el}$. The findings of this study highlight the opportunity for HCSB plants for industries with low- to medium (40–250 °C) heating demand.

1. Introduction

Industrial use of electricity and heat accounts for about 30% [1] of global greenhouse gas emissions. The replacement of fossil fuels with renewable sources is the key strategy to limit global warming to below 1.5 °C (e.g., [2]) and achieve net-zero greenhouse-gas emissions by the middle of the century [3]. This energy transition is particularly challenging and costly for energy-intensive industries that require electricity and heat [4,5]. In Australia, for example, the overall percentage of renewable energy generation in the industrial sector in 2021 was only around 10% [6]. Therefore, the need to investigate and promote new technologies for generating renewable energy for industrial electricity and heat is critical.

As part of this effort, this study focusses on industrial combined heat and power (CHP) generation using renewable sources. Specifically, we investigate design options for CHP systems with both solar thermal and bioenergy. Numerous studies have investigated industrial systems, operating with either solar thermal (e.g., [7–9]) or bioenergy (e.g., [10,11]); however, a focus on hybrid concentrated solar biomass (HCSB) systems is relatively limited (e.g., [12]). The synergetic utilization of concentrated solar thermal and bioenergy in hybrid systems offers a number of advantages including increased flexibility and dispatchability [13,14]. HCSB plants can use various biomass feedstocks, including waste residues [15]. The integration of a concentrated solar power (CSP) system leads to lower biomass feedstock demand compared to stand-alone bioenergy plants, reducing feedstock and transport costs [16]. The thermal energy generated by both technologies can also be used for electricity generation. A grid connected HCSB plant based on the Rankine cycle, was commercially demonstrated about a decade ago in the 22.5 MW_e *Termosolar Borges* plant in Lleida, Spain [17]. Another option is the provision of industrial process heat [13,18]. In 2017, a 16.6 MW_{th} HCSB systems was developed to supply heat and electricity to the local community of Brønderslev, Denmark [19].

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Nomenclature

Abbreviations

AD	Anaerobic digestion
APH	Air preheater
CAL	Covered anaerobic lagoon
CHP	Combined heat power
CSP	Concentrated solar power
DB	Duct burner
ESH	External superheater
DNI	Direct normal irradiation
GE	Biogas engine
HCC	Hybrid combined cycle
HCSB	Hybrid concentrated solar biomass
HRSG	Heat recovery steam generator
HTF	Heat transfer fluid
IAM	Incident angle modifier
LHV	Lower heating value
NCMC	*Northern Co-operative Meat Company*
NSW	New South Wales
ORC	Organic Rankine cycle
PTC	Parabolic trough collector
SAM	*System Advisor Model*
TES	Thermal energy storage

Symbols

Q	Thermal energy [MW_{th}]
W	Electric energy [MW_{el}]
t	Time [hour of year]
η_{th}	thermal efficiency [%]
η_{el}	electrical efficiency [%]
η_{sf}	Thermal efficiency of solar field [%]
A_{sf}	Solar field reflective area [m^2]
DNI	Direct normal irradiation [MWh]
θ	Irradiation incident angle at time [degree]
φ	Solar elevation angle at time point [degree]
γ	Solar azimuth angle at time point [degree]
η_{loss}	Mirror losses [%]
η_{sha}	Shadow efficiency [%]
ω	Mirror angle [degree]
η_{iam}	Incident angle modifier efficiency [%]
ρ_m	Mirror reflectance [%]
η_t	Tracking efficiency [%]
η_{geo}	Geometry defects [%]
η_{soil}	Dirt and soiling effects [%]
η_{gen}	General error [%]
L_F	Surface to focus length [m]
L_{SF}	Aperture length [m]
H_{gain}	Mirror gains [%]
L_{row}	Row distance [m]
L_{gap}	Piping between mirrors [m]
T_{MIN}/T_{MAX}	Daily min/max temperature [°C]
t_{min}/t_{max}	Hour of min/max temperature
t_d	Day lengths [hours]
ϕ	Local latitude [degree]
δ	Sun declination angle [degree]
n	Number of day
η_e	TES hourly energy losses [%]
η_c/η_d	TES charging/discharging efficiency [%]
y_{chg}/y_{dsg}	Charging/discharging mode [on/off]
V_{tes}	TES tank volume [m^3]
ρ_{htf}	TES HTF density [kg/m^3]
c_{htf}	TES HTF specific heat [kJ/kg K]
ΔT_{tes}	TES temperature difference [°C]
D_{tes}	TES tank diameter [m]
H_{tes}	TES tank height [m]
LHV_{bio}	Biomass lower heating value [GJ/tonne]
C_{bio}	Biomass cost [AU$/tonne]
m_{bio}	Biomass feed rate [tonne/hour]
$CAPEX$	Capital cost [Australian Dollar]
$O\&M$	Operation and maintenance [AU$/year]
$LCoE/H$	Levelized cost of elec./heat [AU$/MWh]
CRF	Capital recovery factor [%/year]
$WACC$	Weighted average cost of capital [%/year]
LT	Lifetime [years]

Subscripts

hcsb	Hybrid concentrated solar biomass
csp	Concentrated solar power
bio	Biomass
gas	Biogas
tot	Total
tur	Turbine
ge	biogas engine
pro	Abattoir process
sf	Solar field
tes	Thermal energy storage
dni	Direct normal irradiation
recLoss	Receiver losses
pipeLoss	Piping losses
chg	Thermal energy storage charging
dsg	Thermal energy storage discharging
db	Duct burner
elec	Electricity
heat	Heat

This study investigates HCSB plants in the context of CHP generation for red meat abattoirs and tanneries in Australia. A number of previous studies have investigated HCSB systems in the context of industrial cogeneration (Table 1). These previous studies investigated the technology at various scales and applications, from high-level assessments, e.g., for the European continent [20], to specific case studies such as a hotel [21], abattoir [12], local community [22], or an existing industrial plant [11]. HCSB systems can be designed with many different energy generating technologies [23,24]. Some studies have investigated HCSB plants with, e.g., internal combustion engines [25], and gas turbines [22,26]; while other studies focussed on HCSB plants with Rankine cycle [16] and organic Rankine cycle (ORC) systems [11,12,22,27,28].

The present work aims to evaluate the integration potential of HCSB systems for cogeneration in industries with low- to medium temperature heat demand (40–250 °C), such as red meat abattoirs. To the best of our knowledge, this is the first study that investigates HCSB systems in the context of red meat abattoirs in Australia. The study presents two novel HCSB design options for integration with a major red meat abattoir in New South Wales (NSW), Australia. Energy efficiency, $CO_{2\text{-}e}$ abatement potential, and costs are evaluated. The technologies included in this study are mature and readily deployable. By investigating different design options, the findings are more broadly applicable to other abattoirs or industrial applications beyond the specific investigated abattoir.

1.1. Energy demand for meat processing

Australia is one of the top three global exporters of beef, accounting for around 17% of global trade [32]. Around 22% of Australia's beef

Table 1
Technology specifications and cost estimates from previous studies, considering conversion rates of 1 AU$ ~ 0.62 €, ~ 0.75 US$ and ~ 2.67 R$.

	Unit	Soares et al. 2018 [29]	Chacartegui et al. 2015 [8]	Cascartelli et al. 2015 [30]	Tzivanidis et al. 2016 [31]	Borello et al. 2013 [21]	Guadalupe Almeida et al. 2018 [12]	Sterrer et al. 2014 [11]	Borunda et al. 2016 [7]
Solar field	AU $/m^2	645.2	344	355	371	/	43.3	510	/
Collector type	/	TMx/hp-36	SkyTrough	Euro Trough 100	Euro Trough 150	Parabolic trough	Fresnel	Euro Trough 150	Poly Trough 120
Receiver type	/	/	Schott PTR80	/	/	/	/	Schott PTR 150	/
Reflective area	m^2	10,000	/	/	25,000	2,580	122,000	9,810	32,486
Non solar field multiplier	/	/	/	/	/	2.63	1.5	2.55	/
Heat transfer fluid (HTF) and/or piping	Type	/	Therminol VP-1	Therminol VP-1	/	/	Water	Therminol VP-1	Therminol 55
	AU$	/	/	338,571	/			483,871	/
	AU$/kg	/	2.9	/	/	/	/	/	/
Thermal storage (TES) and/or TES HTF	Type	NA	Hitec XL	/	/	/	/	NA	/
	AU $/m^3	NA	760	/	2,419	/	/	NA	/
	AU$/kg	NA	1.57	/	/	/	/	NA	/
CSP + TES cost	AU$	NA	/	/	/	12,693,548	/	NA	/
Biomass boiler capacity		5 MW_{th}	NA	/	/	1.16 MW_e	27.4 MW_{th}	/	/
Biomass boiler cost		1,093,548 AU $/$MW_e$	NA	/	/	180,290 AU $/$MW_e$	438,436 AU $/$MW_{th}$	/	/
Power block	Type	Rankine cycle	ORC	ORC	ORC	Steam engine	NA	ORC	ORC
Working fluid	Type	Water	3 different	/	Cyclohexane	Water	NA	/	/
Capacity	MW_e	1	5	5	1	0.13	NA	/	/
Turbine	AU $/$MW_e$	2,081	725,806	463,842		2,729,529	NA	/	/
Evaporator	AU $/$MW_e$	/	/	61,776	/	558,313	NA	/	/
Economizer	AU $/$MW_e$	/	/	30,161	/	186,104	NA	/	/
Feed pump	AU $/$MW_e$	/	/	19,002	/	/	NA	/	/
Cooling tower pump	AU $/$MW_e$	/	/	19,002	/	/	NA	/	/
Condenser	AU $/$MW_e$	/	/	68,040	/	186,104	NA	/	/
Wet cooling tower	AU $/$MW_e$	/	/	165,449	/	/	NA	/	/
Regenerator	AU $/$MW_e$	/	/	39,388	/	/	NA	/	/
Balance of plant	AU $/$MW_e$	/	/	592,404	/	/	NA	/	/
Power block	AU $/$MW_e$	1,290,323	/	1,725,730	2,903,226	3,660,050	NA	/	/
Total plant cost	AU $/$MW_e$	15,285,669	/	8,628,650	/	11,919,951	/	/	/
O&M	%	2.9	/	/	/	/	2	/	/
Plant lifetime	years	25	/	/	/	/	25	/	/

meat is produced within the state of NSW – Australia's most populous state [33,34]. Red meat processing has thermal energy demand for cooling, equipment sterilisation, plant wash-down, carcase processing, rendering and blood cooking [35]. Presently, the energy demand of abattoirs in NSW is met by grid electricity (32%) and the onsite combustion of natural gas (37%) and coal (19%) [34]. The remaining energy demand is supplied by a mix of renewable energy resources, including bioenergy. In 2018, the red meat sector was responsible for 63.5 $MtCO_{2\text{-}e}$ of Australia's greenhouse gas emissions, of which meat processing accounted for approximately 1.3 $MtCO_{2\text{-}e}$ [38]. Of these emissions, 44% are direct emissions (Scope 1), while 56% are indirect emissions (Scope 2) [38][1]. The rising energy costs [36,37] and switching to alternative renewable energy systems will likely be important factors impacting the future prosperity of abattoirs.

The annual thermal and electric energy demand of abattoirs depends on their scale. It is greater when the process of rendering is included in the plant operation. The estimated annual energy demand for thermal and electric power for thirteen beef abattoirs and tanneries in NSW is listed in Table 2. It is estimated that NSW abattoirs require around 4,000–300,000 GJ of thermal energy and between 3,500–90,000 GJ of electricity (Table 2).

1.2. Energy supply at beef abattoir

This study aims to understand the HCSB deployment potential at red meat abattoirs. Because the energy supply system at each abattoir is unique, there is no standard solution. In order to investigate the application of HCSB systems under 'real-world' conditions, this study uses real data from the *Northern Co-operative Meat Company* (*NCMC*), a major beef and veal abattoir and tannery located in Casino, NSW, Australia. The abattoir has a kill capacity of 1,900 head per day (950 beef and 950 veal). The energy supply system at *NCMC* is similar to that of other

[1] Scope 1 emissions are produced onsite, e.g., through the combustion of fuel at the industry site. Scope 2 emissions are produced during electricity generation of grid connected technologies and are related to an industry through electricity purchase.

Table 2
Beef abattoirs in New South Wales: Location, capacity, integrated renewable energy technology, and energy demand. *estimated range[2].

Location	Capacity [heads/day]	Integrated renewable energy	Heat demand [GJ/year]	Power demand [GJ/year]
Casino	1,900 [35]	12 MW_{th} biomass boiler [35]	176,904	78,072
Tamworth	840 [39]	Biogas from covered anaerobic lagoon [39]	39,824–300,861*	35,316–89,867*
Wagga Wagga	1,300 [40]	Biogas from covered anaerobic lagoon [40]	289,306 [41] (reduced by 557 [40])	
Wingham	800 [42]	6 MW_{th} biomass boiler [41]	294,832 [41]	
Inverell	1,000 [43]	Biogas from biodigester tank [39]	210,436 [43]	68,477 [43]
Whittingham	750 [44]	Biogas from covered anaerobic lagoon [39]	29,858–225,645*	26,487–67,401*
Young	300 [45]	–	10,595–26,950*	11,974–90,258*
Yanco	600 [42]	–	23,895–180,516*	21,189–53,920*
Scone	600 [42]	–	23,895–180,516*	21,189–53,920*
Cootamundra	200 [46]	–	4,978–37,608*	4,414–11,233*
Monuya	500 [47]	–	19,92–150,430*	17,658–44,934*
Wattle Springs	100 [48]	–	3,982–30,086*	3,532–8,987*
Polo Flat	200 [49]	–	7,965–60,172*	7,063–17,973*

[2] Where no annual energy demand could be found in the literature an annual energy demand range was estimated, using: i) the kill capacity of the abattoir, ii) the beef hot standard carcass weight of 289 kg/head [2], and iii) assuming that 1.3 GJ per tonne hot standard carcass weight is needed for abattoirs with slaughtering only (47% electricity and 53% heat), and iv) 5.2 GJ per tonne hot standard carcass weight is needed for abattoirs with slaughtering including rendering (23% electricity and 77% heat) [4].

abattoirs as shown in Fig. 1. The current energy supply system of the abattoir can be described as follows:

- Electricity is drawn from the network. Fig. 2a shows the electric energy demand at the abattoir. The load curve was generated from hourly meter data from 2016–17 [35]. During weekdays the plant requires about 1.75–5 MW_{el}, while during weekends the load curve is assumed to be stable at about 1.2 MW_{el}. The weekday and weekend operations amount to 6,017 h and 2,743 h per year respectively.
- Thermal energy is produced using a biomass boiler. Fig. 2b shows the thermal energy demand load curve at the Casino abattoir. At full load (3,761 h per year), 8 MW_{th} is delivered for rendering. In this process, 2 MW_{th} of saturated steam at 16 bar is consumed. In addition, about 8 MW_{th} is consumed for hot water supply, which is provided directly by the boiler (2 MW_{th}) and by the water recovered from rendering (6 MW_{th}). The hot water is required for various processes, each at the approximate temperature of 82 °C (2 MW_{th}), 55 °C (4 MW_{th}), and 40 °C (2 MW_{th}). Once used, the hot water is mixed with the make-up water at 27 °C, and returned to the boiler at 40 °C

With the aim to reduce investments in new plant components, this study investigated the integration of HCSB systems with the existing boiler system. The biomass boiler at the Casino abattoir is shown in Fig. 3a. The 12 MW_{th} water tube boiler has a steam generation capacity of 18 t/hour at 200 °C and 16 bar. According to plant engineers, the boiler operates at around 83% efficiency. The biomass boiler is operated by a fuel mix of pine sawdust, hardwood sawdust and nutshells (Fig. 3b). In this study a fuel moisture content of 25% is assumed, as well as a lower heating value (LHV_{bio}) of 18.6 MJ/kg, at a cost (C_{bio}) of AU$ 57/tonne, aligning with Ref. [35]. An estimated loss of 5% (measured in MJ) is assumed owing to, e.g., possible variation in the LHV of the biomass, heat transfer effects, incomplete combustion, or dirty tubes.

2. Methods and material

This study focuses on two possible HCSB CHP design options for the *NCMC* abattoir:

1) A simple retrofit solution using a solar thermal organic ORC system, that is preheated by steam produced by the existing biomass boiler (ORC HCSB system), and
2) A relatively sophisticated hybrid combined cycle (HCC) supplied by the existing biomass boiler, a new solar thermal unit and superheating system fired with biogas (HCC HCSB system).

As mentioned before, both HCSB options integrate the existing biomass boiler (Fig. 3a). Because the boiler is relatively simple and small, the produced steam is insufficient to meet the heat and electricity demand at the same time and needs to be integrated with other steam generation technologies. These integrated plant components for the two selected HSBC design options include a power cycle, a solar field, and a thermal energy storage (TES). Additionally, the HCC HCSB design option includes an anaerobic digestion (AD) system for treating liquid wastewater, a biogas engine (GE) and duct burner (DB). Both design options and the component selection were informed by a detailed review of the literature and expert knowledge.

The proposed design options are simulated to supply the energy load for the abattoir over the course of one year. For both HCSB design options we estimate equipment costs and evaluate overall economic feasibility and emission abatement potential. We also appraise solar field sizing and siting. While our approach was to focus on a specific case study, by examining different design options, the findings are more broadly applicable to other abattoirs.

2.1. Process simulation

Process simulation and thermodynamic analysis of the power cycle was performed using *CoolProp* [50], which was selected because it is an open source software and can be integrated into a number of common computational platforms, including *Microsoft Excel*. The software package has been previously described in, e.g.,: [51,52]. The CSP subsystem was simulated using the physical trough model from the *System Advisor Model* (*SAM*) [53]. *SAM* was selected because it is specifically designed to simulate solar thermal power plants, e.g.,: [54]. The component models were integrated by matching the thermal energy input into the power cycle, with output from the CSP and bioenergy unit.

2.2. Power cycle

As described earlier, HCSB plants can generate electricity using a number of different technologies. This study focusses on Rankine cycle and ORC systems. In both cases, heat is converted into electricity as described by, e.g., Tartière and Astolfi [55]. The HCC HCSB system is designed with Rankine cycle. Rankine cycle systems are more mature than ORC systems and their main working fluid is water/steam. The direct use of water/steam is particularly interesting considering the potential for direct integration with abattoir's hot water system (without requiring expensive heat exchanging systems).

The ORC HCSB plant is designed with ORC. ORC systems are often used for industrial CHP plants because of their high performance, reliability, relative simplicity, and low-cost, e.g., [56,57]. As of 2017, the

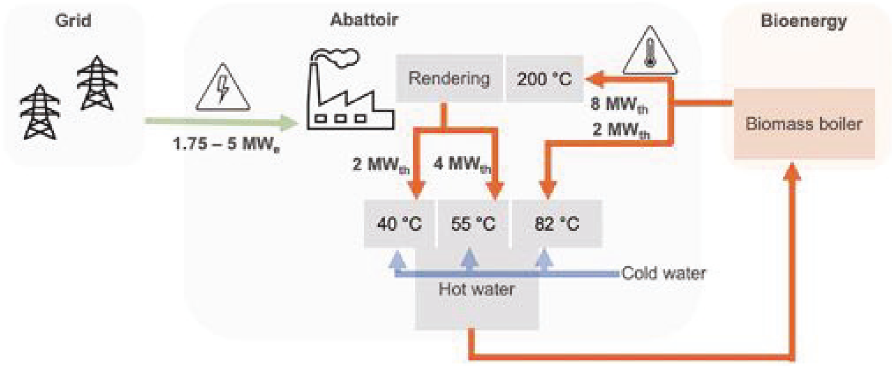

Fig. 1. Existing thermal and electric energy supply into the abattoir in Casino, NSW.

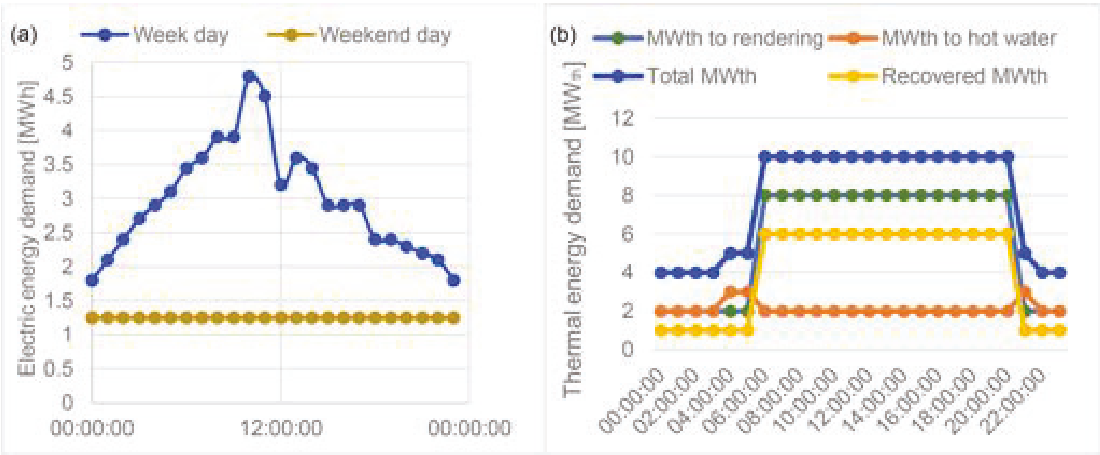

Fig. 2. Typical load curves at the Casino abattoir: (a) Week day and weekend day electric -, (b) weekday thermal energy demand.

Fig. 3. (a) Existing biomass boiler and (b) biomass feedstock, photos taken by co-author Ximenes in 2021.

global installed capacity of ORC was >2,701 MW in over 705 projects [55]. ORC systems make use of a range of renewable low-temperature sources, including waste heat, geothermal [58], solar thermal and/or bioenergy [10,19] and can be deployed at different scales from micro (few kW) to medium scale (~20 MW) applications [55]. ORC systems are operated with a range of different working fluids [59–63]: selection of the appropriate working fluid depends on the working temperature, system stability and efficiency requirements, scale of operation, and safety and environmental concerns [61]. *Toluene* was selected as the working fluid in this case study as it has a low global warming potential of 3.3 and a good thermodynamic efficiency, enabling a smaller solar field [59]. Its specifications can be found in Table 3.

The thermodynamic model considered the hourly (t) thermal energy supply [MW_{th}] to the HCSB plant (Q_{hcsb}) that can be provided by the CSP unit (Q_{csp}), biomass boiler (Q_{bio}) and, for the second design option, by the supplementary consumption of biogas (P_{gas}). This is shown by Eq. (1):

$$Q_{hcsb}(t) = Q_{csp}(t) + Q_{bio}(t) + Q_{gas}(t) \quad (1)$$

Eq. (2) shows that for the second HCSB design option the total

Table 3
Properties of ORC working fluid *Toluene*, adapted from Tzivanidis et al. [31].

Property	Value
Critical temperature [K]	318.6
Critical pressure [bar]	41.23
Saturation temperature [K]	295
Saturation pressure [bar]	30,7
Global warming potential [-]	3.3

generated power [MW_{el}] combines electricity generated from the turbine (W_{tur}) and the GE (W_{ge}):

$$W_{tot}(t) = W_{tur}(t) + W_{ge}(t) \quad (2)$$

The thermal efficiency of the power cycle (without GE) can be determined as.

$$\eta_{th} = Q_{pro}(t)/Q_{hcsb}(t), \quad (3)$$

where Q_{pro} is the rate of waste thermal energy supplied to the abattoir.

The electrical efficiency (η_{el}) is given by:

$$\eta_{el} = W_{tot}(t)/W_{hcsb}(t) \quad (4)$$

In order to minimise efficiency losses, this study assumes full load turbine operation for both HCSB design options. A minimum temperature difference (ΔT) of 10 °C is considered for all heat exchanges [9]. Electric generator efficiency is assumed to be 97.5% [32], The net electrical efficiency discounts 8% of the power gross output for cycle auxiliary's consumption [32].

2.3. Solar field

This study focusses on the deployment of parabolic trough collector (PTC) owing to technical maturity and suitable working temperature range. In PTC direct normal irradiation (DNI) is concentrated onto a line receiver system and thereby collected and converted into solar thermal energy [64]. A number of thermal solar collectors, e.g., linear fresnel collector, compound parabolic concentrator, and evacuated tube collector, have been used and investigated for industrial process heat systems. Among CSP collector types, PTC is the most mature with demonstrated long-term reliable deployment (over 25 years) [65]. In recent years, PTC has been increasingly investigated for industrial applications [66]. PTC working temperatures that range between 85 and 393 °C are also well aligned with the thermal energy demand for a wide range of industrial processes in the low to medium temperature range. A number of different PTC collector and receivers have been developed. As widely deployed technologies, the *PT Eurotrough 150* collector and *Schott PTR80* receiver have been selected for this study (Table 4).

PTC can be operated with a range of different heat transfer fluids (HTF). The selection of the HTF depends on the thermodynamic properties of the working fluid. Each HTF has a different maximum working temperature. To increase the lifetime of the HTF, the chosen maximum working temperature should be at least 10 °C higher than the highest cycle temperature (Pers. Comm. Zourellis 2021 [67]). For the ORC HCSB plant, *Therminol 66* was selected as HTF, while for the HCC HCSB plant *Therminol VP-1* was chosen.

The hourly thermal energy gain [MW_{th}] from the CSP unit combines thermal energy from the solar field (Q_{sf}) and TES (Q_{tes}), as described by Eq. (5):

Table 4
Technical specification of *PT Eurotrough 150* collector and *Schott PTR80* receiver, adopted from *SAM* [53].

Feature		Value
Tracking efficiency	η_t	0.99
Dirt and soiling effects	η_{soil}	0.97
Geometry defects	η_{geo}	0.98
General error	η_{gen}	0.99
Mirror reflectance	ρ_m	0.935
Surface to focus length	L_F	2.11 m
Aperture length	L_{SF}	150 m
Piping between mirrors	L_{gap}	1 m
Row distance	L_{row}	15 m
Aperture width	L_w	5.76 m
IAM	$a_0,$ $a_1,$ a_2	1, 0.0506, −0.1763

$$Q_{csp}(t) = Q_{sf}(t) + Q_{tes}(t). \quad (5)$$

The thermal energy gain of the solar field is described by Eq. (6):

$$Q_{sf}(t) = (Q_{dni}(t) \times \eta_{sf}(t) \times A_{sf}) - Q_{recLoss}(t) - Q_{pipeLoss}(t) \quad (6)$$

and considers receiver ($Q_{recLoss}$) and piping losses ($Q_{pipeLoss}$), following the assumptions made by *SAM* [53], the solar field area (A_{sf}), thermal energy gain from solar resources (Q_{dni}) and the efficiency of the solar field (η_{sf}).

The thermal energy from the sun (Q_{dni}), reaching the mirrors depends on the hourly irradiation (*DNI*) and the normal irradiation incident angle (θ):

$$Q_{dni}(t) = DNI(t) \times cos\theta(t) \quad (7)$$

which itself depends on the solar elevation (φ_t) and azimuth (γ_t) following:

$$cos\theta(t) = \sqrt{1 - cos^2\varphi(t) \times cos^2\gamma(t)}. \quad (8)$$

Solar angles for every hour of the year are calculated by *SAM* for the specific location of Casino, NSW.

The solar field efficiency is defined as:

$$\eta_{sf}(t) = \eta_{loss}(\theta(t)) \times \eta_{sha}(\omega(t)) \times \eta_{iam}(\theta(t)) \times \rho_m \times \eta_t \times \eta_{geo} \times \eta_{soil} \times \eta_{gen} \quad (9)$$

where estimates for fixed values can be obtained from Table 4, while the hourly mirror angle and shadowing is calculated by *SAM* and the other hourly values follow:

$$\eta_{loss}(\theta(t)) = 1 - (L_F \times tan\theta(t)/L_{SF}) + \eta_{gain}(\theta(t)), \quad (10)$$

$$\eta_{gain}(\theta(t)) = (L_F \times tan\theta(t)\_L_{gap}/L_{SF}), \quad \text{and} \quad (11)$$

$$\eta_{iam} = a_0 + a_1 \times (\theta(t)/cos\theta(t)) + a_2 \times (\theta(t)^2/cos\theta(t)). \quad (12)$$

The simulation of the CSP unit in HCSB systems requires hourly meteorological data as input, including: DNI, ambient temperature and wind speed. Hourly DNI data was obtained from the Australian *Bureau of Meteorology*, which publishes satellite derived DNI data for Australia [68]. The data is available at a spatial resolution of 5 × 5 km and available since 1995. The quality and accuracy of the *Bureau of Meteorology* DNI data has been evaluated by a number of authors in previous studies (e.g., [69,70]). Previous studies have demonstrated a strong correlation between the *Bureau of Meteorology*'s satellite derived DNI data and ground measurements to justify this approach [69,70]. Hourly DNI data was extracted from the satellite derived raster files, using raster packages in *R* [71].

Daily minimum (T_{MIN}) and maximum (T_{MAX}) temperature was obtained in the form of ground measurements at the Casino airport weather station from the Australian *Bureau of Meteorology* [72]. To determine hourly air temperatures this study used a mathematical model [73,74], as follows:

The hourly temperature for the period between daily minimum and maximum temperature, $t_{max} \geq t \geq t_{min}$ was calculated by.

$$T(t) = T_{MIN} + (T_{MAX} - T_{MIN}) \times \left\{ sin\left[\frac{\pi}{2} \times ((t - t_{min})/(t_{max} - t_{min}))\right] \right\}^{1.4} \quad (13)$$

and likewise, the hourly temperature for the period between daily maximum and minimum temperature, $t_{min} \geq t \geq t_{max}$, was calculated by

$$T(t) = T_{MAX} - (T_{MAX} - T_{MIN}) \times \left\{ sin\left[\frac{\pi}{2} \times ((t - t_{max})/(24 + t_{min} - t_{max}))\right] \right\}^{1.2}. \quad (14)$$

The time of minimum t_{min} and maximum t_{max} temperature can be calculated using the following assumption:

$$t_{min} = 12 - (t_d/2), \quad \text{and} \tag{15}$$

$$t_{max} = 12 - \left((t_{min} \times (12 - t_{min}))/13.5\right), \tag{16}$$

where t_d is the length of the day (between sunrise and sunset), calculated as

$$t_d = \frac{2}{15} \times arcos(-tan\phi \times tan\delta). \tag{17}$$

ϕ is the local latitude and δ is the solar declination angle:

$$\delta = 23.45 \times \sin(2\pi/365 \times (n + 284)), \tag{18}$$

with n as the number of days, starting with January 1st.

2.4. Thermal energy storage (TES)

To improve the dispatchability and minimise energy supply risks this study considers the integration of a thermal energy storage (TES) system. A number of different TES systems for ORC systems have been discussed and tested. For example, Chacartegui et al. [9] have investigated water–oil tanks, hot rocks, concrete, pebbles, molten salts, and phase change cytogenic energy storage systems. For this study a TES solution with molten salts was selected, because of its commercial maturity [75].

The hourly thermal energy of the TES (Q_{tes}) is expressed by Eq. (19), following the approach in Ref. [54]:

$$Q_{tes}(t) = (1 - \eta_e) \times Q_{tes}(t-1) + \left(\eta_c \times \left(Q_{chg}(t) - Q_{dsg}(t)\right)/\eta_d\right), \tag{19}$$

where efficiencies can be obtained from Table 5. Charging (Q_{chg}) and discharging flow rate (Q_{dsg}) are limited by maximum charging and discharging rates ($Q^{max}_{dsg/chg}$) and defined as,

$$0 \le Q_{chg}(t) \le y_{chg}(t) \times Q^{max}_{chg}, \quad \text{and} \tag{20}$$

$$0 \le Q_{dsg}(t) \le y_{dsg}(t) \times Q^{max}_{dsg}. \tag{21}$$

and

$$y_{dsg}(t) + y_{chg}(t) \le 1. \tag{22}$$

The storage capacity can be expressed in full load hours that can be supplied to operate the power cycle at design point. In actual operation the number of hours is usually smaller than the number specified, due to thermal losses. The thermal capacity of the TES influences its size. The TES volume (V_{tes}) and diameter (D_{tes}) can be calculated following:

$$V_{tes} = Q^{design}_{tes} / \rho_{htf} \times c_{htf} \times \Delta T_{tes} \tag{23}$$

and

$$D_{tes} = 2\sqrt{V_{tes}/\pi \times H_{tes}} \tag{24}$$

which are impacted by HTF density (ρ_{htf}) and specific heat (c_{htf}) as well as the temperature difference between cold and hot TES storage (ΔT_{tes}) and TES height (H_{tes}), which are defined in Table 5.

Table 5
Design conditions and assumed values of thermal energy storage (TES), adopted from Ref. [54].

Feature		Value
Tank height	H_{TES}	12 m
Charging efficiency	η_c	98.5%
Discharging efficiency	η_d	98.5%
TES energy loss	η_e	3.1%

2.5. Use of biogas from abattoir waste streams

The proposed HCC HCSB system considers the integration of a biogas unit. Abattoirs produce large amounts of organic waste that can be processed with AD for biogas production. The Casino abattoir produces 15,400 m^3 of liquid waste water per day, with a methane content of the liquid waste water of 70% [35]. Currently this liquid waste is managed by direct land application. For this analysis we assume that the wastewater is directed to a covered anaerobic lagoon (CAL). Considering methane has a LHV of 33.4 MJ/m^3 (at 20 °C and 1 bar), approximately 4.17 MW_{th} (methane) per day can be produced.

The HCC HCSB system integrates a biogas engine and duct burner, both fed with biogas from the liquid waste streams from the abattoir. In order to consume all the biogas available (4.17 MW_{th}), a biogas engine (GE) (*JMS 416 GS-N.L Jenbacher* model) is considered [76]. The power cycle is aided by exhaust gases from the GE (topping cycle) providing thermal energy to superheat the steam produced by the existing boiler (bottoming steam cycle). This approach is based on the application of HCC, investigated by Andrade Furtado et al. [77]. To increase the exhaust gas temperature of the biogas GE, some biogas is burned in a duct burner (DB) before passing through the external superheater (ESH). After superheating the steam at the ESH, the exhaust gases are also used to (i) preheat the DB combustion air; and (ii) preheat the boiler feedwater in the feedwater heater, allowing for a reduction in the consumption of biomass in the boiler. The Rankine cycle, fuelled by biomass, is modelled at steady state regime. The operation of the duct burner integrated with the exhaust gases is described in detail by Andrade Furtado et al. [77].

Hourly thermal energy gain of biogas (Q_{gas}) is provided by the exhaust gases of the GE (Q_{ge}) and by the supplementary burning of biogas in the DB (Q_{db}):

$$Q_{gas}(t) = Q_{ge}(t) + Q_{db}(t). \tag{25}$$

2.6. Economic assessment

The capital cost (*CAPEX*) of the proposed plants was estimated for different plant components based on the literature (Table 1) and assumptions were validated in consultation with technology experts [67]. As noted by Lovegrove et al. [78], there are only few commercial CSP plants in Australia, limiting access to robust assumptions on costs for CSP components in the Australian context. Thus, the accuracy of the assumptions for this component is limited to only +/- 20% [78]. The current COVID-19 pandemic and the associated temporary slowdown in production and trade is causing an extreme increase in raw material and steel prices [79]. This study assumes the pre/post-pandemic prices to reflect usual market conditions.

According to Chacartegui et al. [8], the PTC solar field costs vary from 306.5 to 354.8 AU\$/m^2 (Table 1). Aligning with Tzivanidis et al. [31] this study conservatively assumes a cost of 371 AU\$/m^2. We used a combined price for piping and HFT of about AU\$ 340,000 as suggested by Cascartelli et al. [30]. The TES HTF *Hitec Solar Salt* costs about 2.67 AU\$/kg [75] and the cost estimate for the whole TES system was 2,419 AU\$/m^3, consistent with Tzivanidis et al. [31].

Cost assumptions for biomass boilers and the required flue gas cleaning equipment are considered very reliable given the maturity of this technology. The power block, consisting of economizer, pumps, condenser, regenerator and balance of plant for the Rankine cycle or ORC turbine with working fluid, was estimated to cost 1,290,326 AU \$/MW_e [29] and 1,725,730 AU\$/MW_e, respectively [31] including 5% of contingence [29]. The cost of the DB was estimated to be AU\$ 200,000 [77]. Costs for gas engine and CAL were estimated to be AU\$ 2,035,000 and AU\$ 9,000,000, respectively [35].

To assess the economic feasibility, the capital cost (*CAPEX*) and operation and maintenance costs (*O&M*), levelised cost of electricity (*LCoE*), and levelised cost of heat (*LCoH*) were compared. *LCoE* and

LCoH were calculated assuming that:

$$LCoE = CAPEX \times (O\&M + CRF) + C_{bio}W_{elec}, \text{ and} \quad (26)$$

$$LCoH = CAPEX \times (O\&M + CRF) + C_{bio}/Q_{heat} \quad (27)$$

which depends on the annual amount of generated electricity (W_{elec}) [MWh_{el}] and heat (Q_{heat}) [MWh_{th}]. The capital recovery factor (*CRF*) is defined as:

$$CRF = WACC \times (1 + WACC)^{LT} / (1 + WACC)^{LT-1}. \quad (28)$$

The weighted average cost of capital (*WACC*) of 6.4%/year and plant lifetime (*LT*) of 25 years is consistent with Lovegrove et al. [80].

3. Results and discussion

In this section we first present the detailed design and operational modes for the two HCSB design options, including the solar field sizing and siting requirements. Next, the technical feasibility and relative advantages and disadvantages of the two design options are presented, including the emission abatement potential. This is followed by an evaluation of the economic feasibility.

3.1. Technical design

3.1.1. Technical design details for the ORC HCSB system

The mass flow and energy balance of the proposed ORC HCSB plant at design conditions and for CHP generation is shown in Fig. 4 and key system properties are listed in Table 6. Steam from the biomass boiler (at 201 °C and 16 bar) preheats the ORC system using a heat exchanger. The temperature of the working fluid increases from 83 °C to 191 °C. HTF heated by the CSP component enters an evaporator at 390 °C. The evaporator increases the temperature of the working fluid to reach ORC turbine inlet conditions of 295 °C and 30.75 bar. The ORC turbine delivers 5 MW_{el} to the abattoir (Table 6). When leaving the ORC turbine, the working fluid enters the condenser at 98 °C. The thermal energy demand of the abattoir is met with 2 MW_{th} of steam (at 201 °C and 16 bar). Hot water at 82 °C is supplied from the heat exchanger (2 MW_{th}) and hot water at 55 °C and 40 °C is supplied by the condenser.

3.1.2. Technical design details for the HCC HCSB system

The mass flow and energy balance of the HCC HCSB plant at design conditions are shown in Fig. 5 and the key properties of the power cycle are listed in Table 6. A GE produces 1.1 MW_{el} in a topping cycle and provides exhaust gas at 370 °C. Further exhaust gas is produced by the DB, that is combined with the hot exhaust from the GE to provide a total of 1.4 MW_{th} at 653 °C. This thermal energy is supplied into the HCSB bottoming system through an external superheater (ESH). At the ESH, steam produced at the biomass boiler or CSP unit is superheated from about 202 °C and 16 bar to live steam conditions of 320 °C and 16 bar. The steam turbine generates up to 3.3 MWh_{el}, leading to a total electricity generation of 4.4 MW_{el}. Additional thermal energy can be recovered from the exhaust gas after the ESH to preheat the DB combustion air to 300 °C at the air preheater (APH) and to preheat the boiler feedwater to 110 °C.

Table 6
Thermodynamic results for two hybrid concentrated solar biomass (HCSB) design options and for the operational modes 'combined heat and power (CHP)' and 'electricity only' generation.

Parameter	Unit	CHP operation		Electricity only	
HCSB design option	-	ORC	HCC	ORC	HCC
Biomass consumption	[t/hour]	2.63	2.19	2.19	0.00
Boiler thermal energy	[MW_{th}]	13.57	11.31	11.31	0.00
Biogas consumption	[MW_{th}]	–	4.16	–	4.16
Net solar thermal energy	[MW_{th}]	13.05	11.65	13.05	11.65
Total thermal energy input	[MW_{th}]	26.62	27.12	24.36	15.81
Thermal energy to abattoir	[MW_{th}]	10.00	10.00	0.00	0.00
Net thermal efficiency	[%]	37.57	36.87	0.00	0.00
Gross power output	[MW_e]	5.43	4.40	5.43	4.40
Net power output	[MW_e]	5.00	4.20	5.00	4.20
Net electric efficiency	[%]	18.79	15.49	20.53	26.57

3.2. Plant operating modes

3.2.1. Operating modes of the ORC HCSB system

For the ORC HCSB plant we have considered three potential operational modes, shown in Fig. 6. Table 6 compares the energy requirements for the different operational modes at design conditions. The selection of the operational mode depends on the availability of solar thermal energy (from the CSP unit) and the thermal energy demand of the abattoir:

i) 'Electricity only' generation (Fig. 6a): Electricity (5 MW_{el}) is generated by the ORC system if sufficient (13 MW_{th}) solar thermal energy can be provided and the abattoir has no heat demand. In this mode the biomass boiler is running at its partial load capacity (using 2.2 t of biomass/hour), producing 10 MW_{th} to preheat the ORC cycle. As shown in Table 6 the net electric efficiency for this operational mode is 20.5%.

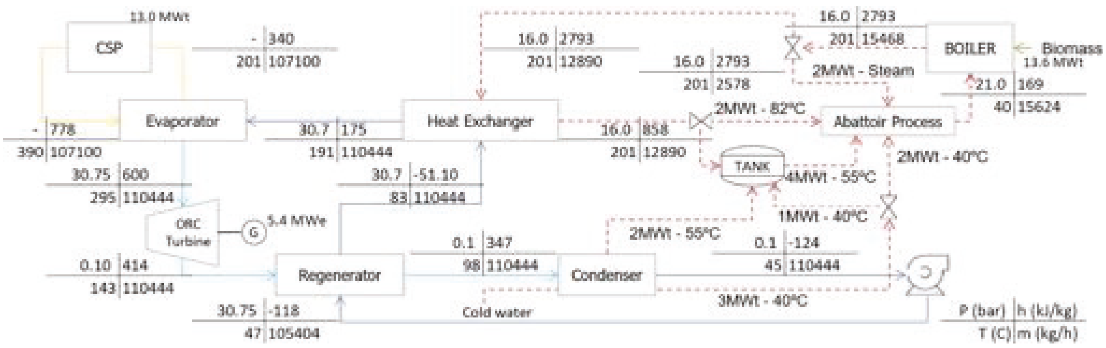

Fig. 4. Mass and energy balance of the organic Rankine cycle (ORC) hybrid concentrated solar biomass (HCSB) design option.

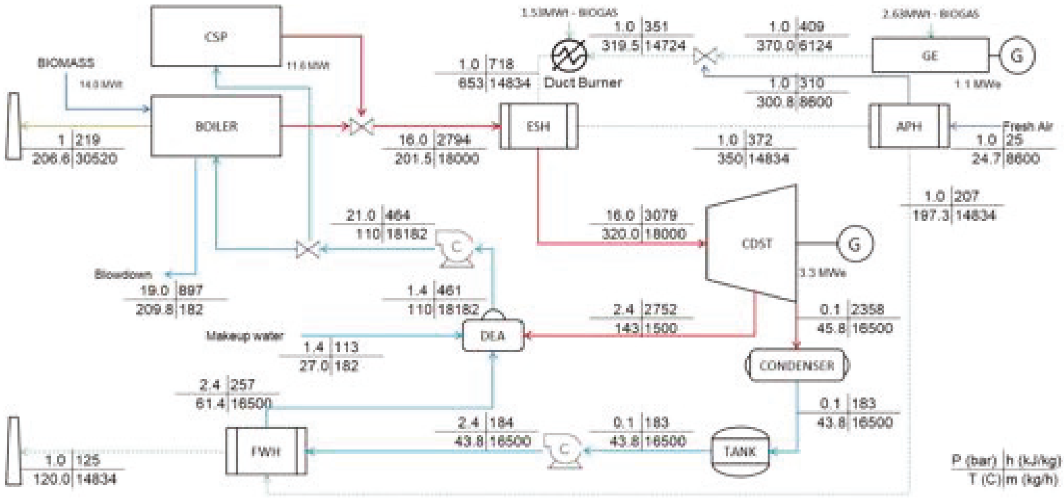

Fig. 5. Mass and energy balance of the hybrid combined cycle (HCC) hybrid concentrated solar biomass (HCSB) design.

ii) 'Heat only' generation (Fig. 6b): If no solar thermal energy is available, the ORC cycle is switched off and the thermal energy demand of the abattoir is met by the biomass boiler (up to 10 MW_{th}).

iii) 'CHP' operation: If the HCSB system produces power and heat, solar thermal energy (13 MW_{th}) is provided to the ORC, and the biomass boiler produces 12 MW_{th} of saturated steam. During CHP operation the thermal energy demand of the abattoir is supplied as follows: 2 MW_{th} steam (201 °C and 16 bar) and 8 MW_{th} hot water, as shown in Fig. 4. The net electric efficiency for this operational mode is 18.8%, while the net thermal efficiency is 37.6% (Table 6).

3.2.2. Operating modes of the HCC HCSB system

Similar to the ORC HCSB plant, the HCC HCSB system can operate in three modes: i) 'electricity only', ii) 'heat only', or iii) 'CHP'. Table 6 compares the energy requirements of 'electricity only' and CHP operation. The net electric efficiency for CHP generation is 15.5%, while the net thermal efficiency is 36.9%. For 'electricity only' generation, the net electric efficiency is 26.6%. Different to the ORC HCSB design option, the HCC HCSB system has two options to operate the power cycle turbine which are shown in Fig. 7: During the 'solar operational mode', the steam turbine is operated by about 12 MW_{th} from the CSP unit, as well as the heat exhaust of the biogas unit. The biomass boiler accounts for the thermal energy demand of the abattoir or is switched off (depending on 'electricity only', or 'CHP operation'). During the 'biomass operational mode' the steam turbine is operated by the biomass boiler, as well as the heat exhaust of the biogas unit. This 'biomass operational mode' is used if the CSP unit is not producing sufficient output. To facilitate the 'biomass operational mode', no thermal energy from the biomass boiler can be used for the abattoir ('electricity only' generation).

3.3. Solar field sizing

For both HCSB design options the annual electricity generation capacity factor depends on the sizing of solar field and TES system. Solar field size is expressed in number of loops and in this study one loop consists of 8 mirrors. The TES capacity is expressed in number of full load hours which can be generated by the stored HTF. The solar field and TES can be oversized to increase the number of hours of electricity generation per year.

3.3.1. Solar field sizing of the ORC HCSB system

In the ORC HCSB plant the net thermal energy from the CSP unit provided to the power cycle is about 13.1 MW_{th} (Table 6). The impact of varying electricity generation per year for solar field sizes of 3–8 solar loops for the ORC HCSB system is given in Table 7. The thermal energy capacity at design conditions (summer solstice around noon) varies between 13.2 and 35.3 MW_{th} for the six solar field sizing scenarios. The TES capacity is increased according to solar field sizes to avoid energy spillage and varies between 3 and 11 h. The ORC turbine operates at a capacity factor of 16–36% for different solar field sizes, generating between 7,020–15,575 MW_{el}. This minimizes the need to purchase electricity from the grid to 13,133–17,472 MW_{el} per year.

3.3.2. Solar field sizing of the HCC HCSB system

For the HCC HCSB plant the net thermal energy from the CSP unit provided to the power cycle is about 11.7 MW_{th} (Table 6). The impact of varying electricity generation per year for solar field sizes of 0 and 3–5 solar loops for the HCC HCSB system is given in Table 8. Different to the ORC HCSB design option the power turbine can be operated by the biomass boiler and biogas unit alone (without solar thermal energy). Because of this a HCC system without CSP unit (0 solar loops) is added to the comparison. The HCC HCSB system can generate between

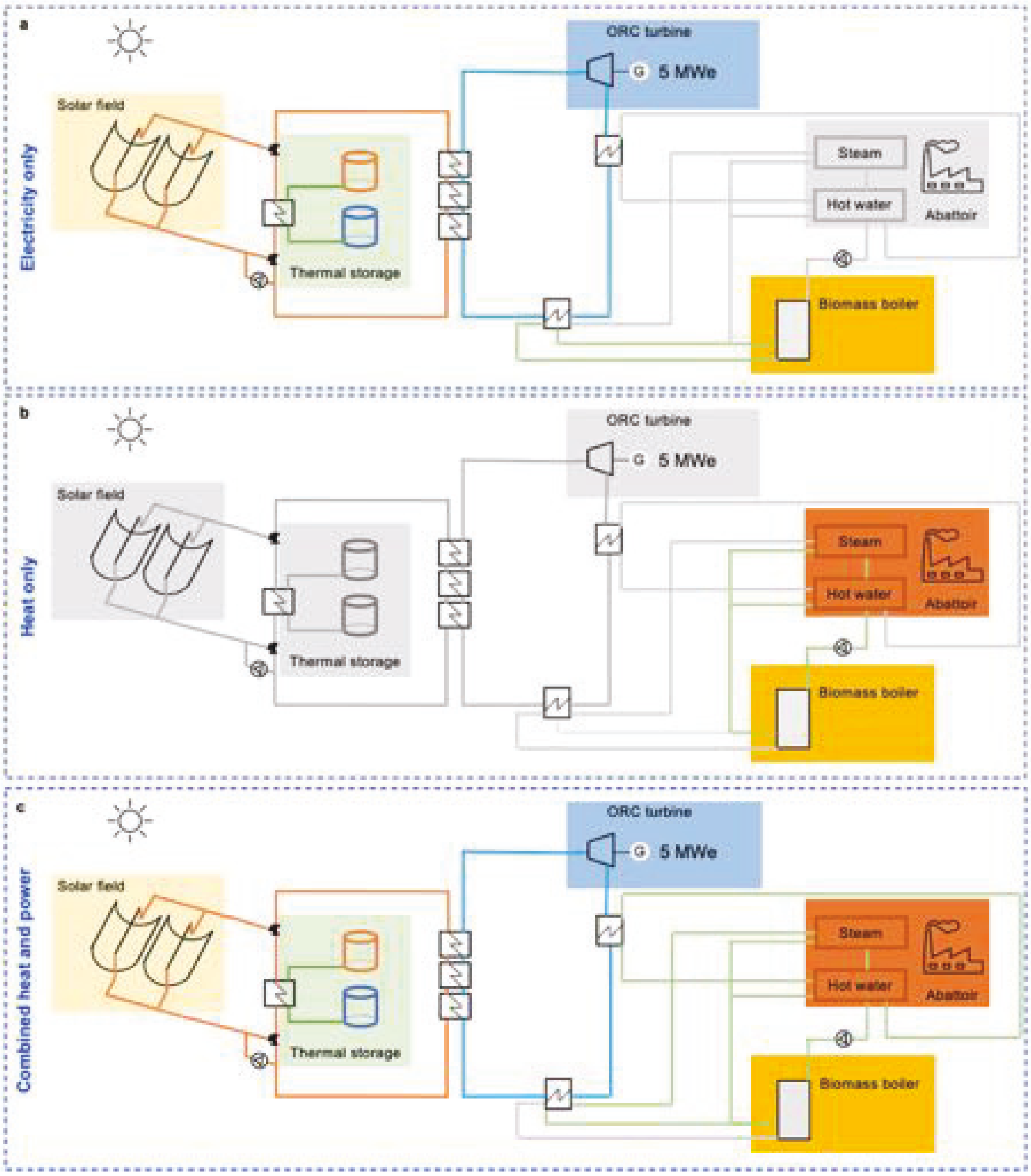

Fig. 6. Simplified illustration of organic Rankine cycle (ORC) hybrid concentrated solar biomass (HCSB) design option and its three operational modes, supplying (a) electricity, (b) heat, and (c) combined heat and power.

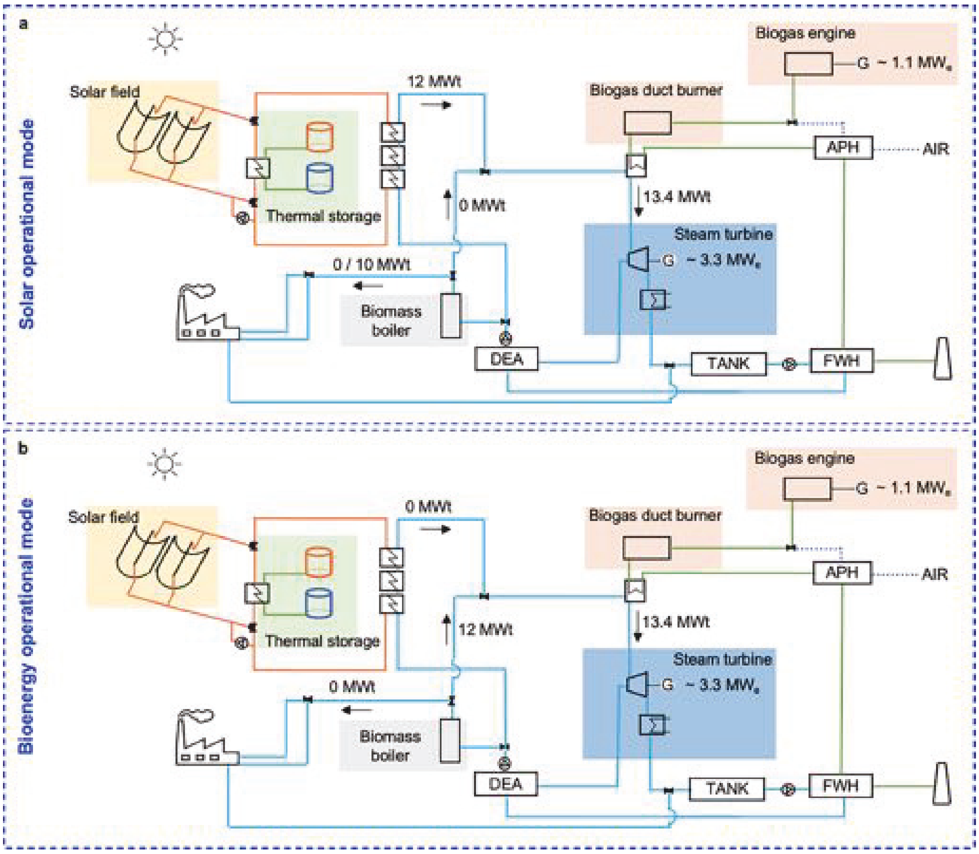

Fig. 7. Simplified hybrid combined cycle (HCC) hybrid concentrated solar biomass (HCSB) plant operation relying on (a) solar thermal energy and (b) on bioenergy from the biomass boiler.

Table 7
Solar field sizing for the organic Rankine cycle (ORC) hybrid concentrated solar biomass (HCSB) design option.

Solar field sizing	3 loops	4 loops	5 loops	6 loops	7 loops	8 loops
Thermal energy at design [MW_{th}]	13.2	17.7	22.1	26.5	30.9	35.3
Number of mirrors	24	32	40	48	56	64
TES capacity [hours]	3	4	6	8	9	11
TES capacity [m^3]	235.6	314	471.1	628.2	707	863.7
Solar + TES annual capacity factor [%]	16	21	25	29	32	36
Biomass consumption [t/year]	11,086	11,586	12,005	12,404	12,763	13,186
Electricity generation [MWh_{el}/year]	7,020	9,200	11,040	12,660	14,015	15,575
Electricity purchase from grid [MWh_{el}/year]	17,472	16,263	15,268	14,471	13,849	13,133

17,948–23,663 MWh of electricity per year for the different solar field sizing (Table 8). This minimizes the need to purchase electricity from the grid to 7,629–11,674 MWh of electricity per year.

Table 8
Solar field sizing for hybrid combined cycle (HCC) concentrated solar biomass (HCSB) design option.

Solar field sizing	0 loops	3 loops	4 loops	5 loops
Thermal energy at design [MW_{th}]	0	13.3	17.7	22.1
Number of mirrors	0	24	32	40
TES capacity [hours]	0	3	4	7
TES capacity [m^3]	0	500.5	667.4	1,167.9
Solar + TES annual capacity factor [%]	0	17	23	28
Biomass consumption [t/year]	14,669	13,783	13.510	13,246
Electricity generation [MWh_{el}/year]	17,948	21,390	22,587	23,663
Electricity purchase from grid [MWh_{el}/year]	11,674	8,996	8,236	7,629

3.3.3. Solar field siting

Depending on the chosen solar field size there are different land footprint requirements. The solar field reflective and total area requirements for both HCSB plants are listed in Table 9 as a function of solar field size (number of loops). The abattoir owns fallow and pasture land which can be used for siting of the solar field (Fig. 8). To avoid heat losses, the distance between solar field and electricity cycle should be kept to a minimum. Typically this distance should not exceed 1.5–2 km, and should ideally be less than 300 m (Pers. Comm. Zourellis, 2021 [67]). Fig. 8a shows a circle of 1.5 km around the existing biomass boiler at the abattoir. Paddocks in the south-west and north of the abattoir qualify for siting of the solar field. However, because a railway is located in the south of the abattoir, paddocks in the north are preferably selected

Table 9
Impact assessment of different hybrid concentrated solar biomass (HCSB) systems, comparing sizing [ha] and scope 2 emissions [$tCO_{2\text{-}e}$/year].

	ORC HCSB plant						HCC HCSB plant		
Solar field sizing	3 loops	4 loops	5 loops	6 loops	7 loops	8 loops	3 loops	4 loops	5 loops
Solar field reflective area [m^2]	19,620	26,160	32,700	39,240	45,780	52,320	19,620	26,160	32,700
Solar field total area requirement [ha]	4.9	8.8	13.7	19.7	26.9	35.0	5.5	9.8	15.3
TES diameter [m]	5.0	5.8	7.1	8.2	8.7	9.6	7.3	8.4	11.1
Scope 2 network emissions [t CO_2-e/year]	137.6	128.0	120.2	113.9	109.0	103.4	70.8	64.9	60.1

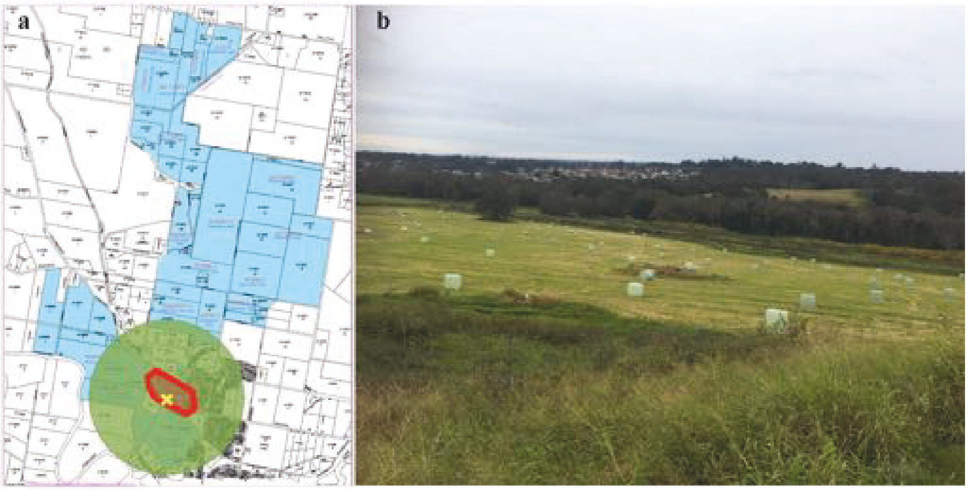

Fig. 8. Land owned by the abattoir in (a) map and (b) photo (taken by Ximenes in 2021). (a) Land owned in turquoise. The red circle is the location of the abattoir buildings, the yellow cross is the location of the biomass boiler, the green circle marks a radius of 1,500 m around the biomass boiler. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to avoid the need to run hot oil tubes across the railway line. Another option, which is especially interesting for industrial co-generation is the siting of PTC on roof areas. When considering roof areas for siting of the solar field, smaller and lighter collectors should be chosen for installation on the roof [81].

3.4. HCSB design option comparison

Energy supply systems at abattoirs are unique and the integration of renewable resources, such as solar thermal or bioenergy (solid or biogas), need to be designed individually, taking into account the individual energy demand. The *NCMC* abattoir has a thermal energy supply system similar to that of other abattoirs in NSW (Table 2) and the presented results are applicable to other abattoirs. The two proposed HCSB plants range from a relatively simple retrofit design (ORC HCSB system) to a sophisticated system with several new components (HCC HCSB system), using biogas as a third energy resource (beside solid biomass and solar). Both HCSB systems have advantages and disadvantages which are discussed in detail below.

The ORC HCSB plant is particularly applicable to abattoirs with existing biomass or coal boilers (e.g., see Table 2) that could integrate a solar thermal ORC system in a similar way and thereby reduce their need to purchase electricity from the grid. On the other hand, the ORC HCSB system has the limitation that the biomass boiler alone cannot meet the thermal energy demand of the ORC power system. The operation of the ORC turbine, and thus electricity generation always depends on the availability of thermal energy from the CSP component and the biomass boiler is only used for preheating (Fig. 4). Compared to other HCSB plants presented in literature this is a major difference. In former studies (e.g., [16,82]) the CSP component holds the minor role as ‘fuel saver’ or ‘complementary’ technology in HCSB systems. The proposed ORC HCSB system mainly relies on solar resources for energy generation and is thereby less flexible in terms of dispatchable energy generation. The integrated TES can extend the operational time by a few hours, but cannot guarantee operation around the clock.

The HCC HCSB design option considers a solar thermal and bioenergy system that is superheated by the combustion of biogas. Compared to the ORC HCSB system, this design option is significantly more complex including a greater number of technological components. On the other hand, this design option offers a beneficial approach to exploiting a waste stream with the utilisation of biogas. Abattoirs produce large amounts of organic wastes which can be used for energy generation using AD. Additional benefits of AD systems include odour and methane emission reduction [83,84], making it attractive for many abattoirs (Table 2). Studies have shown that the produced biogas of liquid waste streams from abattoirs alone is not enough to supply 100% of renewable energy [83,85,86]. Furthermore, the HCC design has an overall higher electrical efficiency than standalone biogas systems. Additionally, the biogas unit produces a steady output of electricity (1.1 MW_{el}) to the abattoir which increases the overall percentage of renewable energy that can be supplied to the *NCMC* abattoir. Because the steam is superheated by the biogas unit, electricity generation can be facilitated by solar thermal and biomass boiler unit independently with implementations on the energy generation flexibility. A possible weekly operation of the HCC HCSB is shown in Fig. 9.

Both HCSB plants investigated in this study reduce carbon emissions, compared to current operations. The current scope 2 emissions of the Casino abattoir which are attributed to the purchase of electricity from the grid are about 171 $tCO_{2\text{-}e}$ per year. The remaining emissions after HCSB deployment, associated with grid-electricity purchase, lay

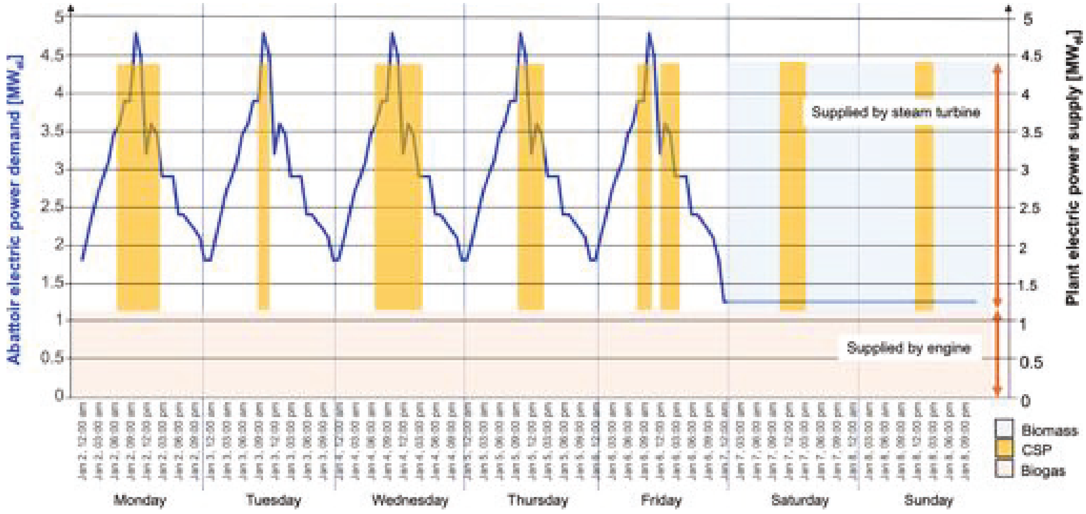

Fig. 9. Abattoir electric power demand [MW_{el}] (blue line) and electric power supply [MW_{el}] by the hybrid combined cycle system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between 60 and 140 $tCO_{2\text{-}e}$ per year (Table 9). The carbon abatement potential is especially high for the HCC HCSB plant because it can generate more electricity, with the potential to reduce 64.9% of the emissions.

3.5. Economic analysis

The estimated capital costs for the two design options are given in Table 10 and Table 11 respectively. Here we compare the cost for different solar field sizes. Based on the solar field sizes the capital cost of the ORC HCSB plant ranges from AU$ 16.8–30.4 million. This is cheaper compared to the HCC HCSB plant, which ranges from AU$ 24.3–30.7 million. The higher capital cost of the HCC HCSB plant results from including a GE, DB and CAL. The solar field is generally the costliest plant component.

The LCoH and LCoE for the different plants are shown in Table 12 and Table 13. The LCoH ranges from about 48–78 AU$/$MW_{th}$ for both HCSB design options. For the ORC HCSB system the LCoE ranges from 246.1 to 332.1 AU$/$MWh_{el}$ and for the HCC HCSB plant (with CSP) from 151.7 to 163.5 AU$/$MWh_{el}$. These costs are higher than the current commercial power purchase agreement from the grid that is offered to the abattoir [35]. The lowest cost of energy generation of 133.9 AU $/$MWh_{el}$ can be reached for the HCC HCSB design option without the CSP unit (0 solar loops). This is not surprising as the energy generation

Table 10
Capital cost (CAPEX) of organic Rankine cycle (ORC) hybrid concentrated solar biomass (HCSB) plant in million Australian Dollar [m AU$].

	ORC HCSB plant					
Solar field sizing	3 loops	4 loops	5 loops	6 loops	7 loops	8 loops
Solar field [m AU$]	7.6	10.0	12.4	14.9	17.3	19.7
TES [m AU$]	0.6	0.8	1.1	1.5	1.7	2.1
Gas engine, duct burner and CAL [m AU$]	0	0	0	0	0	0
Turbine and balance of plant [m AU$]	8.6	8.6	8.6	8.6	8.6	8.6
Total plant investment [m AU$]	**16.8**	**19.4**	**22.2**	**25.0**	**27.6**	**30.4**

Table 11
Capital cost (CAPEX) of hybrid combined cycle (HCC) hybrid concentrated solar biomass (HCSB) plant in million Australian Dollar [m AU$].

	HCC HCSB plant			
Solar field sizing	0 loops	3 loops	4 loops	5 loops
Solar field [m AU$]	0.0	7.6	10.0	12.4
TES [m AU$]	0.0	1.2	1.6	2.8
Gas engine, duct burner and CAL [m AU $]	11.2	11.2	11.2	11.2
Turbine and balance of plant [m AU$]	4.3	4.3	4.3	4.3
Total plant investment [m AU$]	**15.5**	**24.3**	**27.1**	**30.7**

from biomass is generally more cost effective than from CSP [87]. Economic feasibility is impacted by heat demand and/or the availability of grid connection. The economic results indicate that the proposed HCC HCSB system would be most attractive for the case where there is high heat demand or very costly grid electricity purchase.

For both HCSB plant design options, 100% of the thermal energy demand of the abattoir can be supplied. For both design options a fraction of the original electricity demand still needs to be purchased from the grid. In Table 12 and Table 13 the annual electricity purchase costs for the ORC HCSB plant and the HCC HCSB plant are compared. For the different design options the electricity purchase costs vary between AU$ 0.8–1.9 million. The biomass costs range between AU$ 631,918–754,994 year for both HCSB design options. During some of the operating hours the HCSB plant produces less electricity than needed for the abattoir, while in other periods more electricity is generated than needed. For the ORC HCSB plant this excess electricity ranges between 2,805–7,022 MWh_{el} per year, while for the HCC HCSB plant it ranges between 7,935–9,605 MWh_{el} per year. We have considered three key options on how to use the excess electricity:

i) The abattoir could analyse their hourly electricity demand and fulfil load shifting, in which operations with high electricity demand are shifted into hours in which the HCSB plant is generating electricity.

ii) The excess electricity can be sold with power purchase agreements to the electricity network or another local industry or consumer. The

Table 12
Economic performance of the organic Rankine cycle (ORC) hybrid concentrated solar biomass (HCSB) design option 1, comparing annual electricity costs in million Australian Dollar [m AU$], and costs of energy generation [AU$/MWh].

	ORC HCSB plant					
Solar field sizing	3 loops	4 loops	5 loops	6 loops	7 loops	8 loops
Annual electricity costs [AU$/yr]	1,908,050	1,758,990	1,636,132	1,537,450	1,461,307	1,376,317
LCoE [AU$/$MWh_{el}$]	332.1	285.3	265.7	255.9	251.5	246.1
LCoH [AU$/$MWh_{th}$]	47.5	52.8	59.7	65.9	71.7	78.0
Excess electricity per year [MWh_{el}/yr]	2,805	3,776	4,621	5,444	6,177	7,022
Biomass costs [AU$/yr]	631,918	660,340	684,258	707,013	727,471	751,581

Table 13
Economic performance of the hybrid combined cycle (HCC) hybrid concentrated solar biomass (HCSB) plant, comparing annual electricity costs in million Australian Dollar [m AU$], and costs of energy generation [AU$/MWh].

	HCC HCSB plant			
Solar field sizing	0 loops	3 loops	4 loops	5 loops
Annual electricity costs [AU $/yr]	1,319,709	988,945.7	894,927	819,696
LCoE [AU$/$MWh_{el}$]	133.9	151.7	161.6	163.5
LCoH [AU$/$MWh_{th}$]	48.9	66.0	74.3	78.7
Excess electricity per year [MWh_{el}/yr]	7,935	8,699	9,137	9,605
Biomass costs [AU$/yr]	836,114	785,635	770,094	754,994

electricity spot prices in the Australian electricity market vary for different hours of the year and costs can exceed 200 AU$/$MWh_{el}$ [36]. Especially during evening hours, the HCSB plant can provide electricity at lower costs than the electricity grid.

iii) The abattoir could add another electrical machine into their operation, which could use the electricity in hours with less demand for the abattoir (e.g., during weekends). One interesting option is a biomass briquetting machine. Raw biomass feedstock, grown on the abattoir land could be harvested, dried, and pressed into briquettes, which are then sold as energy product or used for combustion in the biomass boiler.

4. Conclusion

This study presents the techno-economic performance of two hybrid concentrated solar biomass (HCSB) design options for cogeneration in a major beef abattoir in Australia. The organic Rankine cycle (ORC) HCSB design option considered a solar thermal ORC system integrated to the plant steam cycle, which is fed by the existing biomass boiler. The hybrid combined cycle (HCC) HCSB design option examined the use of a biogas engine integrated with a solar thermal system and the existing biomass boiler. The results of this study can be concluded as follows:

The hybridization and integration of several renewable technologies (such as solar thermal or bioenergy) into thermal energy supply systems of abattoirs offers an option for renewable cogeneration. The ORC HCSB system is attractive because of its relatively easy integration. The technical concept is applicable to other abattoirs that already deploy combustion boilers. The HCC HCSB system is more cost-effective than the ORC HCSB system and the levelised cost of energy (LCoE) can be decreased. By incorporating this technology in all beef abattoirs in New South Wales, up to 1.3 $MtCO_{2-e}$ could be avoided per year.

The techno-economic analysis shows that HCSB solutions are currently unlikely to be cost-competitive compared to other energy sources. Greater value for the HCSB plants can be achieved if incentives recognise the advantages of i) low temperature heat recovery for industrial cogeneration in the context of energy efficiency ambitions, ii) energy self-sufficiency of abattoirs, and iii) carbon abatement.

Future work can include detailed off-design analysis of the two HCSB systems as well as detailed modelling for thermal energy demand variations of abattoirs.

Data availability

- Solar resources data needs to be purchased from the *Bureau of Meteorology*: https://www.bom.gov.au/climate/how/newproducts/IDCJAD0111.shtml
- SAM is a openly available thermodynamic modelling software that can be downloaded here: https://sam.nrel.gov/
- Biomass data is available from the *Department of Primary Industries* for SA 2 regions in NSW, for detailed data at spatial scale of 25qm (used in this study), data can be requested from the corresponding author of this paper.
- The power cycle was modelled using the open access software *CoolProp* [50], which can be downloaded here: https://www.coolprop.org/index.html.

CRediT authorship contribution statement

Ella Middelhoff: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Leandro Andrade Furtado:** Methodology, Software, Investigation, Visualization, Writing – review & editing. **José Alberto Reis Parise:** Validation, Writing – review & editing. **Fabiano Ximenes:** Writing – review & editing. **Nick Florin:** Writing – review & editing.

Declaration of Competing Interest

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

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8.A.5. List of bioenergy projects with temperature and scale range

Electricity generation	Project name	Size [MW_e]	Temperature [°C]	Technology description	Source
Rankine cycle	Plane Creek Mill	14	n.a.	Bagasse combustion	[173]
Rankine cycle	Proserpine Sugar Mill	17	n.a.	Bagasse combustion	[173]
Rankine cycle	Racecourse	48.5	n.a.	Bagasse combustion	[173]
Rankine cycle	Bingera Sugar Mill	5	n.a.	Bagasse combustion	[173]
Rankine cycle	South Johnstone Sugar Mill	20	n.a.	Bagasse combustion	[173]
ORC	Turboden standard unit - CHP	0.33 - 10	310 - 315	Different kinds of biomass	[174]
ORC	Turboden standard unit - power	0.77 - 16.7	310 - 315	Different kinds of biomass	[174]
ORC	Brønderslev	16.5	312	Woodchip combustion	[11]
Co-firing	Liddell co-firing	5	n.a.	Sawmill waste combustion	[64]
Co-firing	Wallerawang co-firing	n.a.	n.a.	Wood waste combustion	[64]
Co-firing	Mount piper co-firing	5	n.a.	Wood waste combustion	[64]
Co-firing	Muja co-firing	5	n.a.	Wood waste combustion	[64]
Gas turbine	Varnarno, Sweden	6	~800	IGCC of wood chips	[175]
Gas turbine	Energy Farm (Bioelectrica), Italy	10.9	n.a.	IGCC	[175]
Gas turbine	Eggborough, UK	8	n.a.	IGCC of short-rotation crops	[175]

Electricity generation	Project name	Size [MW_e]	Temperature [°C]	Technology description	Source
Micro-gas turbine	Cressnock Waste Water Treatment cogeneration	n.a.	n.a.	Capstone microturbine biogas digester	[176]
Micro-gas turbine	Swineline Farm, South Africa	0.065	n.a.	Capstone microturbine biogas digester	[177]
Gas engine	Reedy Creek Landfill Gas	0.5	n.a.	Landfill anaerobic digestion	[176]
Gas engine	Remount Landfill Gas	1.1	n.a.	Landfill anaerobic digestion	[176]
Gas engine	Rochedale Landfill Gas	3.3	n.a.	Landfill anaerobic digestion	[176]
Gas engine	Bondi waste water treatment	1.5	n.a.	Waste water anaerobic digestion	[176]
Gas engine	Cronulla waste water treatment	0.8	n.a.	Waste water anaerobic digestion	[176]

8.A.6. List of CSP projects with temperature and scale range

Electricity generation	Project name	Size [MW$_e$]	Temperature [°C]	Technology description	Source
Rankine cycle	SEGS V	30	349	Trough with thermal oil	[178]
Rankine cycle	Andasol I	50	393	Trough with thermal oil	[178]
Rankine cycle	Shams I	100	400	Trough with thermal oil	[178]
Rankine cycle	Crescent dunes	110	565	Tower with molten salts	[178]
Rankine cycle	Aurora Solar Energy Project	135	n.a.	Trough with molten salts	[178]
ORC	eCare Solar Thermal	1	280	Trough with thermal oil	
ORC	IRESEN CSP pilot	1	300	Fresnel with thermal oil	
ORC	Saguaro power	1	300	Trough with thermal oil	
ORC	Stillwater GeoSolar Hybrid	2	n.a.	Trough with thermal oil	
ORC	Brønderslev	16.5	312	Trough with thermal oil	
Co-firing	Liddell solar boost	3	270	Fresnel with direct steam generation	[103]
Co-firing	Kogan creek solar boost	44	270	Fresnel with direct steam generation	[95]
Co-firing	Colorado integrated solar project	2	300	Trough with thermal oil	[95]
Co-firing	Escalante Station	36	393	Trough with thermal oil	[95]
Co-firing	Wilson Sundt solar boost	5	400	Trough with thermal oil	[95]
Gas turbine	Solgate	0.25	800	Tower with solar gas turbine	[98]
Gas turbine	Solugas	0.2	800	Tower with solar gas turbine	[105]

Electricity generation	Project name	Size [MW_e]	Temperature [°C]	Technology description	Source
Micro-gas turbine	AORA Tulip	0.1	1,000	Tower with solar micro-gas turbine	[46]
Combined cycle	Martin next generation soar energy center	75	n.a.	Trough with thermal oil	
Combined cycle	Ain Beni Mathar	20	393	Trough with thermal oil	
Combined cycle	Hassi R'mel	20	393	Trough with thermal oil	
Combined cycle	Dadri	14	250	Fresnel with direct steam generation	
Combined cycle	Duba 1	43	n.a.	Trough with thermal oil	