Policy Paper:

Modernising Resource Recovery and Energy Policies

Decoupling Biochar Bioenergy Systems from Linear Energy from Waste Systems for Circular and Regenerative Benefits

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Contents

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Background:

Thermal treatment technologies are commonly employed to divert organic waste materials from landfill into more positive uses including (but not limited to) energy from waste. However, thermal processes can differ fundamentally in their outputs/products, operational conditions, and associated environmental impacts or benefits including linear/circular economy and climate aspects. These distinctions are important in providing regulatory frameworks that facilitate thermal treatment systems that optimise environmental benefits and promote sustainable practices for genuine circular economy and action on climate change.

Overview:

This policy paper examines the necessity of separating regulation of *linear* energy from waste (EfW) (full combustion and incineration) from more *circular* and *regenerative* thermal treatment systems for biochar, bioenergy, renewable fuels and chemicals (such as pyrolysis and gasification). The paper emphasises the positive implications for action on climate change, circular economy, air quality and waste management, among other factors. It proposes a modified *Resource and Energy Recovery Hierarchy* to accompany the conventional Waste Hierarchy commonly used to assess 'higher order use' of resources, which builds upon precedent concepts for circular liquid fuels in the Queensland Energy From Waste Policy (2021) by additionally recognising circular carbon in solid form (e.g. biochar) and gas form (e.g. syngas & derivatives).

Key Points:

- **Not all thermal treatment systems are the same**. Some are linear with few or no co-benefits (single use full combustion EfW facilities), while some are more circular and regenerative, such as slow pyrolysis producing biochar for rehabilitation of degraded soils and a wide range of other beneficial uses (as shown in **Figure 1** and discussed further within this paper and its Appendices).
  - There are also **significant differences** in context of climate, sustainability and other environmental objectives to be considered, including carbon emissions/removal, air and water quality, waste residues, and water use (among others), as well as very significant differences in **size and scale** of activity (e.g. centralised large scale incinerators vs decentralised smaller to small scale pyrolysis plants down to flame capped kilns). These differences are detailed further in **Appendix 2**.

- **Evaluation of 'higher order use'** in recovery of resources by regulators **should consider contributions toward addressing modern critical challenges such as climate change, food and water security and resilience, and sustainability**, among other factors.

- **All thermal treatments (including biochar / bioenergy systems) should satisfy standard/conventional Environmental Impact Assessment and approvals processes, however, their regulation should be proportional to the scale, type and risk of proposed activities.** Smaller, more circular, lower risk systems should be eligible for simpler and quicker approvals in recognition of lower risks and potential higher order use and improved ESG outcomes.

- **Innovation pathways should also be provided** to facilitate pilot scale trials and to introduce commercial scale demonstration plants for new technologies including biochar bioenergy systems with potential to provide improved ESG outcomes.

- Historically, **thermal treatment** via full combustion and incineration was (understandably) viewed as a **waste disposal** method, even when energy may be recovered in a linear 'single use' of resources.

- Currently, **<u>all forms</u> of 'thermal treatment'** are commonly grouped and **regulated *collectively*** together, with no distinction between **linear ('single use')** energy from waste and more **circular and regenerative** forms of thermal treatment that **produce valuable circular commodities** as solids, liquids and/or gases for use within a circular economy (including some providing many life cycles, and for providing the chemical 'building blocks' of many downstream products and derivatives as detailed further below). For example, **biochar, biofuels / wood vinegar and syngas (synthetic gas, comprised primarily of hydrogen and CO) are valuable recoverable commodities** commonly produced by pyrolysis and gasification thermal treatment systems which provide significant climate, sustainability and circularity benefits to warrant high valuation for resource recovery. In some cases, there is also no recognition of the scale of activity and risk, or in permissible location, effectively inadvertently preventing the commercial production of biochar.

- **Positive precedence** has been established by Queensland's Energy from Waste Policy which recognises **recovery of <u>liquid</u> fuels** (only) from waste (including via thermal treatment) **as higher order use of resources than linear combustion for energy / disposal of waste alone.** Other circular carbon commodities, such as biochar and syngas, have potential to provide *even greater* climate, sustainability and circularity benefits to warrant inclusion as higher order use of resources, which should be recognised and adopted by policy and regulatory frameworks in all Australian states.
- **State / territory regulatory frameworks for waste still commonly define the valuable products from pyrolysis and gasification (including valuable biochar, wood vinegar and syngas) as *"wastes"* which must be regulated**. Typically, this is a reflection and legacy of managing *incineration* wastes which did produce problematic bottom ash, harmful char and tars. Regulatory frameworks need to **decouple** biochar and valuable coproducts (particularly those meeting industry standards) from automatically being prescribed as *'wastes'* to recognise desired and intentionally produced value quality products (*'resources'*).
    - An example is the Victorian Waste Framework within the Environmental Protection Act (and Regulations) that prescribes biochar as *Reportable Priority Waste* that cannot be used or applied to land without further assessment and permissions. Similarly, in NSW biochar is currently regulated as a waste product regulated under Resource Recovery Orders and Exemptions (RRO&E). The proposed solution is for Government policies to **decouple** incineration wastes from valuable circular carbon commodities such as biochar, wood vinegar and syngas, and to provide **'End of Waste' mechanisms** to designate products meeting relevant quality and risk criteria as suitable for reuse in the circular economy. Policy decoupling will assist circularity for many organic wastes. Queensland is leading establishment of an *End Of Waste Code* specifically for biochar.

- Systems providing **multiple and/or higher value** circular carbon outputs (solid, liquid and/or gases) can provide **even higher order use of resources**. Examples soil and non-soil applications for biochar are described in **Appendix 3**, and syngas uses including for secondary derivatives such as hydrogen, methanol, and Sustainable Aviation Fuels is described in **Appendix 4**.
- Building upon the existing Queensland EfW Policy concepts, this policy paper proposes a modified ***Resource and Energy Recovery Hierarchy*** that recognises circular carbons in all three forms (solids, liquids and gases) and their respective circularity, sustainability, and climate action benefits. This is illustrated in **Figure 2** below (and shown larger (A3) in **Appendix 1** with comparison to the Qld EfW Policy 2021). **Figures 3 and 4** provide supporting illustrations of the circularity and sustainability benefits of biochar bioenergy systems to justify this approach. Further supporting discussion on technical aspects is also provided further below and in **Appendix 2**.
- Accordingly, the ANZ Biochar Industry Group (ANZBIG) supports **decoupling** of circular and regenerative thermal treatment technologies to produce biochar and other bioproducts, from linear full combustion and incineration thermal treatment within regulatory frameworks, including related definitions of acts, regulations/schedules, waste and resource recovery frameworks, EfW policies and practices. Recognition of higher order uses and multiple co-benefits for improved environmental outcomes can justify separation and adoption within existing regulatory frameworks, including via new *innovation pathways*.

This decoupling will enable more effective regulatory practices to help transition to a more circular economy, including circular carbon such as biochar for rehabilitating and regenerating degraded land, whilst allowing regulators to maintain intended screening of lower order uses for linear energy from waste and disposal. This document details decoupling aspects which can be considered and adopted by government and regulators to facilitate improved circular economy with significant climate and sustainability benefits.

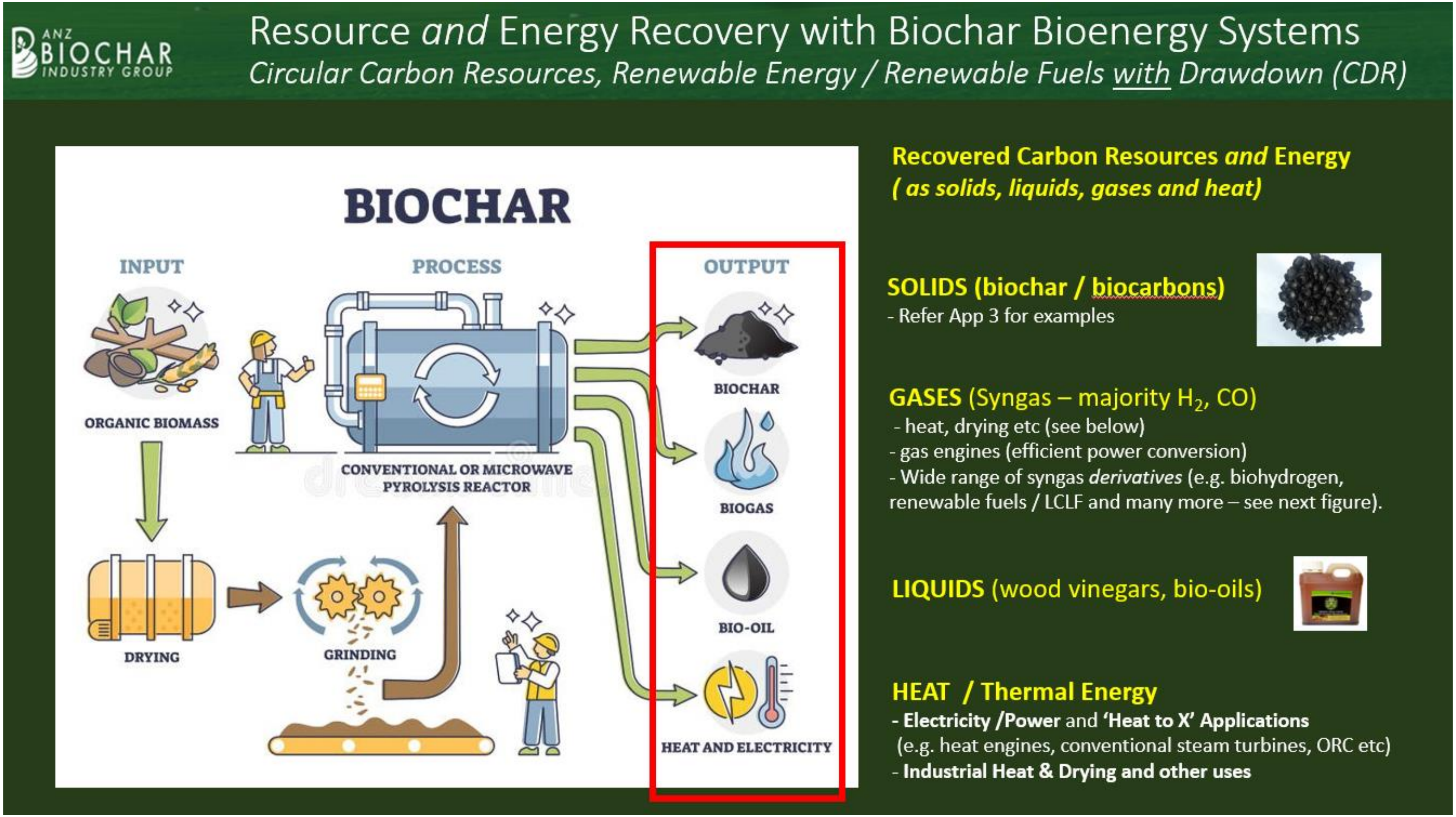


Figure 1: Resource *and* Energy Recovery opportunities with biochar bioenergy systems – including biochar for 'drawdown' / CO_2 Removal (CDR)

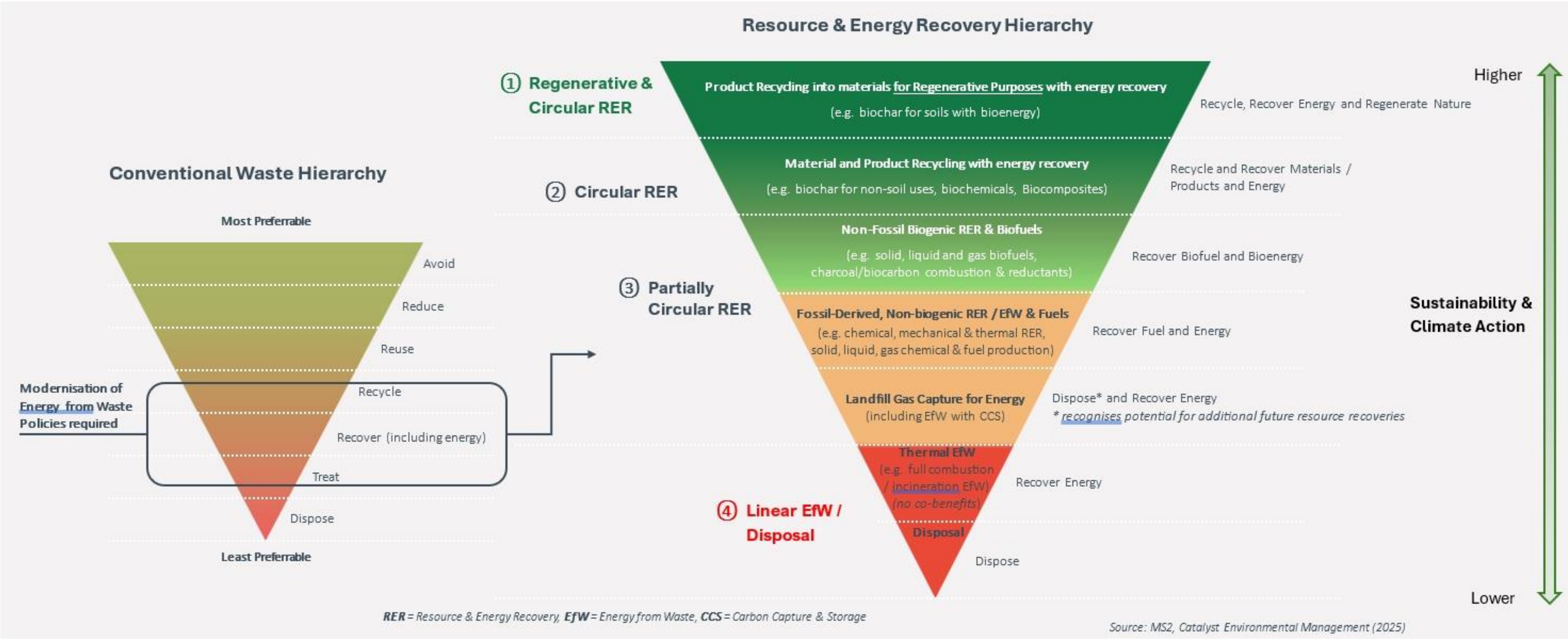


Figure 2: Updated Waste Hierarchy with associated new **Resource & Energy Recovery Hierarchy** (requires use in conjunction with additional considerations per Figures 3 and 4). Refer **Appendix 1** for an A3 version with comparison to the Qld EfW Policy 2021.

Towards a Circular Economy and Net Zero Through Stewardship of Carbon from Biomass

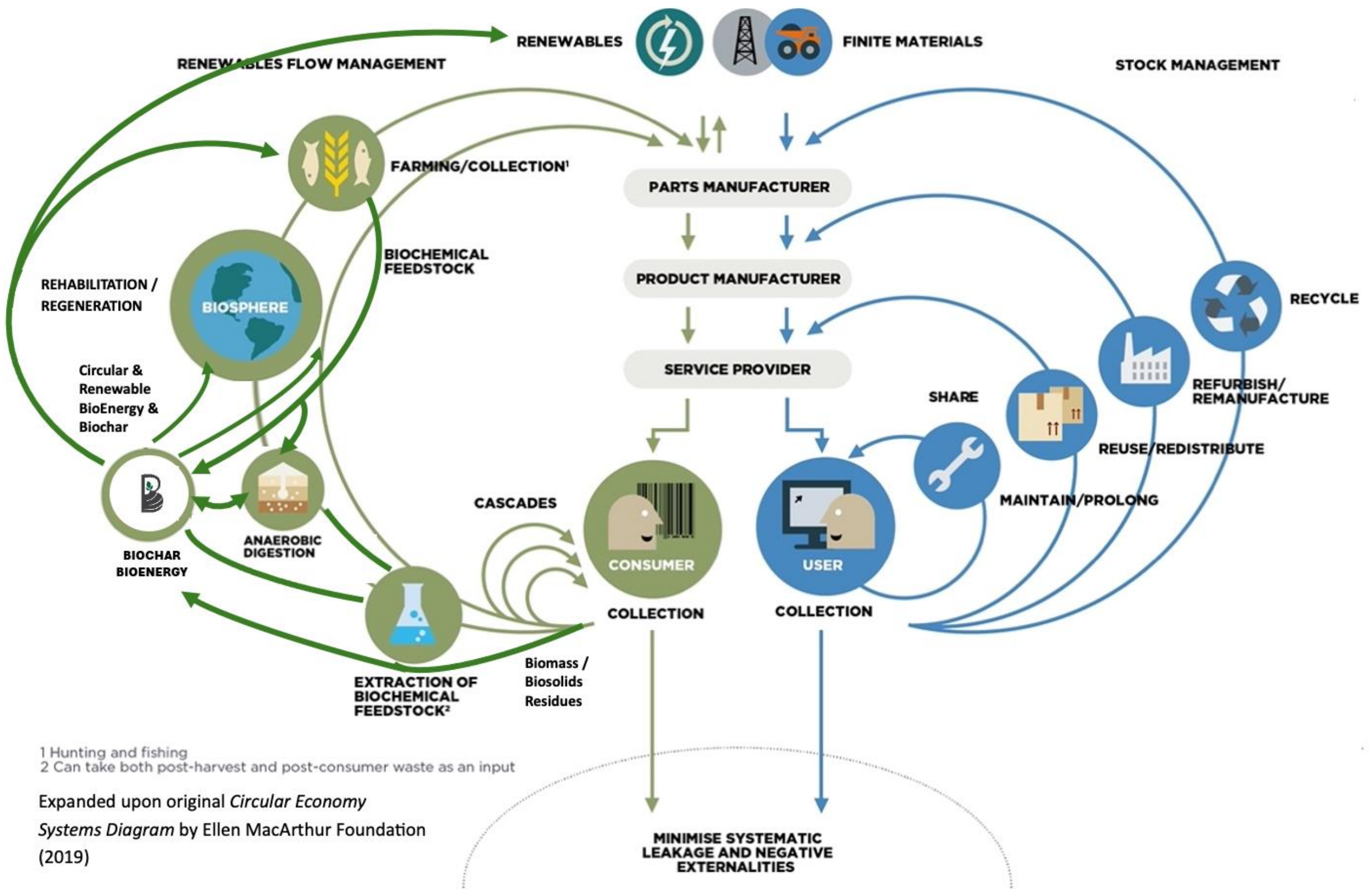


Figure 3: Revised Butterfly Diagram for Circular Economy

Figure 4: UN Sustainable Development Goals as aligned with biochar bioenergy

Relevant Technical and Policy Context

- A summary of technical differences between full combustion and incineration is provided further below to justify policy contexts for separation and decoupling, with further details in **Appendix 2**. **Table 1** below provides a high-level summary of some key differences in climate and environmental performance.
- Conventional full **combustion and incineration produces heat** as its principal beneficial product typically used to make energy/electricity, with the primary components of gas emissions being CO_2 and H_2O, along with secondary pollutants such as oxides of nitrogen and sulphur (NOx, SOx) among others. **All of (or the vast majority of) the carbon contained in the feedstock becomes GHG emissions**.
- In contrast, pyrolysis yields combustible liquid and combustible **gas** (syngas, a fuel) *and* heat, with the principal components of the gas being CO and **hydrogen** (and CH_4 at lower temperatures). Gasification yields combustible syngas and heat as the key outputs, with minor amounts of char, with the principal components of its gas also being CO and H_2.
- Up to **half the carbon in the feedstock is retained in the solid biochar produced via pyrolysis**, and additional carbon recovered in liquid products. This is a **significant point of difference** between full combustion and pyrolysis. Biochar production is one of the key Carbon Dioxide Removal (CDR) methods recognised by the UN Intergovernmental Panel on Climate Change (IPCC). Importantly, biochar bioenergy systems have the potential to **concurrently** provide both clean renewable energy to displace fossil fuels (Emissions Reduction, ER) **and** sequester existing CO_2 from the atmosphere into soil (and non-soil) applications that are durable in the long term (CDR).
- **Clean syngas can also provide the chemical 'building blocks' for making other valuable materials and products (syngas 'derivatives')**, such as renewable/low carbon fuels (including sustainable aviation fuel, SAF), methanol and olefins for circular bioplastics, among others, as illustrated in the figure shown in **Appendix 4**. This further upcycles and valorises feedstock biowastes into valuable commodities in a more circular and sustainable fashion, demonstrating a higher order use of resources.
- **Appendix 2** provides further detailed discussion regarding important differences in **air quality (particulates, nitrogen and sulphur oxides, dioxins and furans)** between full combustion/incineration thermal treatment systems, and pyrolysis and gasification thermal treatment systems. These provide further support to the decoupling of linear thermal treatment systems to facilitate supportive policy changes to encourage deployment of more circular thermal treatment systems.
- **Extensive Policy Alignment -** The ***Australian Biochar Industry 2030 Roadmap*** includes a section detailing the **multiple converging commonwealth policy objectives** supported by the biochar industry which should be encouraged by supportive regulatory frameworks.

Table 1: Indicative Comparison of Linear Waste to Energy (Full Combustion/Incineration) and more Circular Thermal Treatments for Biochar (Pyrolysis & Gasification)

	Incineration / Full Combustion *(excess oxygen, high oxidation)*	**Conventional Gasification** (air-blown) *(partial oxidation)*	**Conventional Pyrolysis** *(low/no oxygen)*
Typical Target Scale Application:	Large Scale, centralised	Multiple scales, centralised & decentralised	Smaller scale, decentralised
Primary Products and Secondary Outputs/Byproducts:	**Primary: Heat** (used to generate power) **Byproducts:** Carbon Dioxide (CO_2), H_2O (steam), Other air pollutants (see further below), Ash Residues (solid waste) in large volumes (e.g. requiring ash dams)	**Primary: Syngas (fuel gas/heat),** 95-80% by mass of infeed **Byproducts: Biochar** (typically 5-20% by mass of infeed), **Ash**	*Each below typically comprises ~1/3 (33%) by mass of infeed:* **Biochar** (solid carbon) **Liquids** (e.g. wood vinegar, bio-oils) **Syngas** (heat / fuel gas)
Resource Recovery / Circularity: *(Linear / Circular Economy)*	**Linear, lower LCA** single use of resources for energy alone	**Improved Circularity** Increased circularity where syngas also used for valuable derivatives. Circular carbon as solid biochar (but lower yields than pyrolysis, as focus is syngas).	**Most Circular (and Regenerative** when biochar used in soils) Circular carbon as solid biochar, liquid wood vinegars / bio-oils. Increased circularity when syngas used for valuable derivatives.
Processing Atmosphere:	Air (highly oxidative)	Partial Air	Low /No Oxygen
Oxygen Presence in Processing:	**Very High**	Moderate	Low-Nil
Primary Reaction Temperature: *(in commercial systems)*	**High** 800-1450°C	**Moderate** 700—1000°C (air blown)	**Low** 350-700°C
Off-gas volume to be treated (pollution control):	**Very high**	**High**	**Low to carbon-negative (CDR)**
GHG/Carbon Emissions:	**Very High** (virtually all carbon is emitted)	Moderate-High	Lowest *(up to half the carbon is sequestered in biochar alone)*
CO_2 Removal (CDR) (via biochar): *(atmospheric carbon sequestration)*	**Nil / Negligible** Virtually all infeed carbon is converted to CO_2	Low-Moderate (dependent on biochar yield) – typically 5-20% of carbon infeed is converted to biochar, remainder to CO_2	Highest **(up to 50% carbon sequestered into biochar)**
Harmful Air Pollutant Emissions[3]: *(Particulates, Heavy Metals, VOC's, POPs, NOx, Dioxins & Furans)*	**Highest** (high controls required) Off-gas requires significant treatment, significant proportion of heavy metals emitted)	**Moderate** (emissions controlled) Lower off-gas volume to treat than incineration but still large. Lower NOx	**Moderate-Low** (controlled in commercial plants) Low off-gas volume to treat. Special combustion systems required to destroy tars, dioxins & furans.

[1] *Conventional air blown gasification,* [2] *Conventional slow pyrolysis*

[3] ***Relative comparison under appropriate emission controls and process controls for all types,*** *noting higher oxidative conditions favour D&F formation. Refer further technical discussion in Appendices.*

Acronyms: LCA (Life Cycle Analysis), POPs (Persistent Organic Pollutants), VOCs (Volatile Organic Carbon), NOx (Nitrogen Oxides), SOx (Sulphur Oxides), HMs (Heavy Metals), GHG (Greenhouse Gas), CDR (CO_2 Removal)

- **Some examples of existing regulatory constraints:**
  - Under the ACT Waste-to-Energy Policy 2020-25 (the ACT 'no burn' policy), "New facilities, proposing **thermal treatment** of waste, by means of **incineration, gasification**, **pyrolysis** or variations of these for energy recovery, chemical transformation, volume reduction or destruction **will not be permitted in the ACT**. The only exception to this is for the safe disposal of medical and biological waste."
  - The NSW Energy from Waste Policy Statement, with thermal treatment defined in Schedule 1 of the *Protection of the Environment Operations Act 1997* ("**thermal treatment** means the processing of waste by **burning, incineration**, thermal oxidation, **gasification**, **pyrolysis**, plasma or other thermal treatment processes"). Under the existing policy, all thermal treatment EfW facilities (including pyrolysis and gasification) can only occur in a handful of specifically nominated zones and nowhere else. This effectively eliminates beneficial commercial biochar plants from most of NSW.
  - The Victorian Environmental Protection Act 2017 and its 2012 Regulations pre-classifies biochar, because it is a form of char, as a *Reportable Priority Waste*. Biochar and wood vinegar producers and importers currently have to seek a *'Waste Designation'* so they can sell or transport their biochar or must seek a permit to use biochar on a case-by-case basis. The Environmental Protection Act also considers all scales and forms of pyrolysis and gasification to be undertaking the prescribed activity of *"Immobilising, thermally degrading or incinerating waste",* which requires the highest and most stringent EIA process. This regulatory requirement is **not risk proportionate** (including by scale of activity).
  - The Queensland Energy from Waste Policy states that the policy "applies to all technologies that produce all forms of energy (fuel, electricity, heating, cooling) from waste materials, including those that operate on biological, thermal and chemical or mechanical principles". Importantly, the policy recognises that recovered carbon in liquid fuels made from waste is a higher order use of resources than single use combustion for energy, as illustrated in a "Energy from Waste Hierarchy" established under the policy (see figure at bottom in **Appendix 1**). This established an important precedent recognising circular carbon over linear uses for energy alone. The policy further states that "**Pyrolysis** means the breakdown of waste at elevated temperatures in the absence of oxygen **to produce char, pyrolysis oil, and syngas**" and "**Gasification** means the breakdown of waste at elevated temperatures under oxygen-reduced conditions to produce a **syngas** comprising mainly of carbon monoxide, hydrogen, carbon dioxide, nitrogen, and methane". This recognises the useful circular products from these thermal processes (pyrolysis and gasification), compared to simple full combustion for energy alone (linear 'single use' energy from waste).

Current Regulatory/Policy Impacts on the Biochar Industry

- **In many states, disproportionate regulation exists** where similar assessment requirements and controls **apply to <u>all scales</u>** and types of 'thermal treatment' regardless of the associated environmental risk, resulting in**.** e.g. a small 2m^3 mobile batch kiln to treat **biomass** worth <$25,000 may be assessed and regulated the same as a very large scale (>500,000 tonnes/yr) incinerator to treat Municipal Solid Waste worth several hundred million dollars.
    - In **Western Australia**, recent reforms under the Environmental Protection Amendment Act have introduced **proportionate risk-based regulation employing a *'hierarchy of regulatory control'*** where ***"the level of regulatory control and oversight will be commensurate to the complexity and potential risk posed by an activity"***. Lower risk, smaller scale and less complex projects are managed under *"general provisions",* whereas higher risk, larger scale and complex activities are regulated under more stringent licencing frameworks. Trigger thresholds apply.
    - **However**, whilst the above approach is generally supported, the grouping of all ***'thermal treatment'*** collectively for licencing still requires additional separation by scale, risk **and duration** of activity (e.g. permanent centralised industrial scale waste incinerators compared to decentralised relocatable small scale biochar production).
    - WA is also transitioning from ***premises-based*** regulation ('prescribed premise') to ***activity-based*** ('prescribed activity'). This could help facilitate mobile biochar production technologies. Clear and risk-proportionate approval pathways for mobile biochar production and/or short term 'campaign-based' biochar production (e.g. invasive weed management and bushfire hazard reduction) remain a complex regulatory challenge in a number of Australian states.
- **Policies intended to regulate or limit the extent of large-scale EfW projects can have unintended consequences, in some cases** effectively banning or severely restricting pyrolysis and gasification projects capable of delivering against multiple public policy objectives, including for climate and circular economy. For example as currently seen in the <u>ACT Waste to Energy Policy 2020-2025</u> (total ban on *all* thermal treatment for energy recovery) and in NSW via the EPA's <u>Energy from Waste Policy</u> and <u>associated legislation</u> and state environmental planning policy (banned in Greater Sydney and heavily restricted elsewhere to a handful of nominated zones). This needs to be rectified urgently (e.g. via innovation pathways justified by the principles and technical reasoning outlined in this paper, *and further if required, which can be supplied upon request*). <u>The Victoria Energy from Waste framework</u> (Section 3.2, page 13) is an example of Government policy that recognises and ***specifically excludes "treating waste biomass through a thermal***

pyrolysis process to sequester carbon" from the scope of their EfW Policy. This is encouraged in all states.

- Disproportionate regulation results in unfeasible costs of testing and compliance monitoring, particularly for small scale distributed circular thermal treatment systems.
- Regulatory approval **classifications** (e.g. **planning and licencing categories**) for thermal treatment systems in some states **currently only provide for waste *disposal,*** and are yet to be updated to recognise *resource recovery* via thermal treatment. For example licencing in NSW currently classifies commercial biochar facilities as *'Waste Disposal – Thermal Treatment'(Cl40, Sch1, POEO Act).* Adopting policies to decouple linear thermal treatment from those generating circular carbon resources can be further facilitated by providing appropriate categories in associated planning approvals and licensing.

Recommended Policy Approaches

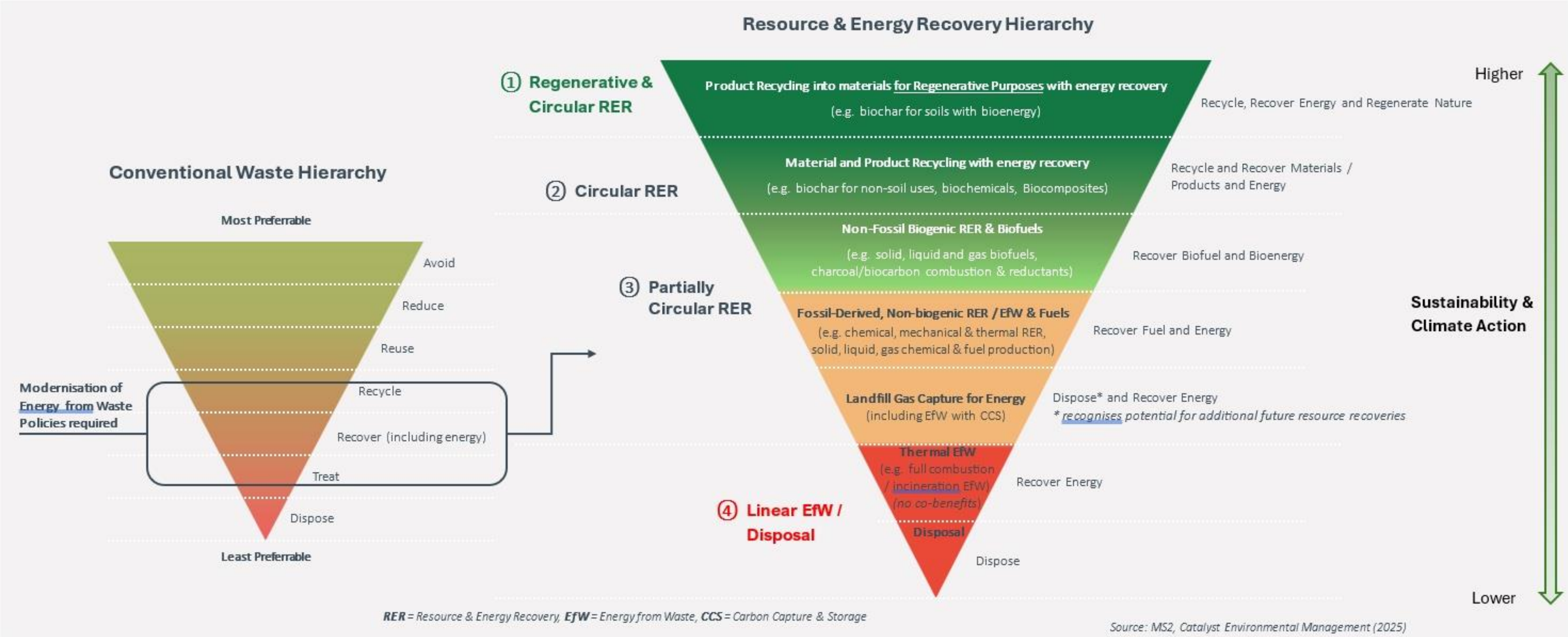
- Create circular economies that facilitate **regeneration of nature** (one of the three critical pillars of circular economy). Ensure this is considered in policy frameworks that assess higher order use of resources when recovering wastes as resources.
- **Incorporate the principles presented in this paper to separate linear and circular thermal treatment systems in policy and regulatory frameworks, providing pathways for implementation of circular thermal treatments such as pyrolysis and gasification**. This should include innovation pathways for pilots and commercial scale demonstrations.
- Adopt a ***Resource & Energy Recovery Waste Hierarchy*** (e.g. as proposed in **Figure 2**) which recognises solid, liquid and gas circular carbons, to modernise assessment of higher order use of resources and decouple linear and circular energy from waste systems.
- Reflect **scale, type, duration and risk** of activities **proportionally** in policies and regulations, including compliance testing and monitoring.
- Consider production and use of biochar as a 'higher order/value use' under resource recovery and energy legislation and regulations.
- Revise definitions relating to *'thermal treatment'* in policies and legislation to **decouple linear** 'single-use' processes (e.g. combustion/incineration for end of life disposal) **from circular and regenerative** processes (e.g. pyrolysis and gasification of biomass).
- Recognise circular thermal treatments producing biochar as forms of *resource recovery* and higher order use, rather than *waste disposal.* This includes creating new/separate planning and licencing classifications/categorisation reflecting thermal treatment for resource recovery where required.
- Define biochar consistent with the ANZ Biochar Industry Group (ANZBIG) to help ensure consistency and fitness for purpose. Biochar is specifically reserved for applications that provide durable removal of carbon in the long term.

- Ensure regulatory and policy pathways **also facilitate co-feeds** (e.g. biomass and biosolids), and provide flexibility to ensure they do not inadvertently exclude potential positive outcomes.
- Create circular economies that value feedstocks (resources) over 'wastes' - Adopt the principles of 'End of Waste Codes' and related guidelines/standards to define when a 'waste' becomes a *resource.*
- Provide support to, and recognition of, industry standards and certification for biochar (including those developed by ANZBIG) to provide confidence in 'fit for purpose' circular carbon products.
- Recognise and support the value of biochar production for climate action, circularity and sustainability (including water and regeneration of nature among many other factors such as the UN SDGs). This should include consideration of these benefits in government procurement systems.
- Recognise and support the potential of the biochar industry to contribute to regional socio-economic development and resilience by creating modern 'green' jobs and industries, supporting agricultural productivity, and building resilience in drought-prone regions.
- Recognise and support the potential value and contribution of biochar to emerging carbon markets (particularly for critical CO_2 removal), via both compliance markets (ACCUs) and voluntary carbon markets. This should include consideration of these benefits in government procurement systems, and prioritisation of crediting method development and recognition.
- **Provide new financial incentives to encourage and foster innovation in circular and thermal treatment systems**. These could include, but not be limited to, the following:
    - Support implementation of the ***Australian Biochar Industry 2030 Roadmap***, including its initiatives for addressing current regulatory hurdles.
    - **Provide low-interest loans** to circular thermal treatment facilities (R&D, pilot and commercial), similar to that done in education (*"HECS for Clean Energy & Climate"*)
    - **Provide Independent/Government mobile testing facilities for validation** of outputs from circular thermal treatment systems *(Aim: to remove or lower one of the key inhibitors to new technology advancement in Australia)*. This could even be linked to low interest loans (above) if required.
    - **Tax incentives** for circular and regenerative technologies, similar to those provided in Europe and (until recently) the USA.

APPENDICES:

- **Appendix 1: Modified Resource and Energy Recovery Hierarchy (A3)**
- **Appendix 2: Further Information to Support Decoupling of Circular Thermal Treatment**
- **Appendix 3: Circular Uses for Biochars & Biocarbons (Soil and Non-soil/Industrial)**
- **Appendix 4: Circular Uses for Syngas and Syngas Derivatives**

Appendix 1: Resource and Energy Recovery Hierarchy (A3)



Example similar existing precedent (Qld EfW Policy 2021):

Existing EfW Hierarchy (Qld, 2021):

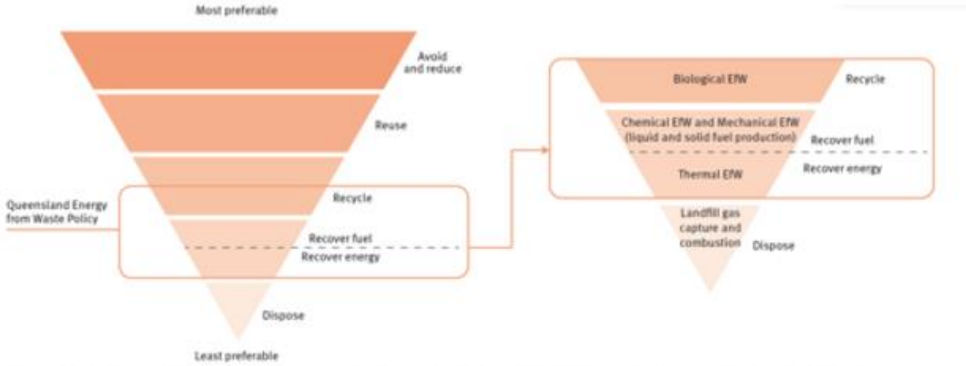


Figure 3: Waste and Resource Management Hierarchy (left), and EfW Hierarchy for residual waste (right) for Queensland

*← Currently recognises circular carbon **liquids** + **EfW** as Higher Order Uses, but **not** yet circular carbon **solids** (biochar) or **gases** (syngas) + EfW for additional resource recovery / 'chemical recycling' + EfW across all 3 physical phases (S, L, G)*

Appendix 2: Further Information to Support Decoupling of Circular Thermal Treatment Systems

This appendix provides further discussion on air quality/emissions and climate-related factors that can be considered in support of differentiating linear EfW systems (full combustion and incineration) from more circular thermal treatment systems to produce biochar from plant biomass, such as pyrolysis and gasification.

1. Nitrogen & Sulphur Oxides (NOx, SOx)

NOx gases (nitrogen oxides) are precursors of photochemical smog (and other environmental and health issues), commonly seen in cities with air pollution caused by fine particulates and NOx gases combustion of carbon (e.g. car engines). SOx gases (sulphur oxides) are precursors of acid rain and other environmental and health issues. NOx and SOx (sulfur oxides) emissions are typically lower in pyrolysis and gasification processes compared to full combustion and incineration due to several factors:

- **Oxygen Limitation**:

  Oxidative conditions favour formation of NOx and SOx. Pyrolysis and gasification occur with limited oxygen, which results in only partial oxidation of the feedstock material. This condition reduces the formation of NOx and SOx, which is more prevalent in complete combustion where an excess of oxygen promotes these reactions. The solid product (biochar) produced in pyrolysis, and to lesser extent by gasification, can contain significant proportions of sulphur and nitrogen from the feedstock in more beneficial form (e.g. for soils), preventing their release into the atmosphere relative to the fully oxidised emissions created by full combustion/incineration.

- **Temperature Control**:

  Pyrolysis and gasification operate at lower temperatures than traditional combustion processes. High temperatures in combustion can lead to the formation of NOx through the oxidation of nitrogen present in the fuel and the air. Lower temperatures help minimize this reaction.

- **Control of Reaction Products**:

  Pyrolysis produces syngas (a mix comprised primarily of hydrogen and carbon monoxide, and other products) which can be cleaned or treated before being used, allowing for further reduction of nitrogen and sulphur compounds compared to directly burning organic waste in full combustion.

Example References:

1. *Zhou, J., et al. (2017). "Comparison of Emissions from Pyrolysis and Combustion of Biomass." Bioresource Technology, 245, 862-870.*
2. *Mishra, P., & Rajak, U. (2016). "Gasification and Pyrolysis of Biomass." Renewable Energy, 99, 1069-1082.*
3. *Basu, P. (2010). "Biomass Gasification and Pyrolysis: Practical Design and Theory." Academic Press.*

2. Particulates

Particulate emissions from pyrolysis and gasification are generally lower than those from full combustion or incineration for several key reasons:

- **Incomplete Oxidation / Reducing Conditions**: Pyrolysis is a thermochemical decomposition process that operates in an oxygen-limited environment, producing char, gases, and liquids/oils without undergoing complete oxidation of the feedstock. This results in fewer solid particulates such as soot and ash compared to full combustion, which completely oxidizes the material to produce carbon dioxide (CO_2) but also releases ash and other particulates. Up to 50% of the carbon content of the feedstock (by mass) can be retained in the solid output (biochar) from slow pyrolysis.

- **Temperature and Reaction Environment**: Pyrolysis and gasification occur at lower temperatures compared to combustion. This reduces the formation of fine particulate matter which is often a byproduct of high-temperature combustion. The temperatures in pyrolysis typically range from 350 to 700 °C, while gasification can typically be 700 to 1,000 °C. In contrast, full combustion usually requires temperatures above 1,000 °C. The lower temperatures in pyrolysis and gasification help to minimize the formation of nitrogen oxides (NOx) and other particulates by reducing the vaporization and oxidation of feedstock materials.

- **Control of Feedstock, Processing Conditions and Products/Outputs (including solid carbon yield (biochar))**: Both pyrolysis and gasification allow for more controlled reactions, which can optimize the breakdown of materials and reduce the formation of harmful byproducts, including particulate matter. In pyrolysis and gasification the biomass feedstock composition can be carefully managed to optimize the process, leading to cleaner emissions. The solid carbon biochars produced can be channelled into beneficial higher order uses for soil and non-soil/industrial applications, rather than being released into the atmosphere as emissions/pollutants as occurs with combustion/incineration.

- **Enhanced Gasification Applications, Controls and Technologies**: Modern gasification and commercial pyrolysis technologies often include processes that condition the syngas (synthetic gas) to remove impurities before it is combusted for energy production, further reducing the particulate matter emitted. Facilities using pyrolysis or gasification often incorporate advanced filtration, cyclones and scrubbing technologies to remove any particulate matter that might still form, further reducing emissions.

- **Lower Ash Content**: Typically, the char and ash produced in pyrolysis and gasification processes are quantifiably lower than those produced from direct combustion, which helps lower particulate emissions.

Example References:

1. *Zeng, Y., et al. (2019). "Particulate Matter Emission Characteristics of Pyrolysis and Gasification of Biomass." Journal of Analytical and Applied Pyrolysis, 144, 104688.*

2. *Sridhar, S., et al. (2012). "Pivotal Role of Synthesis Gases and Char on the Formation of Particulate Matter During Biomass Gasification." Energy & Fuels, 26(2), 1334-1345.*

3. *Bridgwater, A. V. (2012). "Renewable Fuels and Chemicals from Biomass via Fast Pyrolysis and Gasification." IEA Bioenergy Task 34: Biomass Fast Pyrolysis.*

These references provide further discussion of the differences in emissions between pyrolysis, gasification, and full combustion, along with detailed discussions on the mechanisms involved.

3. **Dioxins and Furans -** are toxic compounds that can be formed during the combustion of organic materials, especially those containing chlorine. The emissions of these compounds from pyrolysis and gasification processes are generally lower than those from full combustion and incineration for several reasons. Dioxin formation is generally lower in gasification and pyrolysis compared to incineration due to the reducing atmosphere and lower temperatures during the gasification process, which inhibits the formation of dioxin precursors and the actual dioxin molecules themselves. The constrained oxygen conditions prevents the formation of chlorinated precursors, which are essential for dioxin formation. The formation of syngas before combustion in gasification can also create complete and stable burning, reducing the formation of chlorinated precursors.

    - ***Temperature Control:*** Pyrolysis and gasification typically operate at lower temperatures compared to full combustion. Dioxins and furans are formed in the presence of chlorine at high temperatures, so the reduced thermal conditions in pyrolysis and gasification processes minimize their formation.

    - ***Oxygen Levels:*** In pyrolysis, the process occurs in an oxygen-free or limited-oxygen environment, which prevents complete combustion. As a result, the pathways that lead to the formation of dioxins and furans are disrupted. On the other hand, full combustion provides excess oxygen, leading to higher temperatures and the potential for dioxin synthesis.

    - ***Feedstock Composition:*** The nature of the feedstock can influence emissions. Pyrolysis and gasification can be tuned to process various organic materials without the chlorine-rich components that often lead to increased dioxin and furan production.

    - ***Reactor Design:*** The design of pyrolysis and gasification reactors can further minimize dioxin and furan formation by controlling the reaction conditions, such as temperature, pressure, and residence time.

Example References:

1. *Chuang, M. H., & Lee, W. J. (2016). "Dioxin formation during the gasification of solid waste: a review." Waste Management, 57, 38-48. DOI: 10.1016/j.wasman.2016.07.016.*

2. *Aizawa, Y., & Tominari, Y. (2008). "Formation of dioxins from incineration and gasification processes." Environmental Science & Technology, 42(13), 4930-4935. DOI: 10.1021/es8000166.*

3. *Liu, Y., et al. (2018). "Dioxins and furans in gasification processes: A review." Waste Management, 72, 189-198. DOI: 10.1016/j.wasman.2017.10.021.*

These references provide insight into the mechanisms and comparative emissions of dioxins and furans across different waste treatment technologies.

Appendix 3: Circular Uses for Biochars & Biocarbons (Soil and Non-soil/Industrial)

Appendix 4: Circular Uses for Syngas and Syngas Derivatives