ENERGY TRANSITION

Renewable Process Heat:

A practical guide for the pulp, paper, tissue and packaging industry

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Northmore Gordon

Renewable Process Heat: A practical guide for the pulp, paper, tissue and packaging industry

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The study was conducted by Northmore Gordon Pty Ltd.

The Industry Briefing (pages 4 to 8) was prepared by Appita and presents Appita's interpretation of the study. The technical report (Sections 1 to 6) is the work of Northmore Gordon.

DISCLAIMER

This report provides general information to help organisations in the pulp, paper, tissue and packaging industry plan a pathway to renewable process heat. It is not advice for any particular site or investment. The case studies are high-level assessments based on adapted and anonymised data, and the costs, savings and returns shown depend on the stated assumptions. Readers should obtain independent professional advice before making decisions. To the extent permitted by law, Appita, Northmore Gordon and the report's funders accept no liability for any loss arising from use of, or reliance on, this report.

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Renewable Process Heat

Opportunities and pathways for the pulp, paper, tissue and packaging industry

Prepared by Appita. This briefing is Appita's interpretation of the study conducted by Northmore Gordon. The findings, figures and technical conclusions it draws on are taken from Northmore Gordon's technical report, which follows as Sections 1 to 6.

The industry opportunity

The most important finding of the study is also the most practical: reducing heat demand and recovering heat that is currently wasted is nearly always the most cost-effective first step towards renewable process heat. Every lasting reduction in heat demand also reduces the size, and therefore the capital cost, of whatever renewable heat source a site eventually installs. Decarbonising process heat is therefore not simply a matter of replacing gas-fired boilers with electric equipment.

Most pulp and paper processes reject large quantities of heat that could be recovered, and even in a box plant most of the heat from steam ends up in the air around the corrugator. Recovering waste heat can reduce the need for fuel-fired steam and associated Scope 1 emissions, although the overall financial and emissions benefits will depend on the technology used and the site's energy supply.

Options for producing process heat without carbon emissions are limited, and a technology being available is not the same as it being financially justified. Electric boilers can directly replace gas-fired boilers, but their operating costs and electricity infrastructure requirements can make them difficult to justify economically. Other technologies offer opportunities depending on site conditions, available waste heat and energy costs.

Because operating hours, heat demand variability, waste heat availability, plant layout, energy costs and access to capital differ from site to site, the right combination of measures will differ too. Most sites are likely to use several technologies and energy sources, introduced in stages.

> "Any improvement made and maintained in plant efficiency reduces the capital cost of alternative process heat options."
>
> Technical report, Section 3.2

The following pages set out Appita's interpretation of what these findings mean for operating businesses. The detailed analysis, assumptions and figures are in Northmore Gordon's technical report in Part 2.

ABOUT THE STUDY

Commissioned by Appita with funding from the Australian Industry Renewable Heat Accelerator, this study was prepared by Northmore Gordon to identify practical pathways for reducing emissions from process heat across the pulp, paper, tissue and packaging industry.

The research was informed by industry engagement, including a webinar and workshop held in February and March 2026.

COMMERCIAL ASSUMPTIONS

Gas cost	**$16.00 /GJ**
Electricity cost	**$150.00 /MWh**
CPI	**3%**
NPV discount rate	**7%**
LGC price	**$6.00 /MWh**

Case Study 3 uses actual 2025 spot market prices instead of the electricity cost above.

Understanding the options

The technologies assessed do different jobs and are best compared within those roles. Some recover heat the site already produces and return it at a useful temperature; some replace fuel-fired heat generation with electricity; others replace natural gas with a renewable fuel or gas. Suitability depends on the temperatures of the available heat sources and of the process, the size and pattern of heat demand, electricity tariffs and connection capacity, and the capital required.

For electrically driven options, the coefficient of performance (COP), the ratio of heat delivered to electricity consumed, is a dominant economic driver; all COPs in the report include auxiliary electricity consumption. COP does not apply to fuel-based options, where fuel supply, fuel cost and infrastructure decide the economics.

Technology Typical use	**COP**	**Main constraints**	**Availability**
1 Recovering heat already on site			
Heat pumps Waste heat to drying air, process water and LP steam	4–6 for lifts below 50°C; 2–4 at medium to high temperature	Needs suitable waste heat; electricity demand relatively low only where a high COP is achievable; demand charges	Ready-for-market; Stirling-cycle units still being commercialised
Mechanical vapour recompression (MVR) Boosting low-pressure vapour or flash steam; black liquor evaporation	Slightly below 1 for simple boosting; higher with waste heat recovery (12 in Case Study 2)	Limited lift per compressor; maximum COP 2.0 with a heat pump from dryer exhaust to 150°C steam	In use in black liquor concentrating; TRL 9 system in Case Study 2
2 Electrifying heat generation			
Electric thermal energy storage (eTES) Steam from heat stored when electricity is cheap	1 (storage round-trip efficiency about 98%)	High capital cost; tariff structure critical; usually needs substantial extra supply capacity	Readily available, high reported reliability; offered as heat as a service
Electric boilers Direct replacement for gas-fired boilers	Below 1	Operating cost well above gas on standard tariffs; supply upgrades add capital cost	Mature; better with behind-the-meter renewables, BESS or flexible tariffs
Direct electric heating Corrugator hot beds	Below 1	High operating cost compared with gas-fired steam	Hot beds now; drying cans need complete redesign
3 Renewable fuels and gases (COP not applicable)			
Biomass Large, continuous high-pressure steam loads	n/a	High capital cost; fuel handling; different boiler technology; certainty of fuel supply	Mature; widely deployed internationally
Biogas and biomethane On-site biogas in existing gas plant; network biomethane with no process change	n/a	Biogas needs feedstock; biomethane likely to cost more than gas and a limited resource	Biogas where feedstock exists; biomethane emerging, with limited availability and supply
Hydrogen Not considered useful for this sector	n/a	NOx; suitable burners not readily available; always dearer per unit of energy than electricity	Not assessed further

Source: Section 2 and Table 1 of the technical report.

Where the economics are strongest

Heat recovery options perform best where a substantial waste heat stream is available at a relatively high temperature, because a smaller temperature lift gives a higher COP. Options with a COP of 1 or below generally depend on low-cost electricity, favourable tariffs, behind-the-meter renewables or storage to compete with gas. Most electrified options also need additional electricity supply capacity, which can add materially to capital cost and approval lead times.

What the case studies tell us

The three case studies are modelled, high-level assessments of different technologies on different heat sources, built from adapted and anonymised member data. They indicate what is feasible and provide a basis for site-specific feasibility work; they are not investment forecasts or competing choices. Case Studies 1 and 2 use the study's standard energy prices, while Case Study 3 uses actual 2025 NSW spot prices with a network storage tariff.

MODELLED RESULTS	CASE STUDY 1 Heat pump, exhaust at 85°C	CASE STUDY 1 Heat pump, exhaust at 75°C	CASE STUDY 2 MVR on black liquor	CASE STUDY 3 Electric thermal storage
System	1.8 MW heat pump	2.0 MW heat pump	Waste heat steam generator with MVR	90 MWh storage, 60 MW charge rate
Capital cost	$4.42 million	$4.61 million	$5.92 million	$39.0 million
Annual saving	$1.23 million	$0.91 million	$4.76 million	$6.91 million opex reduction
Simple payback	**3.6 years**	**5.0 years**	**1.2 years**	**5.64 years**
Payback with certificates	1.6 years VEECs	3.3 years VEECs	1.1 years ACCUs	–
NPV (10 years)	$5.00 million	$3.21 million	$30.8 million	$16.2 million $65.7 million over 25 years

Results rounded from Tables 2–5; exact values in Part 2. Gas $16.00/GJ; electricity $150/MWh for Case Studies 1 and 2; Case Study 3 uses 2025 spot prices and a storage tariff, giving an effective price paid of $17/MWh. NPV at CPI 3% and a 7% discount rate. Certificate revenue is based on current scheme rules and pricing; VEECs apply only to Victorian sites participating in the VEU. Each business case includes a line item for LGCs for renewable electricity.

CASE STUDY 1

Exhaust temperature sets the return

Recovering heat from one dryer exhaust tower was modelled for a machine with no existing heat recovery. The 10°C difference between the scenarios matters: a hotter exhaust means a smaller temperature lift, a higher COP and lower electricity cost, shortening payback from 5.0 to 3.6 years. Where direct heat recovery is already installed, a smaller heat pump with a less attractive payback would apply, and the load of about 2,000 kW is likely to need a new transformer and MCC.

CASE STUDY 2

A favourable heat source, not a typical result

The 1.2-year payback reflects an unusually favourable heat source: about 9 MW rejected from black liquor at 130°C, hotter than typical exit temperatures, giving a COP of 12 because most of the delivered energy comes from recovered heat. It should not be read as typical of MVR projects. Capital cost could vary substantially with site layout, electrical infrastructure and heat source temperature.

CASE STUDY 3

Electricity pricing determines the economics

The result depends on how electricity is bought. Charging only when the spot price was below $60/MWh, with a storage network tariff, gave an effective price of $17/MWh; spot prices vary with location and season, and the system was sized to this site's steam demand profile. The 5.64-year payback is higher than desirable, but with an operating life of 20+ years, NPV is a relevant measure alongside simple payback.

Emissions depend on the electricity supply

Electrification reduces emissions from on-site fuel combustion, but its overall emissions benefit depends on the electricity supply and the accounting method used. Without renewable electricity, additional electricity emissions offset most of the avoided gas emissions in Case Study 1 (net reductions of 1,636 and 246 tCO_2-e a year, against 12,239 tCO_2-e avoided) and exceed them in Case Study 3 (a net figure of −73,467 tCO_2-e a year). Case Study 2, with its high COP, shows a net reduction of 14,367 tCO_2-e a year.

Under the market-based Scope 2 method described in the technical report, qualifying renewable electricity procurement, such as a power purchase agreement or retail supply backed by surrendered LGCs, can support zero-emissions claims for purchased electricity. Electricity procurement therefore needs to be considered as part of the investment decision.

Developing a practical pathway

The study supports a staged approach rather than an immediate, wholesale replacement of existing steam systems. Efficiency and heat recovery come first, later investments build on them, and the plan is reviewed as energy markets, infrastructure and technology change. Planning, including a heat balance and a comparison of options by their ongoing value, also positions a business to use short grant funding windows and certificate revenue.

Near term

Planning
Targets, heat balance, metering and monitoring

Efficiency measures
Minimise heat losses from steam leaks, unrecovered flash steam and inadequate insulation.

Direct heat recovery
For example, hot water from air compressors and lube oil systems

Enhanced heat recovery where viable
For example, HTHP from exhaust to drying air; on-site biogas

Medium term

Partial electrification
HTHP for LP steam from dryer exhaust, COP of 3 or more; HTHP and MVR, COP of around 2; eTES, COP of 1 but lower operating cost than MVR

Corrugators
An eBoiler with BESS may become more viable than eTES

Biogas and biomethane
Supplement biogas with external organic waste; biomethane for some of the heat load

Long term

Full decarbonisation
Higher-temperature enhanced heat recovery (HTHP and MVR); direct heat generation (eTES, eBoiler, IR, radiant heating)

Renewable electricity and/or biomethane or biogas
Possibly a combination of both

The final portion
The most expensive to electrify

Efficiency first underpins every stage. Any improvement made and maintained in plant efficiency reduces the capital cost of alternative process heat options.

Based on Sections 3.2 and 3.3 and Figures 4 to 6 of the technical report.

Why the pathways differ by sector

Figures 4 to 6 of the technical report set out separate pathways for each type of operation, reflecting where each recovers its heat. Paper and tissue mills, with large dryer exhausts, start with heat recovery to hot water and drying air, then move to steam from dryer exhausts using heat pumps and, in the long term, MVR. Pulp mills have hot black liquor streams, making MVR on the evaporators and heat recovery from final black liquor cooling medium-term options. Corrugating operations begin with heat recovery from air compressors, chillers and lube oil, with steam from facer and hot plate hood exhausts in the long term. Network biomethane appears in all three pathways, and eTES in the paper and tissue and corrugating pathways.

Early investments should keep later options open

On a paper machine without heat recovery, using heat from air compressors and lube oil systems for hot water reduces steam demand while leaving dryer exhaust heat available for a future heat pump. Where flash steam heats water, it can be freed up for recovery to LP steam with MVR. The right sequence and timing will differ between facilities.

Turning the findings into action

In Appita's view, the findings point to five steps that mills and packaging plants can take before committing to any particular technology.

1 Establish the baseline

Map where heat is generated, used and lost with a detailed heat balance of the plant. Additional or temporary metering may be required to establish a reliable heat balance and verify the performance of proposed improvements.

2 Identify efficiency and heat recovery opportunities

Address steam leaks, unrecovered flash steam, inadequate insulation and boiler blowdown, and examine often-overlooked heat from lube oil cooling, chillers and air compressors. These measures reduce energy use now and the size of later renewable heat investment.

3 Assess the practical constraints

Compare available waste heat with the temperatures processes need, and check integration with the existing steam system, operational reliability and backup, space, and electricity connection capacity. Additional supply capacity can add materially to capital cost and approval lead times.

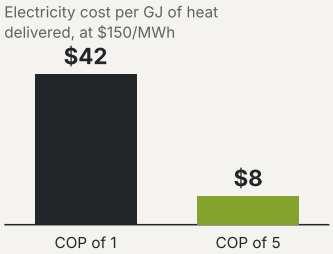
4 Test the business case

Assess capital, savings, operating costs, certificate eligibility and emissions together. For electrified options, electricity prices, tariff structures and technology efficiency can materially influence operating costs and investment returns. Testing these assumptions across a range of scenarios is an important part of feasibility assessment.

5 Develop a staged investment plan

Sequence projects so near-term efficiency and heat recovery support later options, test preferred options through site-specific feasibility studies before major investment, and review the plan as markets and technology change. Offsets are an extra cost and a last resort.

WHY COP MATTERS



Approximate electricity cost per GJ of heat delivered, at an assumed $150/MWh. These figures show the electricity cost component only, not the total cost of delivered process heat.

WHERE TO BEGIN

Three questions for operations and engineering teams:

1. Do we have a current heat balance?
2. Where are our largest waste heat streams, and at what temperature?
3. What electricity capacity and tariff options does the site have?

In the full report

Section 2: technology options
Section 3: planning and sector pathways
Section 4: case studies and Tables 2–5
Section 5: feasibility factors
Appendix 6.1: typical heat sources and sinks
Key Terms and Abbreviations: page 41

PART 2 · TECHNICAL REPORT

Renewable Process Heat: A practical guide for the pulp, paper, tissue and packaging industry

The following technical report was prepared by Northmore Gordon for Appita, with funding from the Australian Industry Renewable Heat Accelerator. It provides the detailed analysis, technology assessments and case studies underpinning the Industry Briefing presented in Part 1.

STUDY CONDUCTED BY

Northmore Gordon

SECTION 1

Introduction and methodology

All industrial facilities are facing pressure to reduce their carbon emissions, eventually to zero. The pulp, paper, tissue and packaging industry in Australasia is no different. Working towards that goal can provide benefits in terms of reduced energy costs, customer engagement and long-term competitiveness in a market that is continuing to increase the perceived value of low emission products.

Appita commissioned this study/ guide with the assistance of the Australian Industry Renewable Heat Accelerator to provide guidance for planning a pathway to renewable process heat for the pulp, paper, tissue and packaging industry.

A webinar was developed and presented in February 2026 by Northmore Gordon covering technologies with the potential to provide or assist renewable process heat development, tailored to the pulp, paper, tissue and packaging industry.

The Appita Annual Conference in March 2026 included a workshop run by Northmore Gordon aimed at gaining industry input and to identify and choose suitable options for 3 high level case studies for analysis as part of the study. Northmore Gordon prepared in advance a list of heat sources and sinks with indicative energy flows and through the course of the workshop this was clarified and expanded. By the end of the workshop, it was clear that 3 options were standouts in terms of impact and potential for real world implementation. The associated technologies were

- High Temperature Heat Pump (Dryer heat recovery)
- Mechanical Vapour Recompression (Black liquor heat recovery)
- Electric Thermal Energy Storage (Electrified steam generation from stored heat)

The case studies were developed using data from member sites to ensure relevance to the local industry but adjusted and adapted to ensure anonymity. Northmore Gordon also used information and experience gathered in prior work with several pulp and paper mills, corrugated packaging plants and other manufacturing facilities facing similar process heat decarbonisation difficulties. Almost all process heat for the pulp, paper, tissue and packaging industry comes from steam generated by burning fuel, mostly natural gas, with some heat recovery. Steam is typically used at 150°C to 180°C saturated.

Reducing heat demand per unit of production through efficiency improvement and recovery is nearly always the most cost-effective first step. Where electric powered options are considered, Coefficient of Performance (COP) is a dominant economic driver: at an assumed electricity cost of $150/MWh, a technology with a COP of 1 costs approximately $42 per GJ of heat delivered, while a heat pump at COP of 5 reduces this to around $8 per GJ. All COPs indicated in this report include auxiliary electricity consumption.

Electrification of process heat can be zero-emissions when the electricity is sourced under credible renewable electricity arrangements — for example, a power purchase agreement (PPA) with a renewable generator, or retail supply backed by surrendered Large-scale Generation Certificates (LGCs) — consistent with the GHG Protocol Scope 2 market-based method. Where no such arrangement is in place, a grid emission factor (or residual mix factor) should be applied.

Site owners seeking the highest-integrity claims may choose to prioritise arrangements that demonstrate additionality that is, procurement that supports new renewable capacity rather than existing assets. This is a quality consideration rather than a threshold requirement and reflects evolving best practice in corporate renewable energy procurement.

There are a limited number of options to produce process heat without carbon emissions. To proceed on the path to renewable process heat and stay competitive requires good planning, starting now if you haven't already. There are no perfect solutions or silver bullets, but with the right mindset, commitment and drive to change, it can be done.

The commercial analysis in the case studies made the following assumptions:

Gas Cost	$16.00 /GJ
Electricity Cost	$150.00 /MWh
CPI	3%
NPV Discount rate	7%
LGC price	$6.00 /MWh

All other assumptions are stated within the relevant text.

SECTION 2

Sector Renewable Process Heat Options

The following technologies are potential candidates for decarbonising high-temperature process heat in pulp, paper, tissue and packaging. The sector's key heat duties include steam generation, heated rolls, drying air, hot water and corrugator hot beds.

2.1 Technologies Summary

Table 1 below summarises all the potential technologies that could be used for renewable process heat.

Table 1 Potential technologies for decarbonising high-temperature process heat in pulp, paper, tissue and cardboard packaging

TECHNOLOGY	USE CASE	PROS/ CONS	ELECTRICITY DEMAND MANAGEMENT OPTIONS
Heat pumps	Heat recovery for hot water or steam	Increased electricity demand. Least increase in electricity consumption	BESS can minimise electricity cost
Mechanical Vapour Recompression (MVR)	Heat recovery for steam (or evaporation in black liquor circuit)	Boosting only Increased electricity demand	BESS can minimise electricity cost
Electric boiler	Steam generation	Increased electricity demand COP 1	BESS can minimise electricity cost Can combine with HTHP/ MVR
Direct electric heating	Hot plates on corrugator	Increased electricity demand COP 1	BESS can minimise electricity cost
Electric thermal energy storage (eTES)	Steam generation	High capex Steam as a service available	Alternative to eBoiler + BESS Minimises electricity cost without BESS
Biomass, biogas and biomethane	Steam Generation	Biomethane not yet available	N/A
Hydrogen	Steam generation	Will always be more expensive than electricity, not yet available at scale.	N/A

2.2 Heat pumps

Heat pumps are the most energy-efficient electric option for low to medium temperature process heat where a suitable waste heat source is available.

For low- to medium-temperature applications with a temperature lift below 50°C, industrial heat pumps typically achieve a COP of 4–6, including auxiliary loads.

Medium to high temperature heat pumps often require a secondary heating fluid loop (typically water or glycol) between the heat pump and the process, which adds complexity and decreases COP, typically between 2-4. Tariff structure, particularly demand charges, can also be a barrier. The choice of refrigerant affects the achievable temperature range, system cost and regulatory requirements.

In pulp, paper and packaging applications, heat pumps are best suited to:

- heating drying air, where a large volume of medium temperature heat is required
- process water heating
- low pressure steam generation.

Stirling engine heat pumps are an emerging alternative that use gas (helium or nitrogen) expansion and contraction rather than a refrigerant cycle. They maintain COP more consistently across a wider operating range than Rankine cycle systems but remain in the commercialisation stage and carry significantly higher capital cost.

See Case Study 1 for an example of using a heat pump to enhance heat recovery in paper mill drying.

International Energy Agency latest review of available HTHP technology including MVR. Includes details of equipment suppliers with ready for market systems and technology readiness levels - https://heatpumpingtechnologies.org/publications/project-68-industrial-high-temperature-heat-pumps-task-1-technologies-2025/

2.3 Mechanical Vapour Recompression (MVR)

MVR uses a centrifugal compressor to raise the pressure and temperature of a low-pressure vapour stream — often from evaporators, or low-pressure or flash steam.

The critical limitation of MVR is its COP. Where there is no waste heat input, such as simple steam pressure boosting, MVR has a COP of slightly below 1. It does, however, avoid the flue gas losses from gas fired heating. This makes it similar in efficiency to an electric boiler. The COP improves when it enables recovery of waste heat streams that cannot otherwise be used. MVR is already used in black liquor concentrating processes, compressing the extracted vapour for use as a heating medium.

The temperature lift per compressor is limited, so often more than 1 compressor is used in series.

MVR may be appropriate in other specific circumstances:

- where a large waste vapour stream exists that cannot be recovered by other means
- In combination with a heat pump to generate medium pressure steam
- Directly using flash steam to generate MP steam

See Case Study 2 for an example of MVR use in enhanced heat recovery, producing steam in a pulp mill. In the example case the ROI is very attractive as the source temperature is high and resulting COP is 12.

Using MVR in combination with a heat pump to produce steam at 150°C from paper mill dryer exhausts results in a maximum COP of 2.0. The low COP makes the ROI unfavourable. It does however reduce the opex by half compared to an electric boiler.

MVR could potentially be valuable for reuse of flash steam. If air compressor and lube oil system heat recovery is used for hot water, it would free up the flash steam currently being used.

On a corrugator, if single facer (warm humid air) and hot plate (warm dry air) sections were enclosed, the heat currently lost could be captured and used to generate LP steam using a heat pump and MVR combination. The LP steam could be used in the hot plate section. Flash steam currently used on the hot plate section could be used to generate MP steam with MVR.

International Energy Agency latest review of available HTHP technology including MVR. Includes details of equipment suppliers with ready for market systems and technology readiness levels - https://heatpumpingtechnologies.org/publications/project-68-industrial-high-temperature-heat-pumps-task-1-technologies-2025/

2.4 Electric boiler (with battery energy storage)

Electric boilers are a direct replacement for gas-fired boilers and carry high technical readiness — they are commercially mature and straightforward to integrate into an existing steam system. Their COP is below 1. Under standard Australian electricity tariffs (high fixed demand charges, peak/off-peak structure), the operating cost of electric boilers is substantially higher than natural gas, making a standalone electric boiler difficult to justify on economic grounds alone.

Economics improve with behind-the-meter (BTM) renewable electricity, or battery energy storage (BESS). BESS allows the boiler to operate more cost effectively during high-cost peak periods.

Shifting load between an electric boiler and existing gas boilers can improve the business case for a partial electrification option.

Load controlled eBoilers can also now access flexible demand tariffs which improve the business case.

Electric boilers typically require additional electricity supply capacity (transformer upgrades, switchboard works), which can add significant capital cost.

2.5 Direct electric heating

Resistive heating elements can deliver heat directly to a process or product, offering good controllability and low maintenance. Electromagnetic heating — microwave, dielectric, infrared, induction and ultraviolet — can deliver energy precisely to the point of need. Each has a COP below 1. A relevant sector application is direct electric heating of corrugator hot beds as a replacement for steam. Direct electric heating of drying cans/ heated rollers may be feasible at some point in the future but would require complete redesign of the cans and electrical systems. The current operating cost of direct electric heating is high compared to gas fired steam.

Economics improve with behind-the-meter (BTM) renewable electricity, or battery energy storage (BESS). BESS allows the electric heating to operate more cost effectively during high-cost peak periods.

Direct electric heating would typically require additional electricity supply capacity (transformer upgrades, switchboard works), which can add significant capital cost.

2.6 Electric thermal energy storage (eTES)

Electric thermal energy storage (eTES) stores electrical energy as heat during periods of high renewables penetration, which result in low electricity prices, and releases it as steam or heated thermal fluid (such as thermal oil) in a steady flow.

The economics of eTES depend on load profile, sizing, and tariff structure. For sites with steady, continuous thermal demand — such as pulp and paper — full displacement of gas can be economic, and international deployments demonstrate this at scale. For sites with peaky or intermittent thermal loads, partial displacement is likely to deliver stronger returns. This is because the ROI reduces when covering the capacity required for peak production periods.

eTES enables integration with renewable electricity generation. Unlike BESS, eTES avoids the round-trip efficiency loss of battery storage for heat applications and can reduce peak demand charges without a separate battery system.

The round-trip efficiency of an eTES module is approximately 98%* as the surface area to volume ratio is low and the insulation reduces losses to a minimum. That excludes the usual losses associated with boiler/ steam generator radiant losses and blowdown of course which exist in both the base case and the eTES case. The eTES avoids the losses experienced through flue gas exhaust in a boiler.

eTES is readily available, and existing installations in Australia and internationally report high reliability. Mars Pet Foods has been operating an eTES in partnership with Graphite Energy in their Wodonga facility for a number of years and report high reliability and simple operation.

The tariff structure is critical to make eTES economic. There is some progress in Australia towards retail tariffs that enable this type of system.

Installing an eTES will normally require a substantial increase in electricity supply capacity. The cost of the increased capacity to a site is usually a material component of the capital cost and requires significant lead time for approvals. If a local network upgrade is required, it can be a significant barrier.

eTES is being offered as “heat as a service”, however it would likely require a long-term contract. If it can be provided economically and with an acceptable contract length, it is potentially a convenient approach to reducing scope 1 carbon emissions.

See Case Study 3: for an example of eTES use for partial replacement of gas boilers.

*(https://rethinkresearch.biz/articles/siemens-tries-to-enter-the-etes-market-amid-round-trip-efficiency-questions/).

2.7 Biomass, biogas and biomethane

Biomass combustion is commercially mature for continuous industrial process heat and is widely deployed in the global pulp and paper industry, particularly for high-pressure steam generation. It is well matched to the sector's large, continuous heat loads. The primary constraints are high capital cost and significant site impacts: dedicated fuel storage, mechanical handling infrastructure and a fundamentally different boiler technology compared with gas-fired plant. Maintaining certainty of fuel supply is also a barrier.

Biogas from an on-site waste stream fed to a digester is an attractive option where feedstock is available, as it uses existing gas infrastructure with some modification. If the gas is cleaned of sulphur and the CO_2 inherent in biogas is removed, existing boiler infrastructure can be used. Increased biogas production is possible if there are local sources of suitable organic waste.

Biomethane delivered via the gas network is an emerging option that would require no process changes, though current market indications suggest it will be priced higher than natural gas. The other consideration for biomethane is that it is a limited resource, and the more reliance there is on it for process heat, the more expensive it will become.

2.8 Hydrogen

Green hydrogen can substitute for natural gas in boilers or furnaces, but its very high flame temperature creates NOx emissions challenges that require burner redesign and/or flue gas treatment. Burners for this purpose are not readily available.

Using hydrogen to generate electricity in a fuel cell and then using that electricity for heat is always more expensive than storage and use of renewable electricity.

Regardless of the conversion pathway, renewable hydrogen will carry a higher cost per unit of delivered heat than direct use of renewable electricity or other renewable gases. In the context of this study, hydrogen was not considered to be a useful technology for this sector and is not assessed further.

It may be possible in the future that hydrogen becomes more economical, however the physics involved mean it will always be more expensive per unit of energy than electricity.

SECTION 3

Pathway to renewable process heat

The diagram below outlines the only existing options for pathways to renewable process heat (zero Scope 1 emissions) for process heat in the pulp, paper, tissue and packaging industry. Something to keep in mind is that the solution is likely to include multiple technologies and energy sources. The days of relying on a single technology (fuel fired steam boilers) for process heat are disappearing, unless you have a guaranteed source of biomass for all your process heat needs which is not the case for most sites.

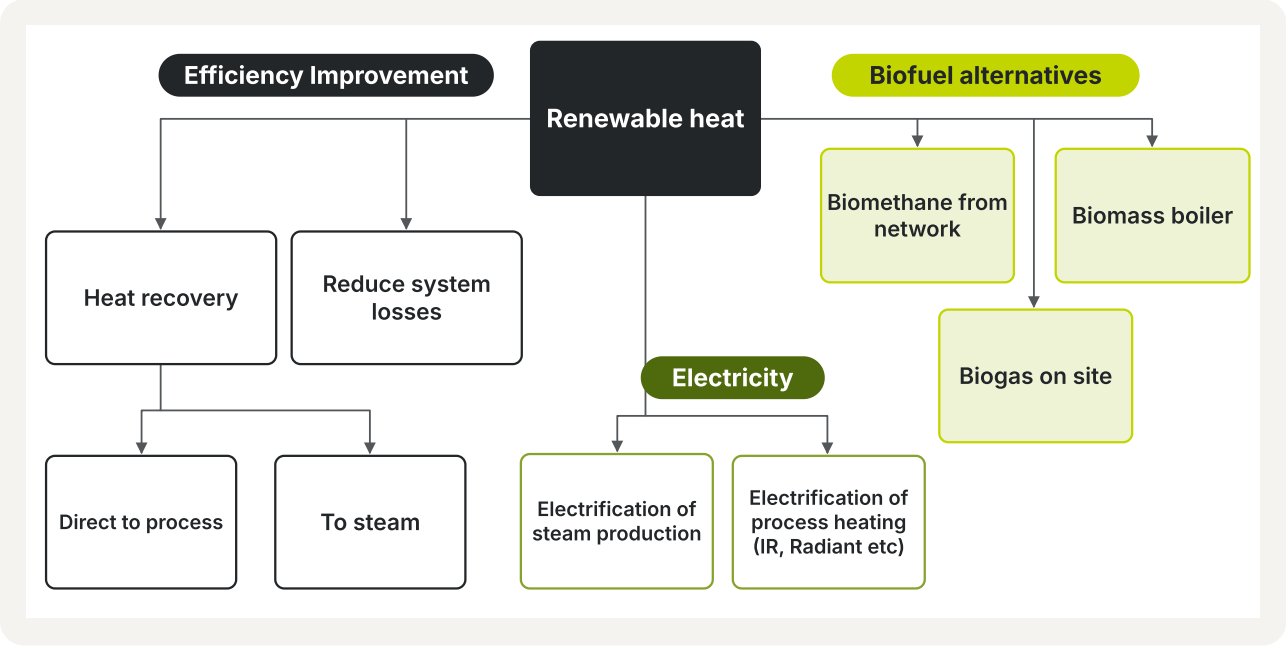


Figure 1 Pathways to renewable process heat in pulp, paper, tissue and cardboard packaging industry

Aiming directly for replacement of process heat using electricity, alternative fuels or enhanced heat recovery without considering process efficiency is a simple approach. Our experience with the industry sector has shown us that there are significant gains to be made by improving process efficiency first. This approach is almost always lower cost and better ROI than alternative heat sources. The improved heat efficiency then reduces the size of the investment needed to provide renewable process heat.

Importantly, there are large quantities of waste heat available for recovery in most pulp and paper industry processes.

Even in a box plant, most of the heat from steam goes into the air around the corrugator machine, so there is potential to capture the heat for recovery.

3.1 Planning is Key

Planning is essential to achieve the most cost-effective path to emission reduction. Planning also enables better use of grant funding and certificate revenue. Government funding windows can be short and having a plan allows the business to take advantage of them more easily.

For process heating, there are numerous options and the best combination will vary from site to site.

Influencing factors include:

- Targeted timeframes for emission reductions, including those driven by regulation
- Plant operating hours
- Heat demand variability
- Waste heat availability
- Design and physical layout of the plant
- Fuel and electricity costs and tariff structures
- Capital availability

Prepare a heat balance for the plant, to ensure you have clear information about potential heat sources and heat demands. A Sankey diagram can be useful for this depending on the complexity. To do this well, you might need to consider additional process and energy measurements, or installing temporary measuring devices to gather the required information.

A plan can include use of offsets to fill the gap, however they are simply an extra cost, so should be a last resort.

A valuable tool for assessing decarbonisation options in a financial sense is to use a Marginal Abatement Cost Curve (MACC). It enables comparison of capital and non-capital options in terms of the ongoing value to a business. The example below was developed for a business with several manufacturing sites. The width of each section shows the tonnes of carbon abatement for that option. The vertical axis shows the cost per tonne of abatement for that option. A MACC generally includes emissions from electricity, however it can be narrowed to focus on process heating.

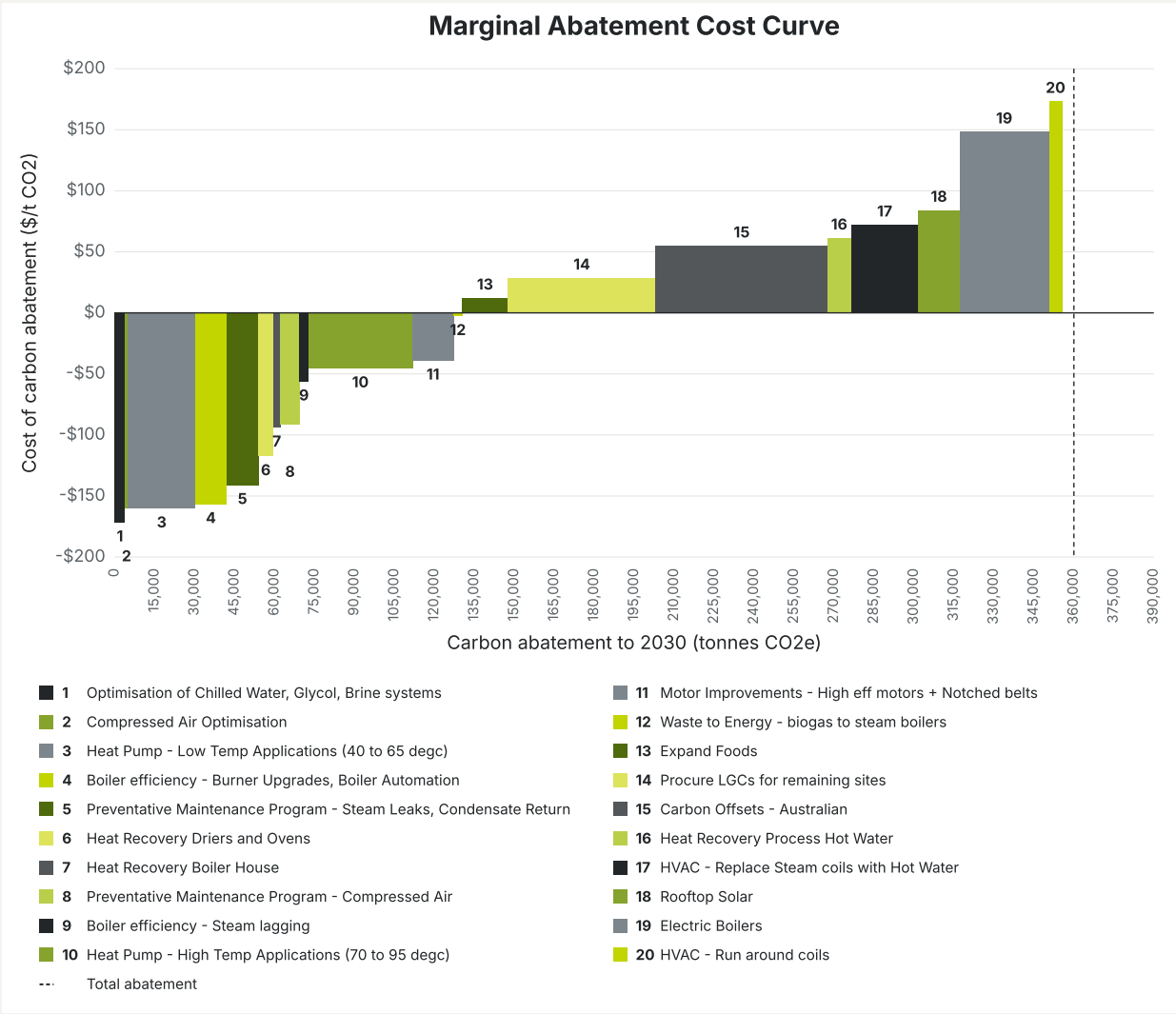


Figure 2 Marginal Abatement Cost Curve for different renewable process heat options

Some option names have been abbreviated to prevent identification of the business (for example, item 13).

A plan can consider several scenarios with different combinations of options. The example below includes all energy use rather than just process heat but provides a picture of what different scenarios might look like. Scenarios can be across a business or site specific.

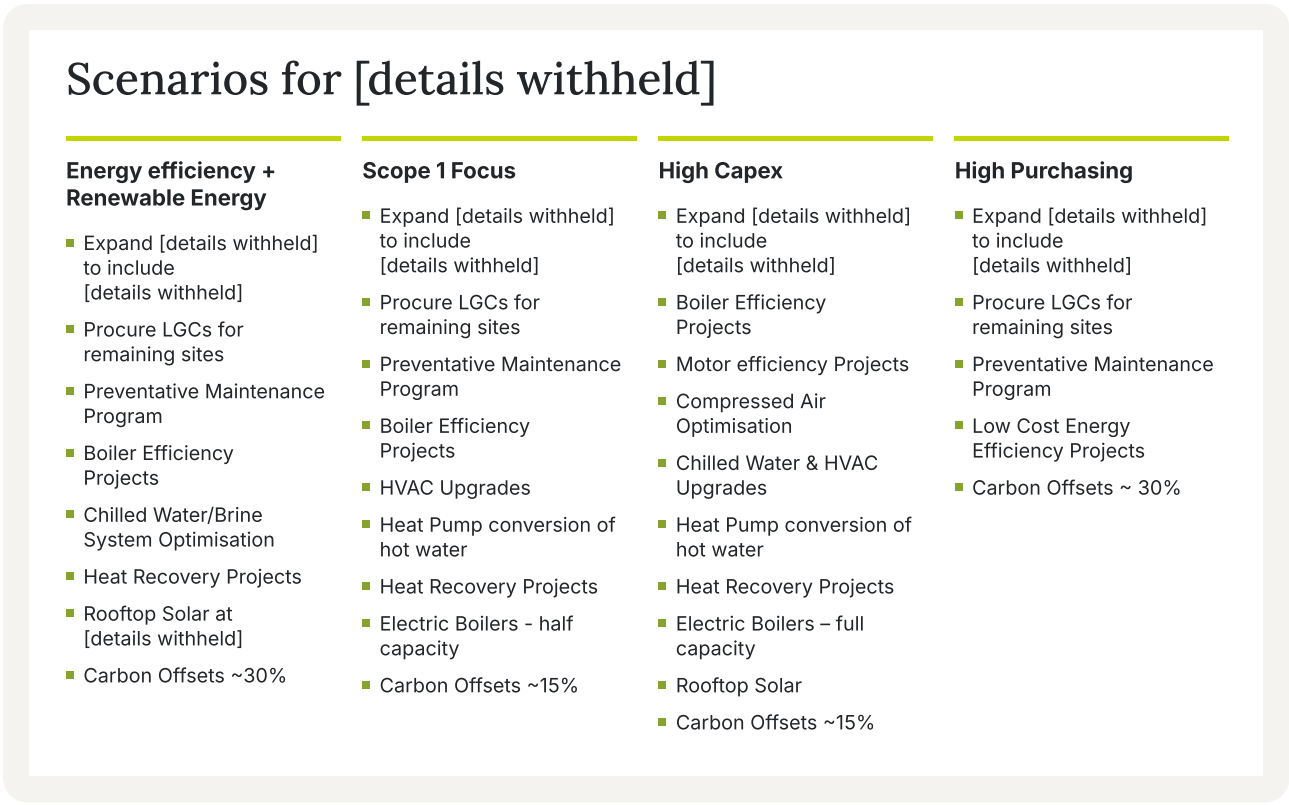


Figure 3 Examples of planning scenarios for different renewable process heat pathways

Certain details have been withheld to protect the identity of the business used in this example.

3.2 Efficiency first

Reducing the heat demand per unit of production is nearly always the most cost-effective way to reduce the carbon emissions of process heat. Combining efficiency improvements with other upgrade projects can improve the business case.

Key efficiency improvements for process heat include:

- Minimise heat losses, e.g. steam leaks, flash steam or insulation
- Maximise heat recovery in boiler systems, e.g. blowdown and flash steam heat recovery
- Maximise use of biogas as a heating fuel rather than generating electricity or flaring
- Maximise heat recovery in processes.

  An often overlooked source of waste heat paper machine lube oil cooling, chillers and air compressors. Although they are small relative to the dryer exhausts, they are still significant and can provide an alternative to using flash steam or dryer exhaust for hot water production. Capturing the heat from these systems is relatively simple to implement. The heat can be captured using either direct heat exchange or a low lift heat pump, freeing up drying air exhaust and or flash steam allowing more efficient heat recovery from drying air to produce steam or flash steam for heat pump/ MVR boosting to LP or MP steam. The capital invested in the first step would reduce the capital cost of the second if full electrification is the eventual aim.

In our experience with the pulp and paper industry, there are usually worthwhile opportunities to improve the performance of boilers and steam systems.

It is theoretically possible to completely decarbonise a paper mill using a combination of direct heat recovery, and heat pumps and MVR, as they put in a proportion of additional energy, making up for steam system losses. The challenge is in making the business case work.

On site biogas, if an option, reduces the size of the remaining task.

To improve the return on investment, there are options to consider, including government grants for project development and capital, and Environmental Attribute Certificates which provide a revenue source after project completion (VEECs, ESC, ACCUs). Note that these are market mechanisms that do vary in value and can be influenced by changes in legislation.

Any improvement made and maintained in plant efficiency reduces the capital cost of alternative process heat options.

3.3 What should I do and when?

The following guidance on timing and sector relevance of emission reduction options considers the realities of implementing emission reduction over time, such as

- capital planning and availability,
- current technology availability and development,
- political drivers,
- expectations of continued change from markets etc.
- Industry expectations on ROI

The overall picture for pulp and paper is similar to other industries with steam as the primary source of process heat.

The guidance is Northmore Gordon's view based on extensive cross industry experience and strategic discussions within manufacturing industries and technology providers. Discussion with APPITA members at the 2026 conference was also considered.

3.3.1 Planning

What are your short-, medium- and long-term decarbonisation targets and how are you going to achieve them? Planning, in particular increasing heat recovery over time, will be essential to enabling the most beneficial approach. Developing a MACC provides a clear guide for use in planning. Apart from "no-brainer" opportunities, planning should be the first step.

To ensure the plan is implemented, it needs to be incorporated into day-to-day business management processes, not operated as a "silo". This may mean changing the wording in some role descriptions and performance measures, both at corporate and site level. There are guides to developing and implementing emission reduction plans readily available. See Appendix 6.2.

The plan might identify that you need to implement or improve metering and monitoring systems to enable effective assessment of potential efficiency or electrification projects and to verify the performance before and after.

3.3.2 Near term

Implement opportunities such as:

- Efficiency measures
- Direct heat recovery
- Enhanced heat recovery where viable. E.g. HTHP from exhaust to drying air.
- On site biogas, if an option, also reduces the size of the remaining task.

Ensure any heat recovery implemented is compatible with and supports longer term decarbonisation options. For example, on a paper machine with no existing heat recovery, using heat rejection from air compressors and machine lube oil systems for hot water generation reduces steam demand without reducing dryer exhaust waste heat availability for future waste heat to steam projects. If flash steam is used to generate hot water, it could similarly be freed up for recovery to LP steam using MVR.

3.3.3 Medium term

As markets and technology change, the lowest cost path to reducing emissions (the MACC curve) may vary from your initial plan. Reviewing plans periodically will enable adjustments to ensure good long-term decision making.

Options to consider:

- Partial electrification using enhanced heat recovery (HTHP) to produce steam from dryer exhaust (or corrugator enclosed single facers/ hot plates). COP of 3 or more but limited in scale as it will only produce LP steam (120°C) for preheating drying air. This option is compatible with expansion to using MVR to produce MP steam. See Case Study 1 for an example of using a heat pump to enhance heat recovery in paper mill drying.
- Partial electrification using higher temperature enhanced heat recovery (HTHP and MVR) to produce steam from dryer exhaust (or corrugator enclosed single facers/ hot plates). COP of around 2, but expensive to run during peak times. See Case Study 2 for an example of MVR use for enhanced heat recovery, producing steam in a pulp mill
- Partial electrification through eTES to produce steam. COP of 1 but lower operating cost than MVR. This option may be useful in combination with enhanced heat recovery for corrugators. See Case Study 3 for an example of eTES use for partial replacement of gas boilers.
- For corrugators, battery electric storage development may mean an eBoiler with BESS may be more viable than eTES in the future. eTES tends to be more economic for larger, less peaky steam demands.
- Supplement biogas generation to full capacity with external organic waste.
- Biomethane purchase for some of the heat load to meet decarbonisation targets if other options won't get you there.

3.3.4 Long Term

There are two realistic options for fully decarbonising for most sites; electrification using renewable electricity and/ or biomethane/ biogas. It may in the end be a combination of both. The final portion of process heat electrification becomes the most expensive. That

portion is variable and providing the heat with renewable electricity has the lowest COP, meaning both capex and opex are higher per unit of heat. Biomethane on the other hand is zero capex but higher opex.

Full decarbonisation options:

- higher temperature enhanced heat recovery (HTHP and MVR)
- direct heat generation (eTES, eBoiler, IR, radiant heating)
- Biomethane
- Increase biogas generation to full capacity with external organic waste.

In the long term it may be possible that eTES becomes more cost effective. As it is existing technology repurposed, it is not expected to develop rapidly and reduce in cost like solar photovoltaics or batteries have in recent decades.

A combination of a smaller eTES and maximising heat recovery using HTHP and MVR may enable a solution with optimised ROI by taking advantage of the strengths of each technology.

Biomethane is a simple, low capital option. The cost of biomethane in the long term is uncertain, but likely to be higher than current natural gas fuel cost.

The capital cost of achieving zero carbon emissions will be lower in the long term if processes are optimised for minimum energy use.

3.3.5 Sector Pathways

The following diagrams show the likely options for industry categories.

Figure 4 Paper/ Tissue Mills,

Figure 5 Pulp Mills

Figure 6 Corrugators.

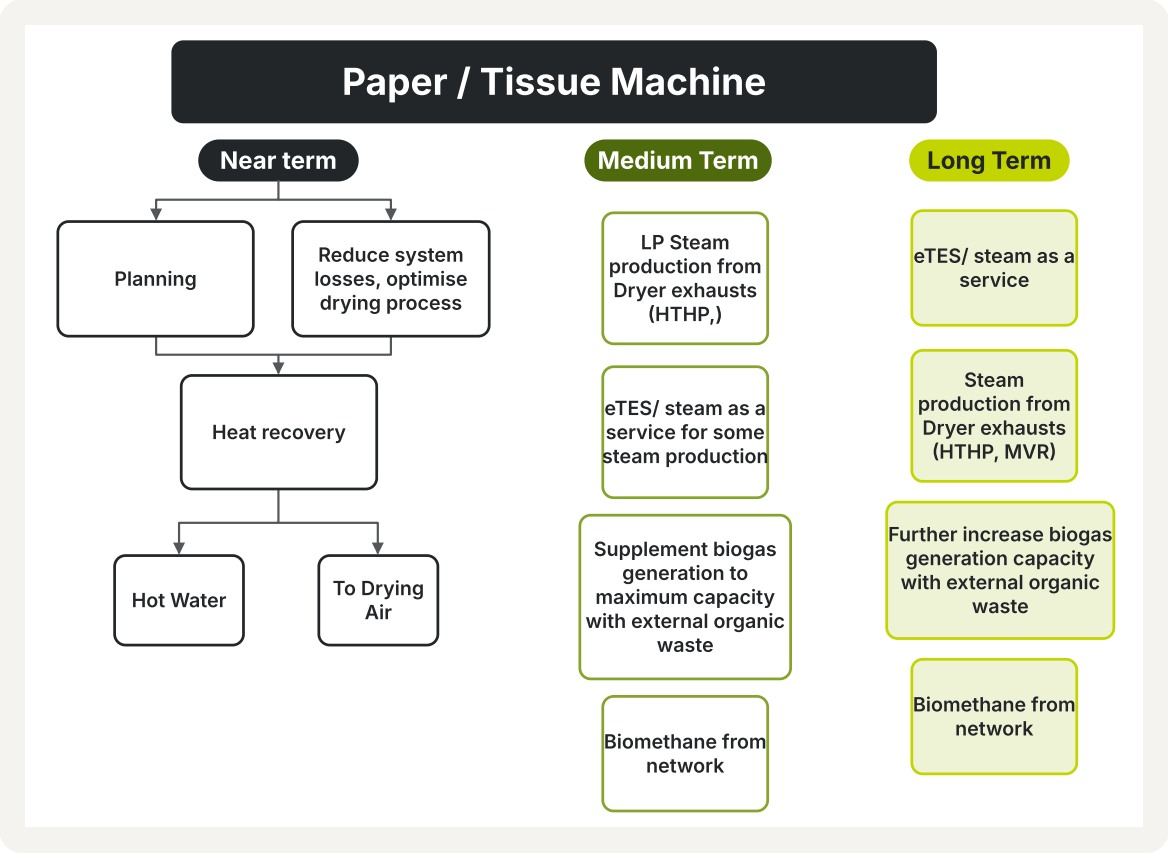


Figure 4 Pathway options for Paper/ Tissue Mills.

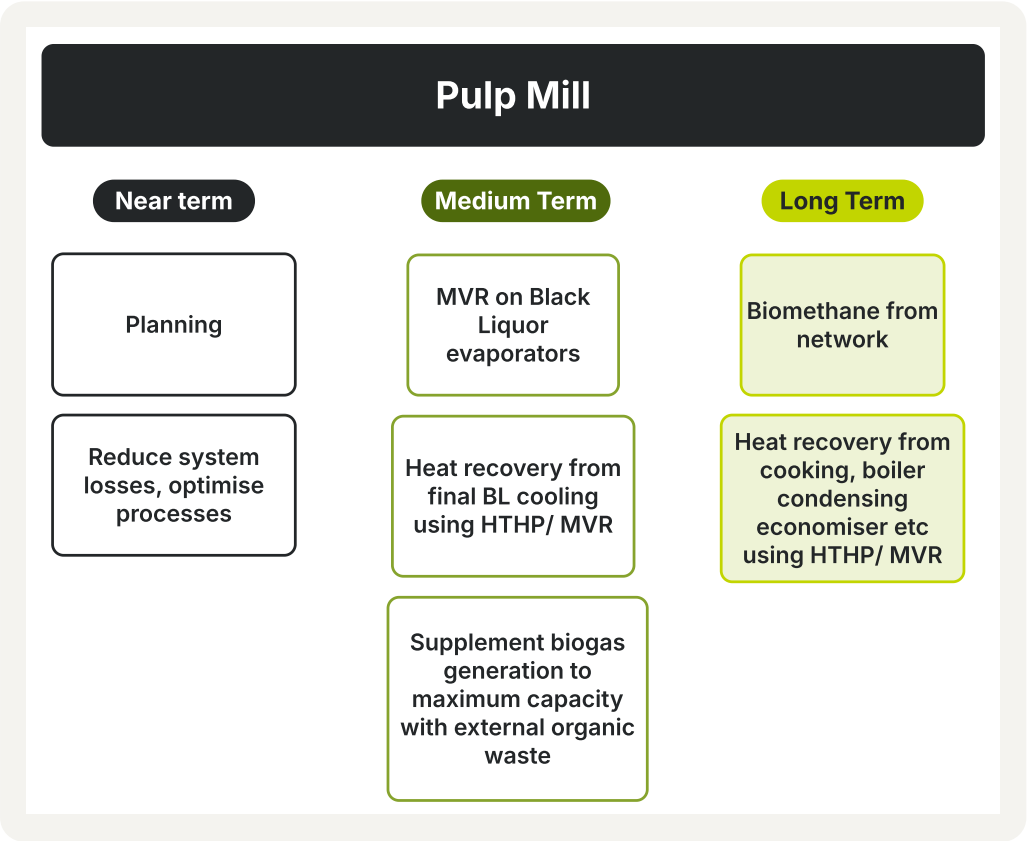


Figure 5 Pathway options for Pulp Mills.

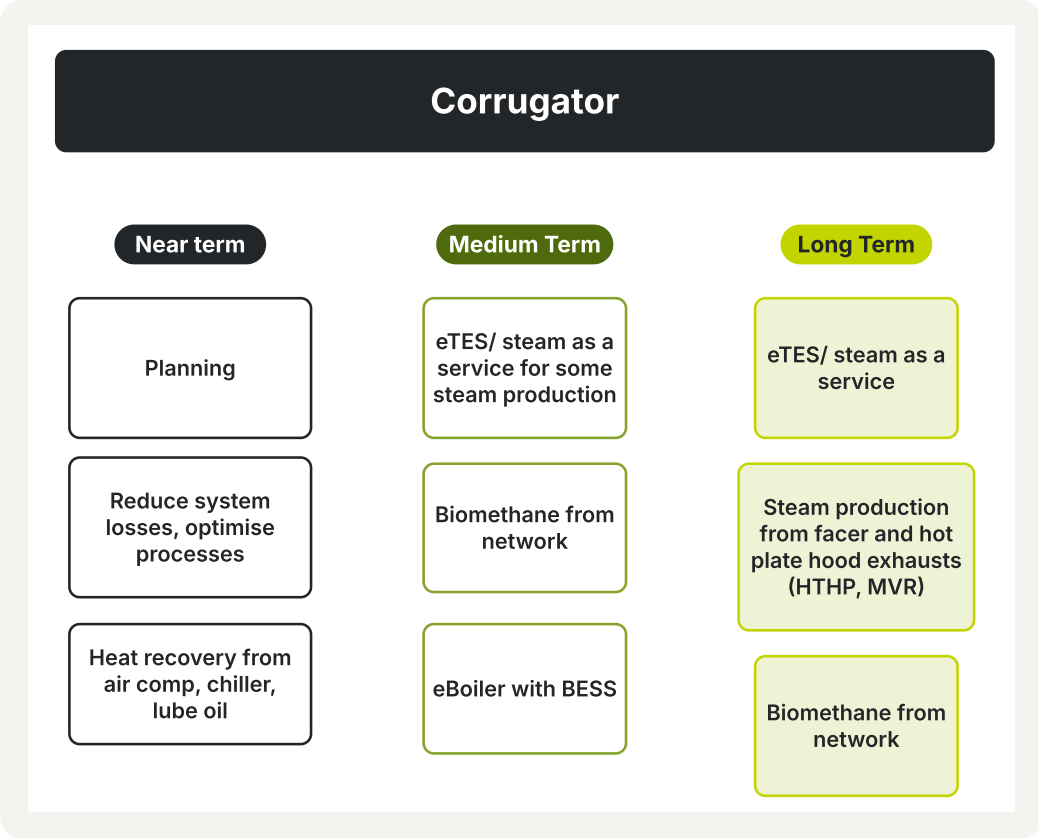


Figure 6 Pathway options for Corrugators.

SECTION 4

Case Studies

4.1 Case Study 1: Heat Recovery from Paper Machine Dryer Exhaust using a Heat Pump

This case study is a high-level assessment aimed at providing a basis for a more detailed site-specific feasibility study. Energy costs were assumed to be $16.00 per GJ for natural gas/ fuel and $150.00 per MWh for electricity (eTES excluded as it uses market exposure for electricity supply).

4.1.1 Current Situation

The dryer exhaust towers of a paper mill discharge air typically at 75°C or higher, resulting in the loss of around 50 MW_{th} of heat energy to the atmosphere. Due to the relatively low temperature of the exhaust streams, conventional heat recovery methods recover less than 50% of the thermal energy required by the dryer system.

The facilities used to develop this analysis have no existing heat recovery to preheat drying air.

The approach described can be used where existing direct heat recovery is installed, requiring less capital spend, however the ROI is likely to be longer.

4.1.2 The opportunity

The dryer supply air is currently heated using steam supplied through steam coils, providing approximately 6.1 MW_{th} of heat energy. One exhaust tower alone contains approximately 12 MW_{th} of available heat at around 75°C, which exceeds the heat demand of the dryer fresh air supply. This presents a significant opportunity to recover waste heat and reduce steam consumption.

4.1.3 Proposed Solution

A heat pump could be installed to recover waste heat from one dryer exhaust and generate LP steam. The proposed system would use the exhaust air stream at approximately 75°C as the heat source and raise boiler feedwater temperature from approximately 95°C to produce steam at around 120°C.

The temperature lift considered for COP estimation is 64°C, as the COP is related to the heat source exit temperature from the heat exchanger, not just the inlet temperature. A heat pump operating with a temperature lift of approximately 64°C could achieve a coefficient of performance (COP) of approximately 3.05. Figure 8 shows the COP of operational heat pumps in similar circumstances at various deltaT (source: https://dryficiency.eu/home)

As the existing dryer heating system currently operates with steam at approximately 150°C, additional steam coils would be required. That would enable each supply air stream to achieve adequate heat transfer and maintain dryer performance using steam at 120°C.

Assuming continuous operation of the paper mill (8600 hours p.a.), the proposed system is expected to reduce natural gas consumption by approximately 221,000 GJ annually while consuming approximately 17,000 MWh of electricity.

Under these operating conditions, the required heat pump input capacity is estimated to be approximately 2 MW. A schematic of the proposed heat pump system is shown in Figure 7

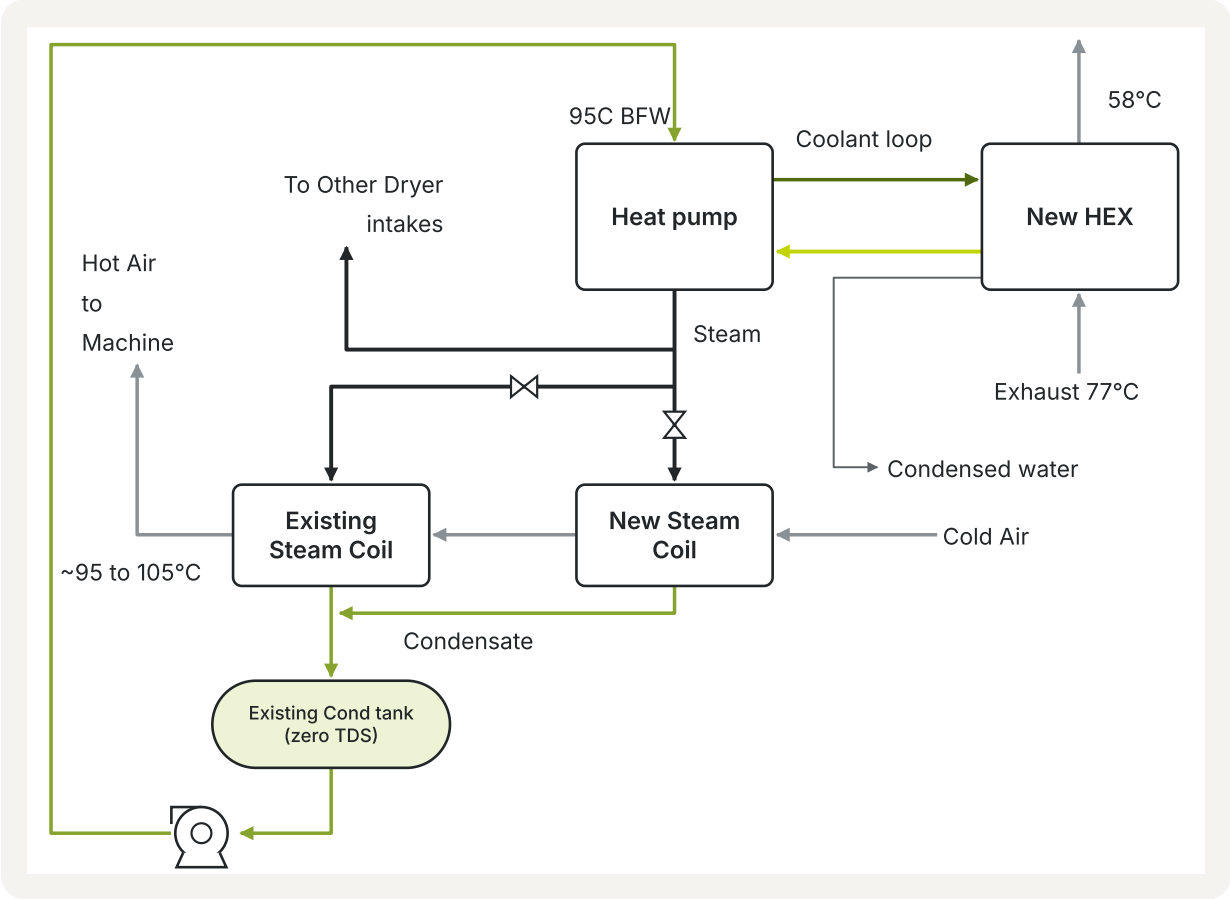


Figure 7 Proposed heat pump system schematic

An additional benefit from using only one exhaust tower as the heat source is that the quantity of water condensed and recovered back to the process is maximised.

A second scenario, where the exhaust is 85°C, has also been considered as some machines operate with this exhaust temperature or higher. The higher exhaust temperature has a significant positive impact on the business case as the COP achieved is improved with the smaller temperature lift, reducing electricity costs and slightly reducing capex. See Figure 8 COP of operational heat pumps at various deltaT below for COPs measured in operation of a similar dryer system (source: https://dryficiency.eu/home). Minimising air infiltration and good insulation are key factors affecting the exhaust temperature, demonstrating the value of improving efficiency before installing enhanced heat recovery.

A capex estimate was created by considering preliminary feasibility work done previously on similar implementations, and heat pump pricing from established suppliers in Europe.

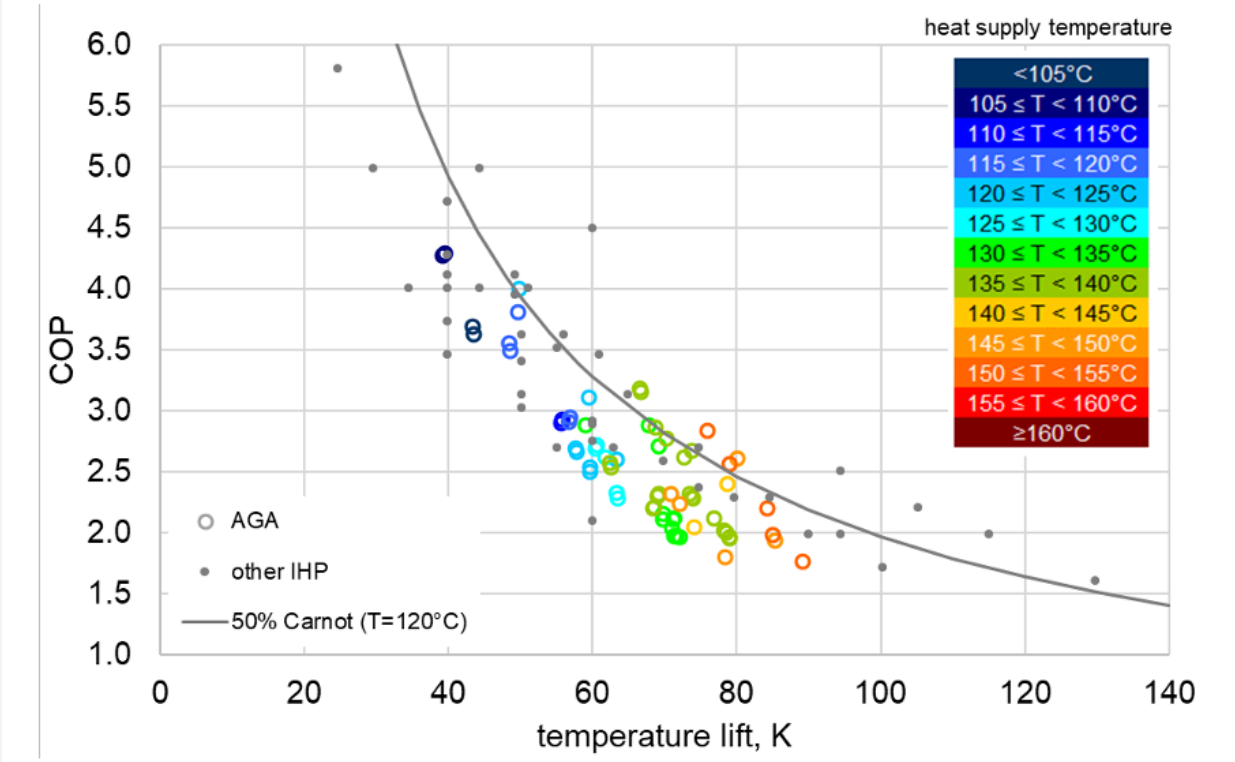


Figure 16: Performance data of the AGA demonstrator in comparison with other IHP

Figure 8 COP of operational heat pumps at various deltaT (source: https://dryficiency.eu/home)

4.1.4 **Other considerations**

Installation of the heat pump would require approximately 32 m² of space. The project would require supply and installation of a new heat exchanger on the exhaust tower, additional steam coils for heating the incoming air streams, and pipework required to integrate the heat pump into the existing system. Existing condensate drains are likely to be adequate as the total steam flow will only be slightly higher than the current steam flow.

The existing steam coil operation could be retained as a backup to the heat pump if needed.

A key consideration is the availability of electrical infrastructure. The proposed heat pump is expected to require approximately 2,000 kW of electrical capacity, and any network upgrades required to accommodate this demand could significantly influence project costs. It is likely that a new transformer and MCC would be required.

Paper machines with existing direct heat recovery could still apply this approach by using a smaller capacity heat pump with a higher temperature lift around the existing heat exchange. The capex would be smaller, but the payback would be less attractive.

The electricity price and COP impact the payback linearly, allowing straightforward sensitivity checks.

4.1.5 A staged approach

A smaller heat pump with separate steam coils could be considered. The lower temperature steam coils would bring the temperature up most of the way, with higher temperature steam in the existing coils completing the heating. The result would be a system with reduced capital cost, providing a higher proportion of the required heat input than using direct heat recovery, eliminating most of the steam required. A detailed feasibility would be required to assess the value of this option as a first step.

4.1.6 Potential Sources of Revenue

ARENA is a potential source of direct funding for this option. The Industrial Transformation Scheme for regional sites can potentially fund up to 50% of project development and capital expenditure.

There is the potential in Victoria, for sites that participate in the VEU, to create VEECs from this option, providing a significant trailing source of revenue.

The NSW ESS (ESCs) and Federal CFI (ACCUs) schemes do not provide any revenue options for this case.

4.1.7 The business cases

Table 2 & Table 3 are showing the business case for 2 different operating temperatures of dryer exhaust

Table 2 For a dryer exhaust operating at 85°C - business case results

METRIC	VALUE	UNIT
Current Steam Usage	188,122	GJ pa
Current Gas Usage	221,320	GJ pa
Additional Elec Usage	15,147	MWh pa
Gas Rate	$16.00	$/GJ
Elec Rate	$150.00	$/MWh
Annual Gas Cost	$3,541,112	Pa
Annual Elec Cost	$2,272,000	Pa
Capacity Charge	$18,137	Pa
Water saving	$65,025	Pa
LGCs for renewable electricity	$90,880	Pa
Savings	**$1,225,120**	**Pa**
Heat Pump Size	1.8	MW
Supply Cost per kW	$800	
Heat pump cost	$1,422,222	
Installation Cost Estimate	$3,000,000	
Capex cost total	**$4,422,222**	
Simple Pay Back	**3.6**	**Years**
NPV (10 years), CPI 3%, Discount Rate 7%	$4,995,989	
VEEC revenue*	$2,369,321	
SPB after VEECs	1.6	Years
Reduced Gas Emissions	12,239	tCO_2-e pa
Additional Elect Emissions without renewable electricity	10,603	tCO_2-e pa
Net Reduction In Emissions without renewable electricity	1,636	tCO_2-e pa

*Based on current scheme rules and certificate pricing, net of typical fees.

Table 3 For a dryer exhaust operating at 75°C - business case results

METRIC	VALUE	UNIT
Current Steam Usage	188,122	GJ pa
Current Gas Usage	221,320	GJ pa
Additional Elec Usage	17,133	MWh pa
Gas Rate	$16.00	$/GJ
Elec Rate	$150.00	$/MWh
Annual Gas Cost	$3,541,112	Pa
Annual Elec Cost	$2,569,967	Pa
Capacity Charge	$20,516	Pa
Water saving	$65,025	Pa
LGCs for renewable electricity	$102,799	Pa
Savings	**$912,855**	**Pa**
Heat Pump Size	2.0	MW
Supply Cost per kW	$800	
Heat pump cost	$1,608,743	
Installation Cost Estimate	$3,000,000	
Capex cost total	**$4,608,743**	
Simple Pay Back	5.0	Years
NPV (10 years), CPI 3%, Discount Rate 7%	$3,211,002	
VEEC revenue*	$1,614,377	
SPB after VEECs	3.3	Years
Reduced Gas Emissions	12,239	tCO_2-e pa
Additional Elect Emissions without renewable electricity	11,993	tCO_2-e pa
Net Reduction In Emissions without renewable electricity	246	tCO_2-e pa

*Based on current scheme rules and certificate pricing, net of typical fees.

4.2 Case Study 2: Heat Recovery from Black Liquor Concentrate

4.2.1 Current Situation

A black liquor stream at 130°C exits the evaporation process and is cooled below 100°C using cooling water. Direct heat exchange can't produce steam at a high enough pressure to inject into the steam main nearby (150°C and 500kPa).

4.2.2 The Opportunity

The waste heat currently rejected via cooling towers is about 9 MW. That is equivalent to 316,000 GJ pa of natural gas consumption and 128 ML pa of cooling water evaporation. The cooling water system would consume approximately 418 MWh pa of electricity to achieve the evaporation required. The heat can be recovered, the water saved, and the electricity consumption avoided.

4.2.3 Proposed Solution

Adding a waste heat steam generator combined with Mechanical Vapour Recompression can produce the required steam conditions for injection into the steam main. The MVR does need a substantial electricity input, however the overall outcome is a significant

reduction in operating cost and carbon emissions.

The system would draw condensate from a nearby condensate tank using a new boiler feed water pump. Most of the BFW would go through the steam generator, with a small flow used in the MVR to ensure the MP steam is saturated. The steam would be piped into the existing steam main supplying the black liquor evaporation system.

Electricity input for the MVR is approximately 770kW, resulting in a COP of 12. The COP is based on useful thermal energy delivered relative to compressor power input, with the majority of the energy originating from the recovered waste heat stream rather than the electrical input itself.

The proposed system schematic is relatively simple as seen in Figure 9.

The MVR used in the costing is a self-contained, containerised system that has a technology readiness level (TRL) of 9 and has been in operation for several years at pilot sites. It would use 7 inverter driven turbo compressors in parallel, allowing efficient load management through adjusting the compressor speed and the number of compressors operating.

A capex estimate was created by considering preliminary feasibility work done previously on similar implementations. The final capex could vary substantially depending on site layout, available electrical infrastructure, and the temperature of the heat source. The example used has a higher than typical BL exit temperature.

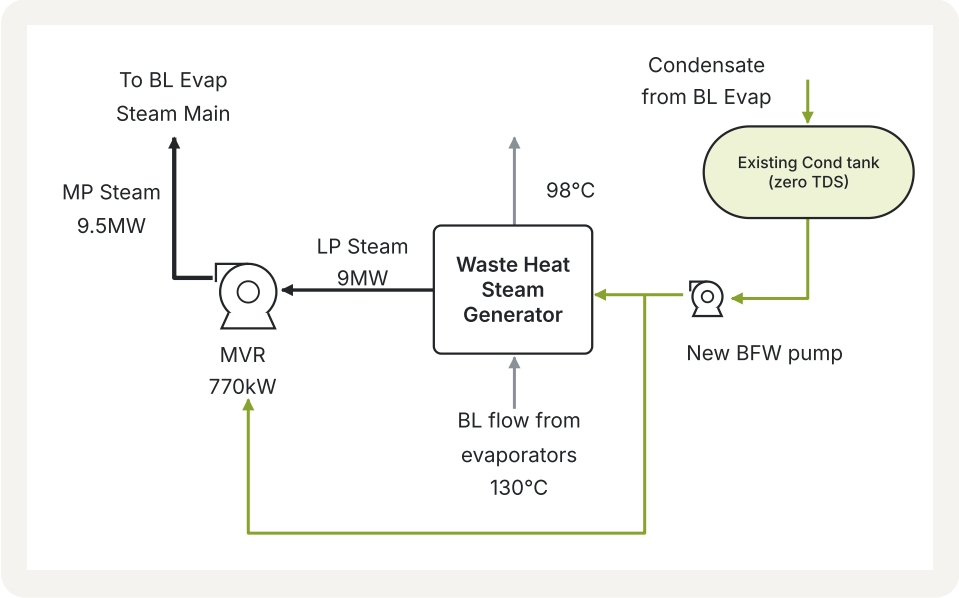


Figure 9 Case Study 2 system schematic

4.2.4 Other considerations

The footprint is the size of a 40ft container, approximately 12.2m x 2.5m. Additional footprint would be required for the steam generating heat exchanger. Ideally the steam heat exchanger would be as close as possible to the MVR to minimise the formation of condensation droplets prior to reaching the compressor rotors.

There would be relatively little additional pipe required for steam and condensate as the steam would be reused locally at the black liquor evaporation system which is also the source of waste heat.

Electricity supply is the biggest variable as its cost depends on the availability of a source for 770kW of LV supply and its proximity to the MVR container.

To achieve the best financial outcome, the MVR should be sized to meet the usual heat availability. Any peaks that exceed MVR capacity can be managed with a small portion of the existing cooling water system capacity.

4.2.5 Potential Sources of Revenue

There is currently no direct funding for a project of this nature.

4.2.6 The business case

See Table 4 for the results of business case for MVR steam generation

Table 4 MVR steam generation business case

METRIC	VALUE	UNIT
Fuel Saving Assuming 88% Boiler Eff	36.8	GJ/h
Operating Hours	8,600	pa
Gas Rate	$16.00	$/GJ
Elec Rate	$150.00	$/MWh
Fuel Saving	316,636	GJ pa
Additional Elect MVR	6,622	MWh
Less Elect Cooling Tower	418	MWh
Water Saved at Cooling Tower	128,117	kL
Gas Saving	$5,066,182	pa
Elect Additional Use	$930,606	pa
Water Saving	$256,234	pa
MVR and balance of plant maintenance costs	$18,080	pa
LGCs for renewable electricity	$39,732	pa
Total saving	**$4,763,903**	**pa**
MVR system cost	$1,817,640	
Steam generator (heat exchanger) cost	$1,100,000	
MVR Transport, engineering, PM, civils, BFW pump, piping, controls, elect connection etc	$3,000,000	
Total capex	**$5,917,640**	
Simple Pay Back	**1.2**	**(years)**
NPV (10 years), CPI 3%, Discount Rate 7%	$30,791,547	
ACCU est net value per annum for 7 years	$430,000	
Simple Pay Back with ACCUs	**1.1**	**(years)**
Reduced Gas Emissions	19,003	tCO_2-e pa
Additional Elect Emissions without renewable electricity	4,635	tCO_2-e pa
Net Reduction In Emissions without renewable electricity	14,367	tCO_2-e pa

International Energy Agency latest review of available HTHP technology including MVR. Includes details of equipment suppliers with ready for market systems and technology readiness levels - https://heatpumpingtechnologies.org/publications/project-68-industrial-high-temperature-heat-pumps-task-1-technologies-2025/

4.3 Case Study 3: Electric Thermal Energy Storage

4.3.1 The current situation

Steam is currently produced at the example site by a series of boilers which run on natural gas, however the case study applies to any fuel.

4.3.2 The opportunity

There is an opportunity to install an electric Thermal Energy Storage (eTES) system to offset a significant portion of the site's natural gas consumption. The eTES system would be controlled to charge during periods of low electricity prices and utilise the stored thermal energy to supply steam when electricity prices are higher. By utilising a network tariff similar to Powercor's Flexible Large Tariff, lower network charges can be achieved during off-peak periods.

There is also the option to procure electricity through the spot market, allowing the eTES system to charge only when electricity prices are lower than the equivalent cost of generating steam using natural gas. This approach can further optimise operating costs while reducing natural gas consumption.

4.3.3 The solution

The proposed electric eTES system would utilise low-cost electricity to generate and store thermal energy for later use in steam production. The system would be charged during periods of low electricity prices and discharged when steam is required, reducing the site's reliance on natural gas-fired boilers.

The eTES stores thermal energy within a high-temperature thermal storage medium, usually graphite or ceramic, using electric resistance heating. During discharge, the stored heat is transferred to boiler feedwater through a heat exchanger to generate steam for use within the existing steam network.

The system can be controlled to charge during off-peak periods, when renewable generation is abundant, and wholesale electricity prices are low. There are network tariffs now in existence that provide minimised demand charges for this type of system provided it is separately metered. This allows the site to take advantage of lower electricity costs while maintaining steam supply during periods of higher electricity prices.

The technology is modular and can be sized to suit the site's steam demand profile. The primary site consideration is the availability of sufficient electrical supply capacity to support the charging load. To maximise financial benefits, the system should be sized to align with the site's typical steam demand and electricity procurement strategy. A diagram of the proposed configuration of the eTES system is shown below in Figure 10.

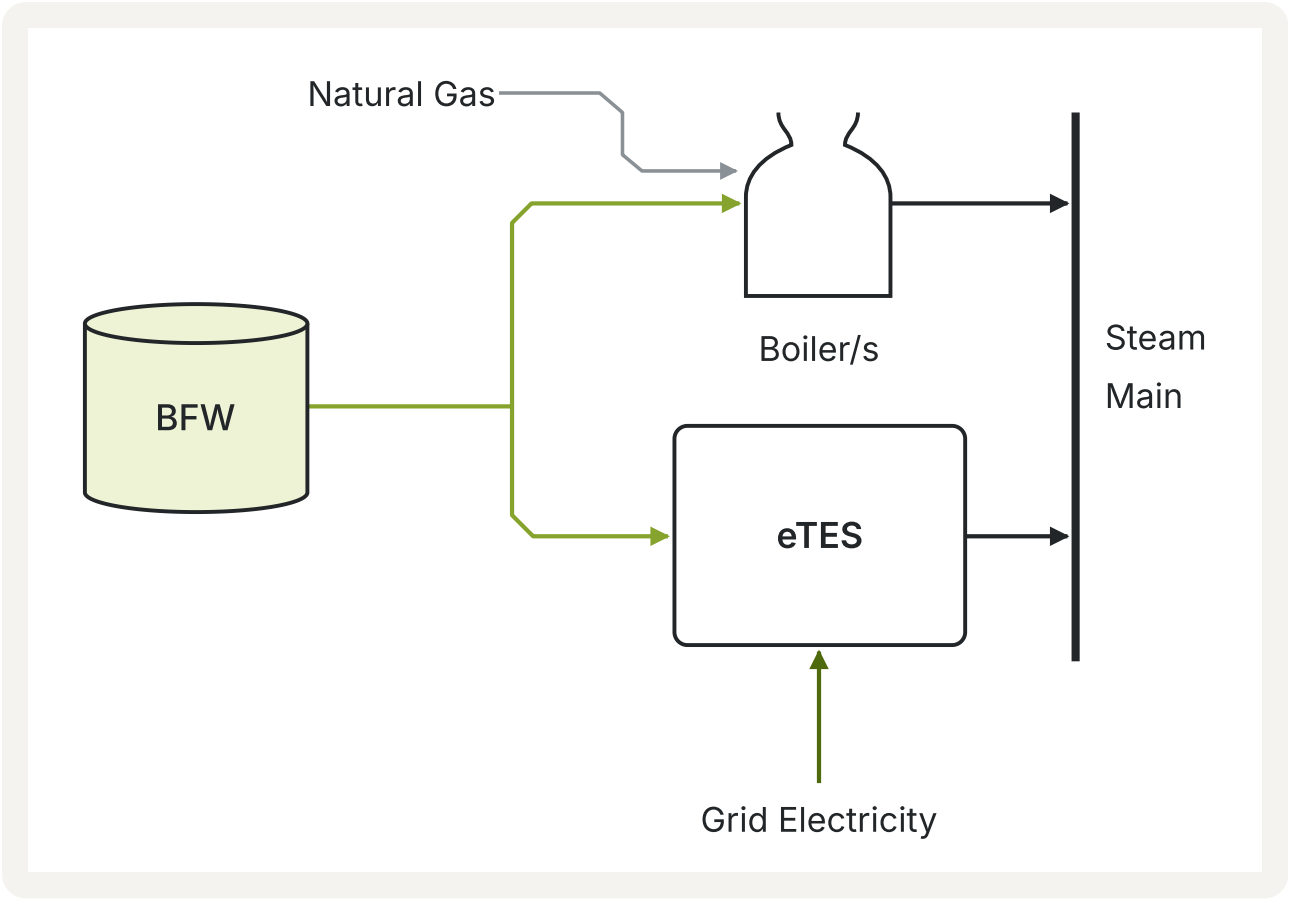


Figure 10. eTES diagram

4.3.4 **The example site**

Hourly steam demand for the site is shown in Figure 11, below. The operating pattern allows for variation in paper grade and some down time. The exact steam pressure is not important for an eTES as it operates at much higher temperatures than a traditional boiler, reducing the steam generation heat exchanger surface area.

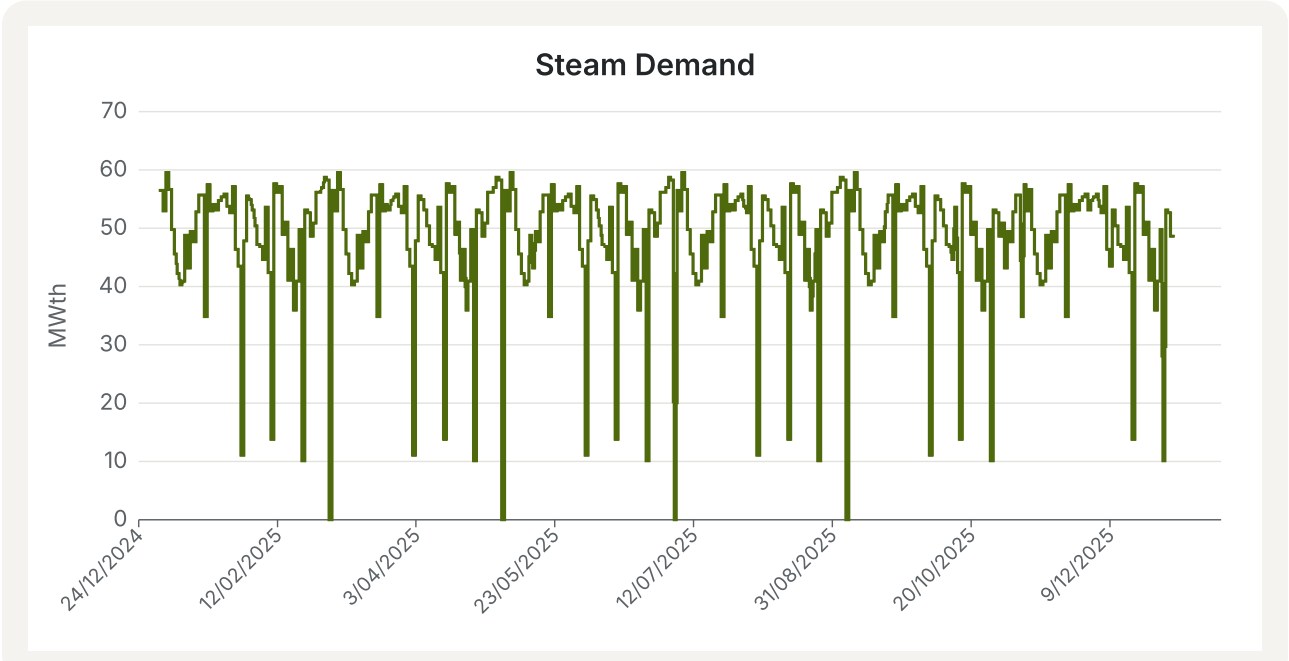


Figure 11 Example hourly steam demand profile

4.3.5 The business case

The business case was developed using actual hourly NSW spot market electricity cost for 12 months (2025), combined with an Essential Energy "BHND4LS HV Storage/Hybrid tariff", plus an allowance for retail margin. A maximum wholesale electricity cost was specified and used in conjunction with network demand charges to control the eTES charging. The eTES size, charge rate and maximum electricity unit cost were adjusted to find an optimum return on investment for a partial electrification of steam generation using the example steam demand.

Note that electricity spot prices vary with location and season.

The result was a 90 MWh storage capacity, 60MW charging rate and a spot market wholesale electricity price cap of $60 per MWh (i.e. the eTES automatically charges when the spot price is below $60 per MWh).

The output rate of the eTES is shown in Figure 12.

The charge state over time of the eTES can be seen in Figure 13 below. During periods of relatively high electricity price it remains empty and idle.

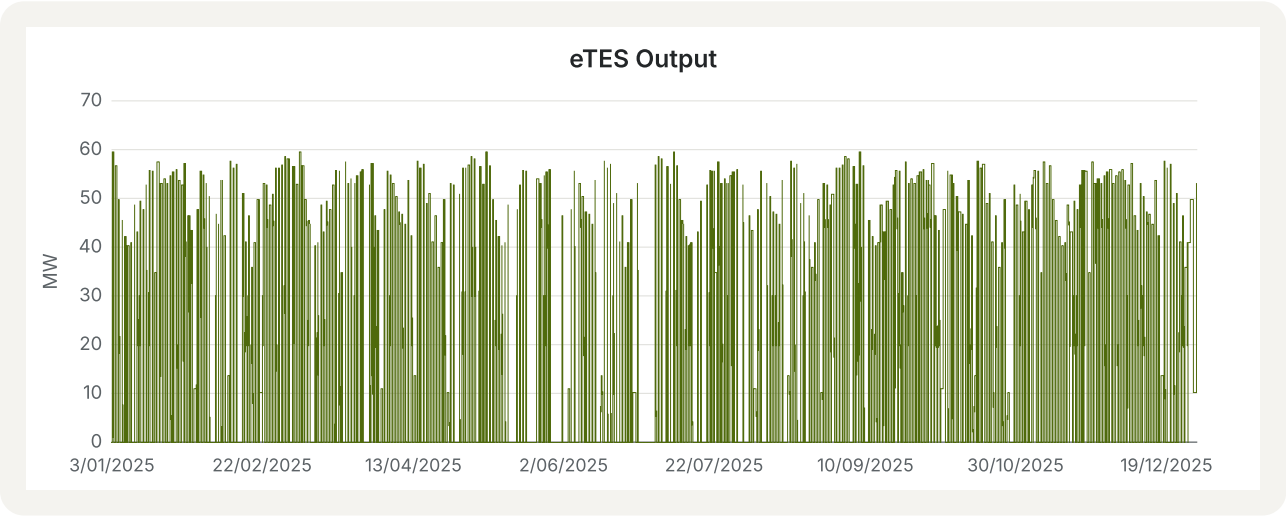


Figure 12 Steam supplied by eTES

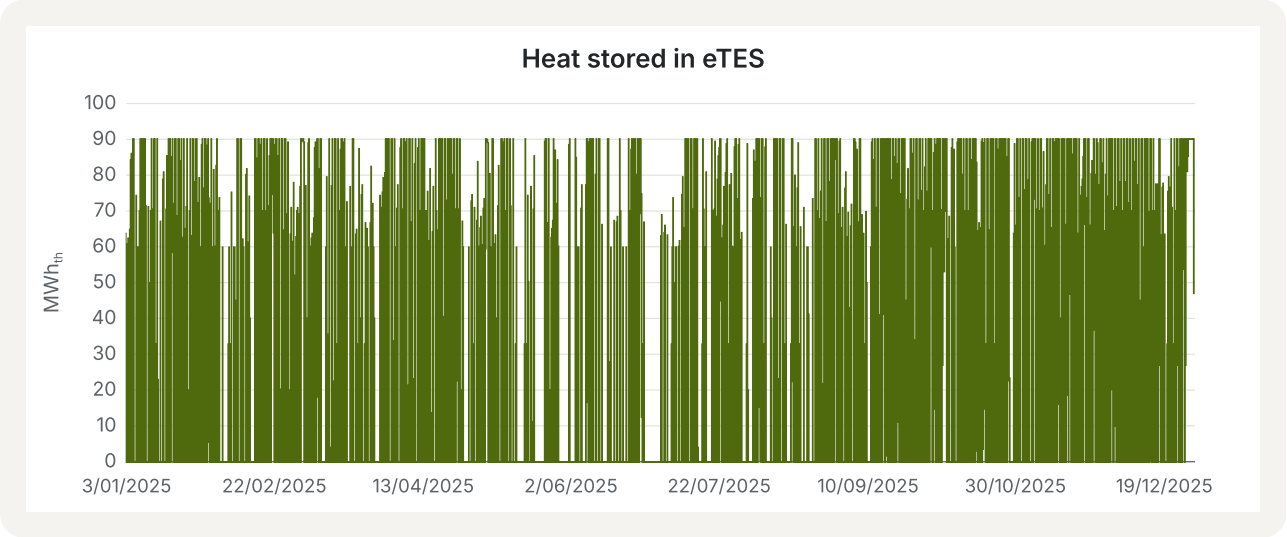


Figure 13 Heat energy stored in eTES

Table 5 Financial results, eTES

METRIC	VALUE	UNITS
eTES capacity	90	MWh
eTES charge rate	60	MW
Maximum electricity spot price to charge	$60	$/MWh
Effective electricity price paid	$17	$/MWh
Gas Rate	$16.00	$/GJ
Site baseline gas consumption	1,600,000	GJ
Fuel saving	666,006	GJ pa
Additional Electricity	157,567	MWh pa
Fuel cost saving	$10,656,095	pa
Electricity Cost	$2,701,382	pa
Annual energy cost saving	$7,954,713	pa
Annual maintenance cost increase	$100,000	pa
LGCs purchased for renewable electricity	$945,405	pa
Annual opex reduction	$6,909,308	pa
Capex	$39,000,000	
Simple Pay Back	5.64	years
NPV (10 years), CPI 3%, Discount Rate 7%	$16,230,951	
NPV (25 years), CPI 3%, Discount Rate 7%	$65,681,601	
Reduced gas emissions	36,830	tCO_2-e pa
Additional elect emissions without renewable electricity purchase	110,297	tCO_2-e pa
Net reduction in emissions without renewable electricity purchase	-73,467	tCO_2-e pa

The high reliability of existing eTES systems provides confidence in the technology. The case study indicates a higher than desirable simple payback, however with a long and relatively low maintenance lifespan of 20+ years, a Net Present Value would be a more useful way of looking at the investment. This is especially the case where production facilities are relatively young.

4.3.6 Additional considerations

The eTES capacity could be stretched potentially to cover the entire steam demand by using heat pumps on the exhaust stacks to preheat BFW, and heat the drying air as described in case study 1, reducing the input required from the eTES. BFW makeup and process water could be preheated with direct heat recovery from air compressors and/or lube oil systems, a low maintenance option to reduce the electrical input required for steam production, especially during peak demand periods when electricity is the most expensive. Flash steam that is currently used to preheat the process water could then be redirected to MVR to again reduce the reliance on the eTES and stretching its capacity across peak demand periods. Those options however are not covered in this case study.

If compared to the likely future cost of biomethane from the natural gas grid for decarbonisation, the business case should improve as biomethane is likely to be at a premium price compared to existing natural gas. That would potentially change the optimum size of the eTES to enable full coverage of steam demand, especially if combined with on-site biogas, heat recovery to BFW and dryer air heating, and MVR to capture flash steam.

SECTION 5

Next Steps

For successful progress towards reducing carbon emissions, the most important step is the planning as described in section 3. Once a broad plan has been developed, more detail can be added by testing options through feasibility studies.

Develop a detailed heat balance for your site as part of your pathway planning

Thoroughly assess the potential for process heat demand reduction and heat recovery.

The high-level case studies in section 4 are intended only to give an indication of their feasibility across the pulp and paper industry. The individual circumstances at a site will influence the outcomes significantly. In preparing a feasibility study for assessing options, there are several key factors to take into consideration.

- Electricity tariffs
- Additional separate electricity connections to enable specific tariffs.
- Network tariffs for energy storage devices that minimise demand charges are now available in some jurisdictions.
- Consider market exposure for separate connections for energy storage devices
- Use forecast electricity emissions factors from AEMO when assessing carbon emission impacts into the future
- Local electricity grid capacity
- Site connection capacity
- High Voltage vs Low Voltage connection – different tariff options

SECTION 6

Appendices

6.1 List of typical heat sinks and sources

See Table 6 & Table 7 for the list of typical heat sinks and sources of corrugating and Paper/ Tissue Mill respectively.

Table 6 Typical Sources and Sinks – Corrugating Process

SECTION	UNIT OPERATION	WASTE HEAT SOURCE OR DEMAND?	RELATIVE SIZE OF HEAT FLOW	HEAT SOURCE QUALITY
Single Facer	Preheating rolls	Demand	Large	N/A
Single Facer	Preconditioning/ humidifying	Demand	Large	N/A
Double backer	Preheater	Demand	Large	N/A
Drying	Steam chests/ hot plates	Demand	Large	N/A
Boiler Feed Water Make Up	Utility	Demand	Small	N/A
Boiler blowdown	Utility	Source	Small	High
Air compressors	Utility	Source	Medium	Medium
Chillers	Cooling	Source	Small	Medium
Corrugator lube oil system	Cooling	Source	Medium	Medium
Single Facer	Hood air extraction	Source	Large	Low
Hot plates	Drying	Source	Large	Low

Table 7 Typical Sources and Sinks – Paper and Tissue Mill Process

SECTION	UNIT OPERATION	WASTE HEAT SOURCE OR DEMAND?	RELATIVE SIZE OF HEAT FLOW	HEAT SOURCE QUALITY
Building Ventilation	Air Heating	Demand	Medium	N/A
Pre-dryer Section Ventilation	Drying Air heating	Demand	Large	N/A
Pre-dryer Section	Drying can Heating	Demand	Large	N/A
After-dryer Section Ventilation	Drying Air heating	Demand	Large	N/A
After-dryer Section	Drying can Heating	Demand	Large	N/A
Boiler Feed Water Make Up	Utility	Demand	Small	N/A
Hot Water	Starch cooking	Demand	Small	N/A
Warm Water	Starch cooking, cleaning, etc	Demand	Small	N/A
Starch production steam	Starch cooking	Demand	Small	N/A
Pulping	Black liquor evaporation	Demand	Large	N/A

Table 7 (continued)

SECTION	UNIT OPERATION	WASTE HEAT SOURCE OR DEMAND?	RELATIVE SIZE OF HEAT FLOW	HEAT SOURCE QUALITY
Pulping	Black liquor final cooling	Source	Medium	High
Building Ventilation	Air Cooling	Source	Medium	Medium
Pre-dryer Section Ventilation	Exhaust Air	Source	Large	High
After-dryer Section Ventilation	Exhaust Air	Source	Large	High
Air compressors	Utility	Source	Medium	Medium
Lube oil system cooling	Utility	Source	Medium	Medium
Chillers	Utility	Source	Small	Medium
Paper towel machine dryer	Exhaust Air	Source	Medium	High

6.2 References and additional information sources

Emission reduction planning guidance:

- Net Zero Business Guide | NSW Climate and Energy Action – This includes additional links https://www.energy.nsw.gov.au/business-and-industry/guides/net-zero-business-guide
- https://ghgprotocol.org/standards-guidance
- https://climateworkscentre.org/resource/guide-to-credibility-for-corporate-climate-transition-plans/
- https://www.aicd.com.au/risk-management/framework/climate/governing-for-net-zero.html

International Energy Agency database of available HTHP technology including MVR. Includes details of equipment suppliers with ready for market systems:

https://heatpumpingtechnologies.org/project68/task1/

Austrian Institute of Technology, HTHP Industrial Pilot Implementations study:

https://dryficiency.eu/home

For further detailed information on eTES, the following is a list of suppliers who currently have a presence in Australia:

- MGA Thermal
- Graphite Energy
- Antora
- Rondo

Biomethane project development information:

Renewable Gas Projects & Producers

Harnessing a New Era of Bioenergy in Australia | Valorify

Biogas system suppliers in Australia:

Hart Bioenergy

HOME | Martin Energy Group Australia biogas CHP energy

PREPARED BY APPITA

Key Terms and Abbreviations

Prepared by Appita as a reader's aid. These explanations reflect how terms are used in this report and do not form part of Northmore Gordon's technical report.

ACCU	**Australian carbon credit unit.** Issued under the federal CFI scheme; one unit per tonne of CO_2-e of eligible emissions reduction.
BESS	**Battery energy storage system.** Stores electricity to avoid high-cost peak supply.
BFW	**Boiler feedwater.** Water supplied to a boiler for steam generation.
BTM	**Behind the meter.** Generation or storage on the site side of the electricity meter.
Carbon offsets	Purchased credits that compensate for emissions; an extra cost and a last resort.
COP	**Coefficient of performance.** Heat delivered divided by electricity consumed, including auxiliary loads. A higher COP means a lower electricity cost per unit of heat.
Demand charge	A network charge based on a site's peak electricity demand.
eBoiler	**Electric boiler.** Produces steam directly from electricity; COP below 1.
ESC	**Energy savings certificate.** Created under the NSW Energy Savings Scheme (ESS).
eTES	**Electric thermal energy storage.** Stores heat from electricity, typically when it is cheap, for later steam generation; COP of 1.
Heat as a service	A provider supplies heat rather than the site buying the equipment.
Heat sink	A process or system that requires or absorbs heat.
Heat source	A stream or system from which useful heat can be recovered.
HTHP	**High-temperature heat pump.** A heat pump works like a refrigerator in reverse, upgrading heat from a lower-temperature source for uses such as drying air or low-pressure steam.
LGC	**Large-scale generation certificate.** Created for each megawatt hour of eligible renewable electricity; surrendered LGCs can support zero-emissions claims for purchased electricity.
MACC	**Marginal abatement cost curve.** Compares options by tonnes abated and cost per tonne.
MCC	**Motor control centre.** Electrical switchgear that supplies and controls motors.
MVR	**Mechanical vapour recompression.** Compresses low-pressure vapour or flash steam so it can be reused as process steam.
NPV	**Net present value.** Future savings less costs, discounted to today's value.
PPA	**Power purchase agreement.** A contractual arrangement to purchase electricity, often from a renewable energy project.
ROI	**Return on investment.** A measure of an investment's financial return relative to its cost.
Scope 1 emissions	Direct emissions from sources a business owns or controls, such as gas-fired boilers.
Scope 2 emissions	Indirect emissions from purchased electricity. The market-based method recognises renewable procurement such as a PPA or surrendered LGCs.
Simple payback	Years for annual savings to repay the capital cost, without discounting.
tCO_2-e	**Tonnes of carbon dioxide equivalent.**
Temperature lift	The rise from heat source to delivery temperature; a smaller lift gives a higher COP.
TRL	**Technology readiness level.** A 1 to 9 maturity scale; TRL 9 is a proven system in operation.
VEEC	**Victorian energy efficiency certificate.** Available to sites participating in the Victorian Energy Upgrades (VEU) program.

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Pulp > Paper > Packaging > Bio-products

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