Cost benefit and life cycle analysis of recycling pathways of CFRP wastes

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Research Background

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Mechanical properties	High strength to weight ratio and corrosion resistance
High consumption	Have been widely used in various industries such as aerospace, automotive, and construction for production of composite sections[1]
Significant amount of wastes	The predicted amount of wasted carbon fibre: 10000t in 2005 --- 57,000t in 2010 --- 88,000t in 2015 --- 130,000t in 2020 --- **263,000t in 2030** [2]
Landfill or incinerated	Unsustainable practices for waste management [3]

[1] Olofin, I. and Liu, R. (2015). The Application of Carbon Fibre Reinforced Polymer (CFRP) Cables in Civil Engineering Structures. SSRG International Journal of Civil Engineering (SSRG-IJCE), 2(7), 1-5.
[2] Witik, R. A., Teuscher, R., Michaud, V., Ludwig, C. and Månson, J.-A. E. (2013). Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. Composites Part A: Applied Science and Manufacturing, 49, 89-99.

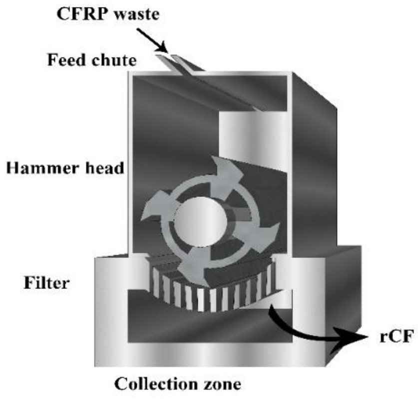
Research Background

A comprehensive evaluation of ten different CFRP and GFRP waste treatment methods (i.e. landfill, incineration, mechanical recycling, catalytic pyrolysis, oxidation, pyrolysis combined with oxidation, fluidised bed, solvolysis using alkali and acid solvents, and electrochemical methods) based on a combined CBA and LCA approach for both European and Australian markets

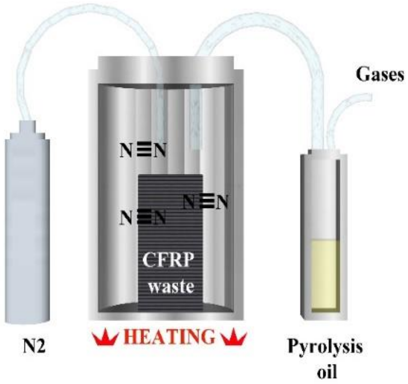
Cost-benefit analysis (CBA) is a systematic approach to determine the possible benefits and related costs presented during a certain investment period.

Life cycle analysis(LCA) is a well-developed evaluation method that investigates the impact on environment and society. My project will focus on two main factors of LCA, which are cumulative energy demand (CED) and global warming potential/CO_2 impact.

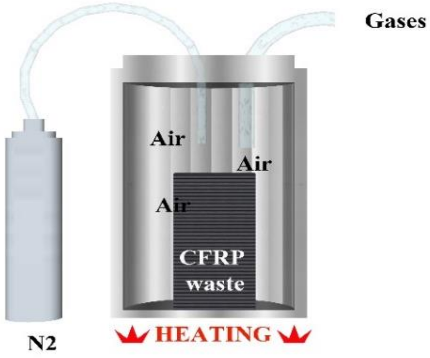
Research Background



Mechanical: Uses shredding, crushing or milling techniques to break down the waste into powdered or fibrous form for reuse as the filler or secondary reinforcement [3]



Pyrolysis: A thermal recycling method in which the waste is decomposed in an oxygen-free environment with/without special catalysts [4]



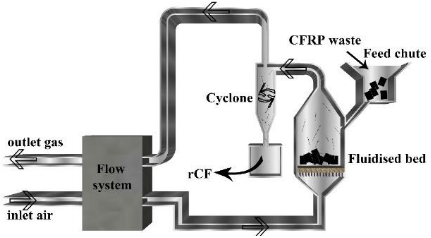
Oxidation: Similar to pyrolysis except the reaction occurs in the presence of the air [5]

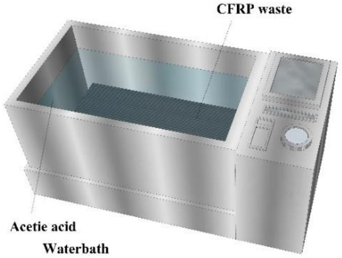
[3] Zhou, B. (2021). Experimental study on mechanical property and microstructure of cement mortar reinforced with elaborately recycled GFRP fiber. Cement Concrete Composites, 117, 103908

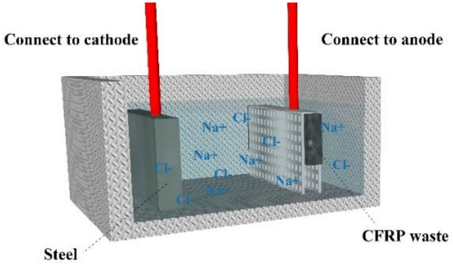
[4] Pimenta, S. and Pinho, S.T. (2011). Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. Waste Management, 31(2), 378-392

[5] Meyer, L.O. (2009). CFRP-Recycling Following a Pyrolysis Route: Process Optimization and Potentials. Journal of Composite Materials, 43(9), 1121-1132

Research Background







Fluidised bed: A thermal recycling method, which employs flow stream to transfer the heat to the composite waste positioned on the silica sand bed [6]

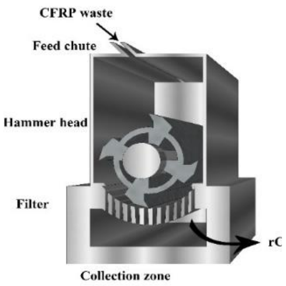
Solvolysis: A chemical recycling method where solvents are used to break down the matrix bond under a specific pressure and temperature and reclaim carbon fibre [7]

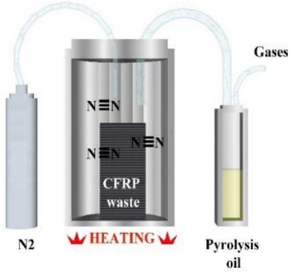
Electrochemical: Resin matrix is removed from fibre surface by using electrical power [8]

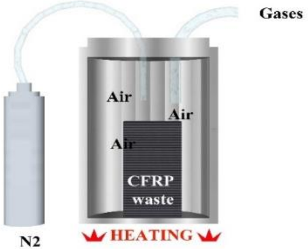
[6] Pickering, S.J. (2006). Recycling technologies for thermoset composite materials—current status. Composites Part A: Applied Science and Manufacturing, 37(8), 1206-1215
[7] La Rosa, A.D. (2016). Recycling treatment of carbon fibre/epoxy composites: Materials recovery and characterization and environmental impacts through life cycle assessment. Composites Part B: Engineering, 104, 17-25
[8] Sun, H.(2015). Recycling of carbon fibers from carbon fiber reinforced polymer using electrochemical method. Composites Part A: Applied Science and Manufacturing, 78, 10-17.

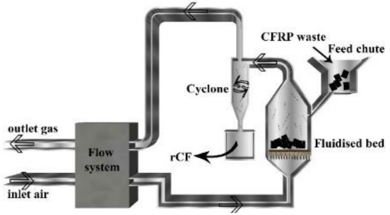
Technology Readiness Level (TRL)

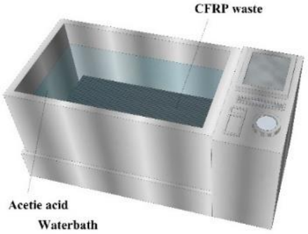
- TRL9 — Successful mission operations
- TRL8 — System complete and qualified
- TRL7 — Demonstration in operational environment
- TRL6 — Demonstration in relevant environment
- TRL5 — Technology valid in relevant environment
- TRL4 — Technology validation in lab
- TRL3 — Experimental proof of concept
- TRL2 — Technology concept formulated
- TRL1 — Basic principles observed

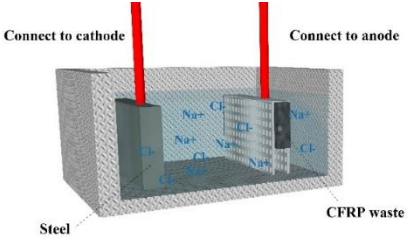












CBA Analysis

$$Co = C4 + C5 + C6 + C7 + C8 + C9$$

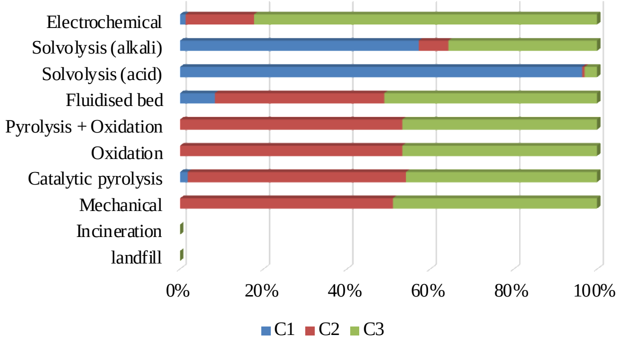
$$C4 = C_{labour} + C_{non-labour} = (1 + 1.5) \times \mathrm{Cl}$$

$$C6 = \mathrm{Cdh}(\mathrm{Dt})(\mathrm{Wd}) + \mathrm{Csh}(\mathrm{St})(\mathrm{Ws})$$

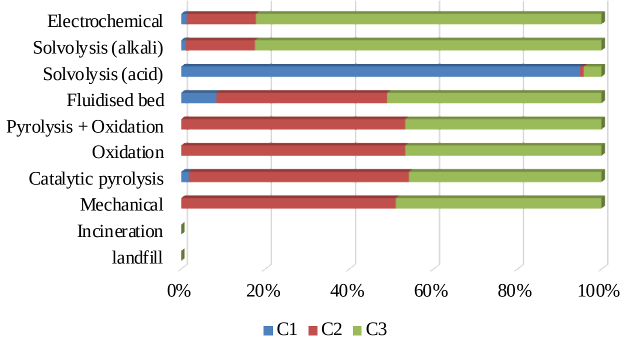
$$C7 = \mathrm{dc}(\mathrm{Wdp})$$

Costs		
Capital cost	Raw material cost	C1
	Utility cost - Rental or purchase of equipment	C2
	Site preparation - Rental or purchase of industrial land for material storage and material treatment	C3
Operational cost	Operating and non-operating labour cost (e.g. administration)	C4
	Maintenance cost (i.e. 0.02 × Investment on equipment)	C5
	Waste pre-processing cost (disassembly and shredding)	C6
	Waste post-processing cost (Waste final disposal cost)	C7
	Supplies (i.e. 0.3 × operating labour cost)	C8
	Cost of material transportation	C9
Benefits		
Recyclable materials recovery	Economic value of recycled fibre	B1
	Economic value of secondary products	B2
Reduction of landfill cost	Reduction in expenditure of landfill site management. This value varied for different recycling methods due to their different productivity capacity	B3
Energy recovery	Production of residue derived fuels (RDFs) from waste FRP	B4

CBA Analysis

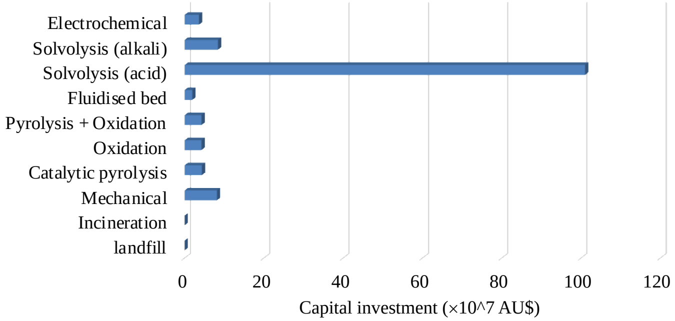


(a)



(b)

Capital investment for different (a) CFRP, and (b) GFRP waste treatments for Australian market.



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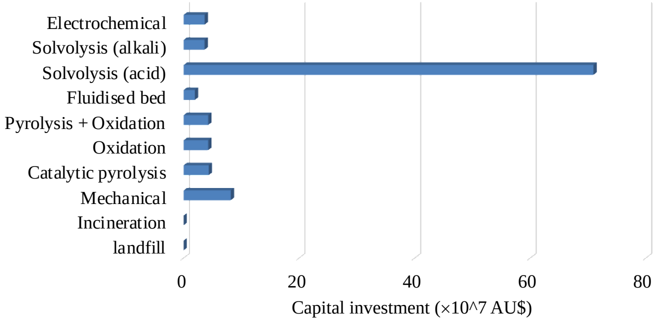


(b)

Total capital investment for different (a) CFRP, and (b) GFRP waste treatments over 10 years for Australian market.

CBA Analysis

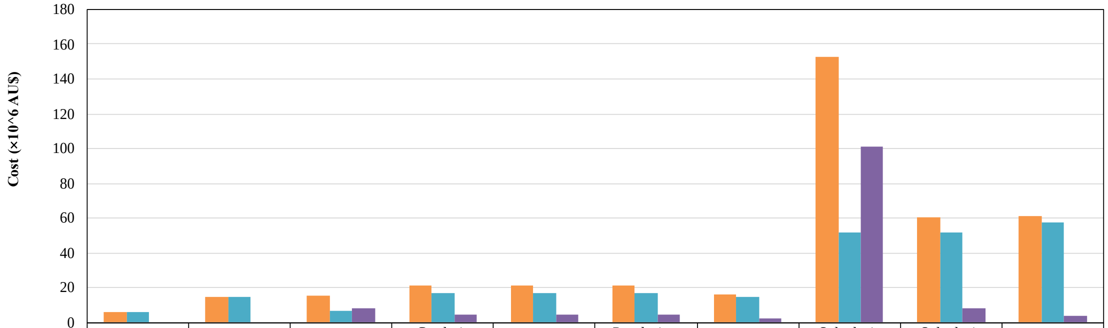
Cost analysis results for recycling of CFRP

- Solvolysis and electrochemical methods require large amount of fund to support their daily operations, with total value over AU\$ 5×10^7 for ongoing cost for solvolysis with acid solution.

- Significant cost reduction by using the alkali solution instead of acid.

- All thermal recycling methods have modest charges on both capital and operational investment

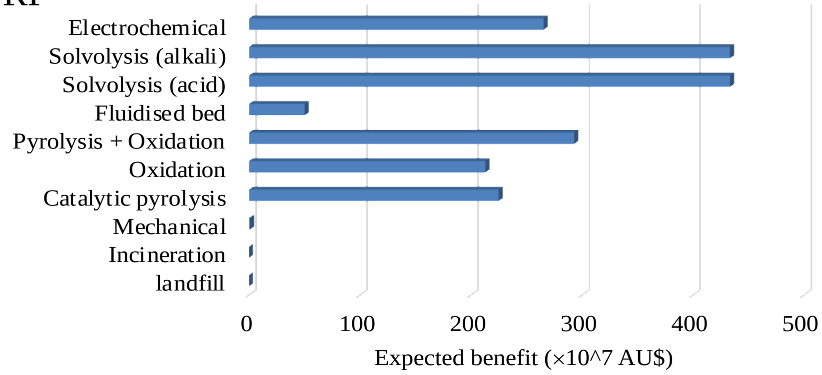
- The general trend of cost analysis is similar for CFRP and GFRP waste as the same equipment is used for both materials.



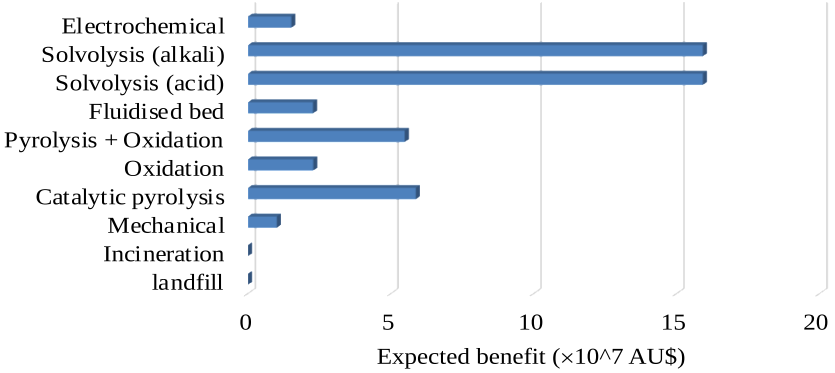
	landfill	Incineration	Mechanical	Catalytic pyrolysis	Oxidation	Pyrolysis + Oxidation	Fluidised bed	Solvolysis (acid)	Solvolysis (alkali)	Electrochemical
Total INV (10 yrs)	6.1	14.5	15.0	21.2	21.1	21.1	16.2	153.0	60.4	61.1
Operational cost (10 yrs)	6.1	14.5	6.8	16.8	16.8	16.8	14.3	52.0	52.0	57.4
Capital investment (10 yrs)	0.0	0.0	8.2	4.4	4.3	4.3	2.0	101.0	8.4	3.6

CBA Analysis

- CFRP



- GFRP



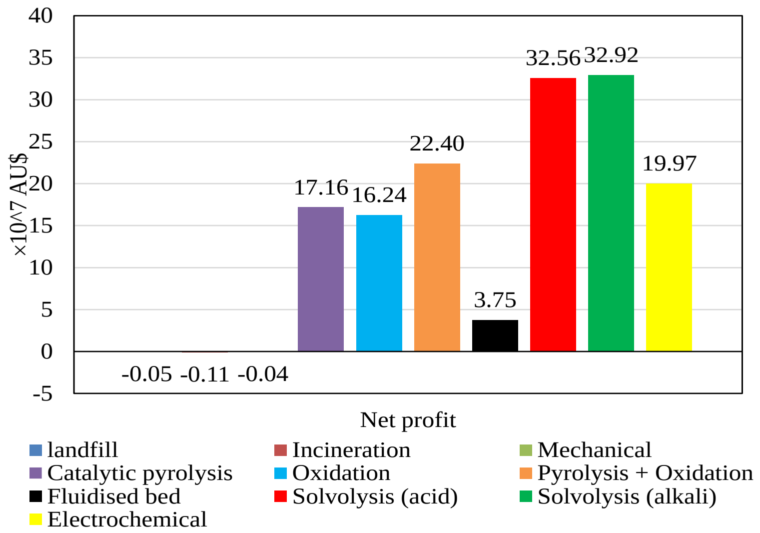
- Solvolysis is able to provide the highest benefit due to high tensile capacity of reclaimed fibre after recycling process

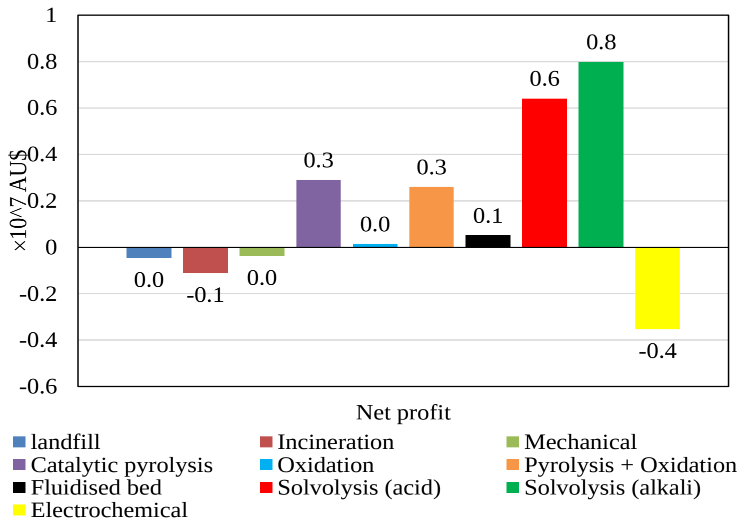
- Pyrolysis and oxidation method is also a promising method for earning high economic returns as more secondary products and energy could be recovered via thermal degradation of the matrix.

- More benefit could be gained by reclaiming fibres from CFRP waste than glass fibre from GFRP waste since there is a relatively lower rate of return of investment for recycling of glass fibre.

CBA Analysis

The Net Profit Value (NPV) for different CFRP and GFRP waste treatments. The NPV is total profit earned due to recycling actions can be viewed at the end of defined investment period.



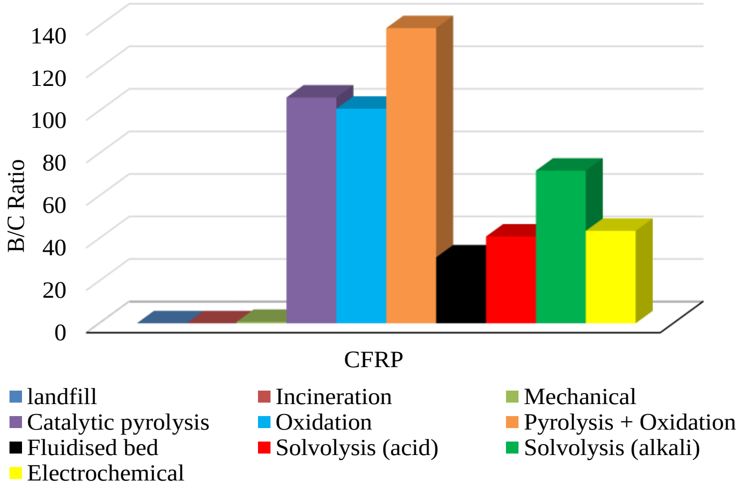


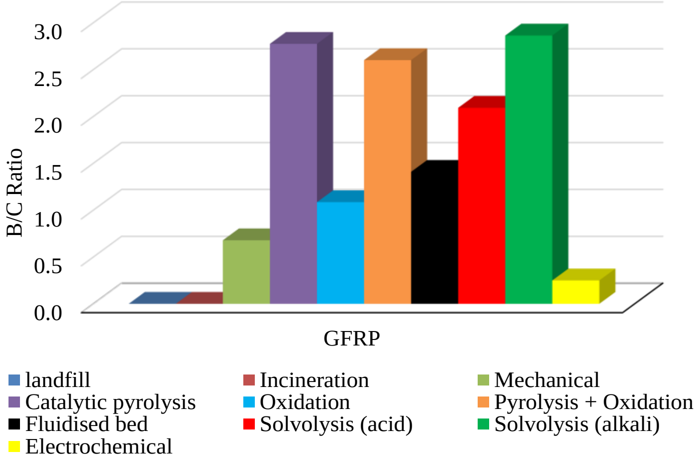
Net profit for CFRP and GFRP waste treatment methods in Australia

CBA Analysis

The benefit-cost ratio (BCR) for different CFRP and GFRP waste treatments. The BCR is an indicator that shows the relationship between the corresponding costs and expected benefits of a certain waste path.

$$BCR = \frac{\text{net income (total benefits } - \text{ corporate income tax)}}{\text{the sum of capital cost and operational cost}}$$

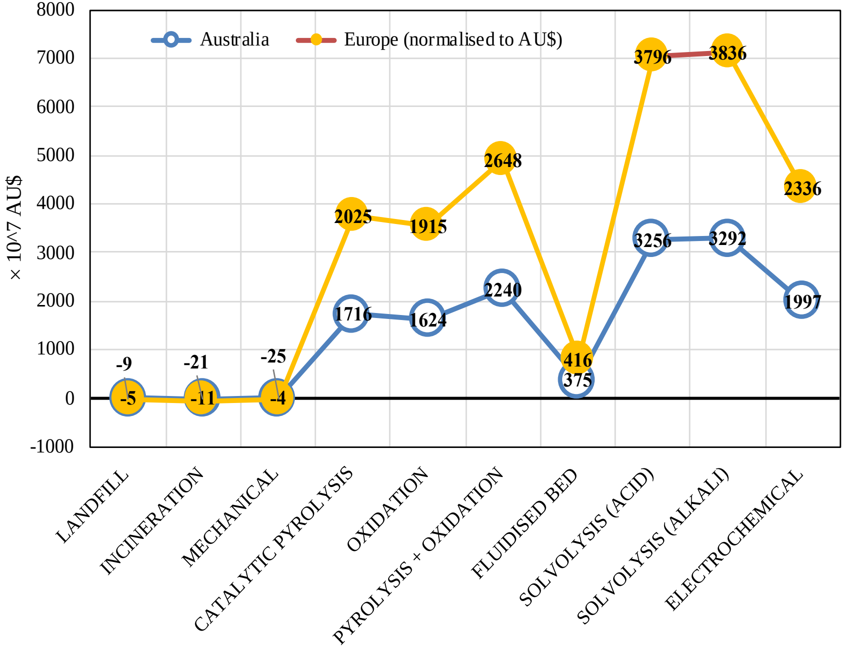




BCR for CFRP and GFRP waste treatment methods in Australia

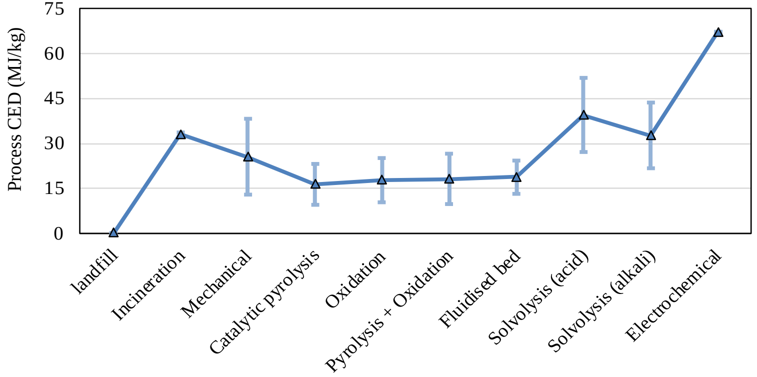
Difference between net profit for Australian & European markets

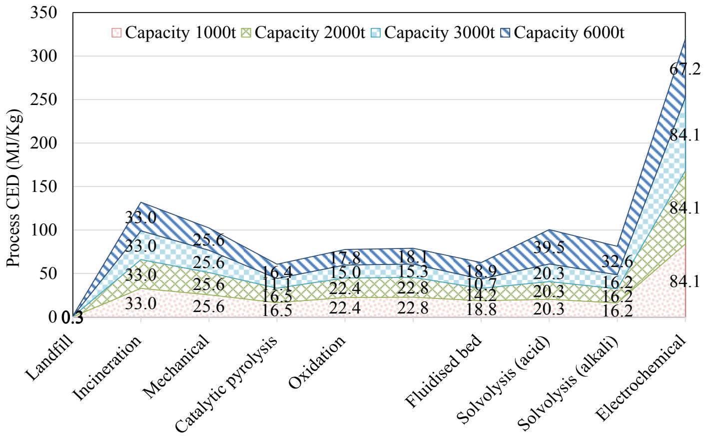
- Pyrolysis and solvolysis are more promising for both Australia and Europe.
- The net profit of pyrolysis and solvolysis recycling methods is higher for European market compared with the Australian one.
- These variations in benefit are due to technological advancement and availability of renewable energy infrastructures during recycling process in each region, and government supports.



LCA Analysis

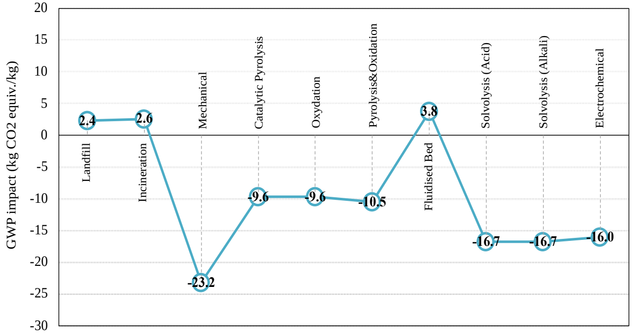
- Cumulative energy demand (CED)
- It also could be used as a framework by industry for decision making on selecting recycling technique by considering energy consumption intensity, especially in relation to non-renewable energy use for each treatment method
- Sensitivity analysis based on waste capacity for CED: four levels of processing capacity were tested for investigating the impact of input quantity on CED, which are 1,000, 2,000, 3,000 and 6,000 tonnes

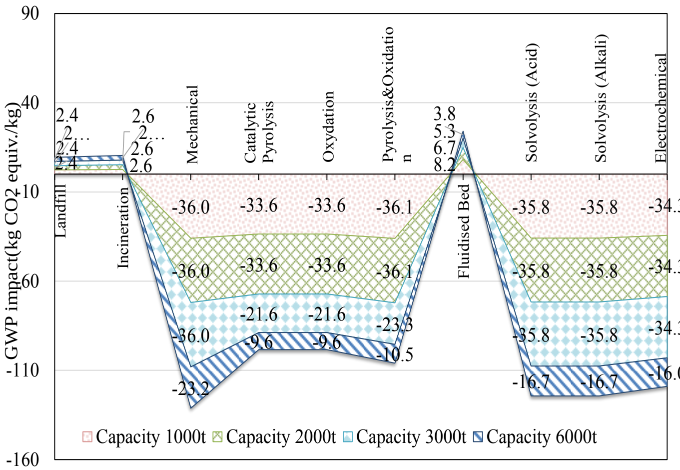




CBA Analysis

- Global warming potentials (GWPs) --- the impact of different greenhouse gasses in the atmosphere
- Lower value indicates lower negative impact on the environment and the negative value means the reduction of greenhouse gas.





Conclusions

Cost-benefit analysis:

- Solvolysis could provide highest profit due to its high value of net profit.
- The performance of solvolysis could vary by using different chemical solutions. Solvolysis with acid solution requires higher capital investment and produces less value of recycled fibre after acidification.
- Thermal recycling methods such as catalytic pyrolysis and pyrolysis plus oxidation also provide high economic return.
- Electrochemical method requires large operational cost.
- The economic returns of different recycling techniques performed slightly different for Australian and European markets.

Life cycle analysis:

- Thermal recycling methods require low energy input with reasonable expected economic profit. Compared with pyrolysis combined with oxidation, electrochemical method requires large amount of electricity to obtain similar profit.
- GWP impact analysis showed that solvolysis and electrochemical methods have lowest CO_2 emission during recycling while landfill, incineration and fluidised bed treatments cannot satisfy the expectations of CO_2 emission reduction and may contribute to global warming.

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