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

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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.

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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).

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[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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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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II. **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, doi: https://doi.org/10.1016/j.apenergy.2021.117942.
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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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Related publications developed but not included in the thesis:

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ABBREVIATIONS

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