Creating a sustainable coal mining value chain from South Africa's historical and arising discard coal

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Abstract. South Africa`s legacy of coal mining has resulted in the accumulation of over 2 Bt of historical coal discard. Moreover, an estimated 60 Mtpa of new discard coal (as arising) is produced from current mining operations due to the unavailability of cost-effective beneficiation technologies to reclaim the waste. The high dependency on coal as a source of energy generation, employment and economic activity in the South African context means that the transition to a lower environmental impact energy supply portfolio will need to be carefully implemented in a considered manner. River Energy (RE) is uniquely positioned to capitalise on the historical and as-arising discard coal through its integrated coarse to ultra-fine waste coal beneficiation technologies which include; Coarse Waste Beneficiation, Fine Coal Beneficiation and Binderless Coal Briquetting. These solutions reduce costs and rehabilitation liabilities from coal processing and maximise yield from coarse and/or ultra-fine waste. A preliminary life cycle assessment on the RE value chain shows a significant net positive impact on human health, ecosystem quality and resource scarcity when discard-derived coal products are used to generate electricity, compared to conventional coal. This highlights the role of discard coal valorisation as part of a sustainable energy solution for the country's transition towards an energy supply portfolio that has a lower environmental impact.

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1 Introduction

The demand for coal persists globally as the consumption of the resource doubled between 1993 to 2023, and is expected to reach 8.77 billion tonnes in 2024, despite international pressure to phase out fossil fuels [1]. South Africa is predominantly dependent on coal for its energy needs, accounting for 73.4% of the electrical supply [2]. Moreover, the coal industry directly employs 96050 people, and generated 192.5 billion rands in sales from a total production of 231.7 Mt of coal in 2023 [3]. The decision to prioritize maintenance on Eskom`s coal power station fleet, as well as the postponement in decommissioning three coal power stations, as a result of the recent energy crisis (load shedding), highlights the importance of the commodity in achieving reliable and affordable energy from base load power generation [4-7]. This is mirrored internationally by the tendency of developed nations, to revert to coal-fired electricity generation in times of severe weather conditions or in response to geopolitical conflicts such as the ongoing Russian invasion of Ukraine which resulted in a global energy crisis since 2021 [8, 9].

South Africa`s 154-year coal mining legacy is estimated to have accumulated over 2 Bt of historical coal discard [10, 11]. Moreover, an estimated 60 Mtpa of new discard coal (as-arising) is produced from current mining operations due to the unavailability of cost-effective beneficiation technologies to process the waste commercially [12]. The quality of this discard coal is known to be equivalent to that of virgin coal, and it is therefore a relatively untapped resource that could provide an additional 10 years of energy supply, at a lower life cycle impact relative to virgin coal mining [13-17].

The abundance of coal resources and reserves, coupled with the extensive infrastructure of coal-fired power stations, high levels of unemployment and political factors mean that coal will continue to be exploited in South Africa for the foreseeable future [18, 19]. At the time of writing, 16 new coal mines are in the project phase of development in the country [1]. Given the global imperative to reduce greenhouse gas emissions, the South African Government has committed to a Just Energy Transition Investment Plan (JET IP) which seeks to decarbonize the energy sector whilst ensuring workers are up-skilled and employed in a low-carbon economy [10]. Therefore, the transition away from a coal-intensive energy sector in the South African context requires careful planning and management over time to adequately address the associated social and economic challenges [5, 10].

While economic growth and prosperity are directly linked to reliable and affordable energy supply, particularly in developing countries such as South Africa, the impact of energy generation on the environment requires equal consideration [20]. The coal mining value chain, including the combustion of the fuel at power stations, has caused significant environmental degradation and health issues for workers and local communities such as air pollution, surface and groundwater contamination, soil erosion, land disturbance, visual pollution and occupational diseases [21-25].

River Energy is an established waste coal-to-energy company that is uniquely positioned to capitalise on the historical and as-arising discard coal through its integrated coarse to ultra-fine waste coal beneficiation technologies which include coarse waste beneficiation, ultra-fine coal beneficiation and binderless coal briquetting (Figure 1). These solutions are designed to maximize product yields, and reduce costs and rehabilitation liabilities from coal processing operations resulting in: increased revenue generation, an extension of the life of mine, and employment creation in a circular economy [26, 27, 28]. The valorization of coal waste rock and mine tailings has several benefits which complement the JET IP in terms of: reducing load-shedding through the maintenance of the current coal-generated energy supply in the interim as the country gradually transitions to cleaner options, as well as contributing towards restoring and repurposing coal mining land that would otherwise be occupied by coal waste [10]. This paper provides an overview of the River Energy waste coal to energy value proposition as a sustainable energy transition solution in the interim as the coal industry seeks to reduce negative environmental impacts associated with its activities, and as the country works towards transitioning towards a lower environmental impact power footprint.

2 Reimagining the coal life cycle

The typical coal mining life cycle (Figure 1) involves eight key stages and processes, namely,

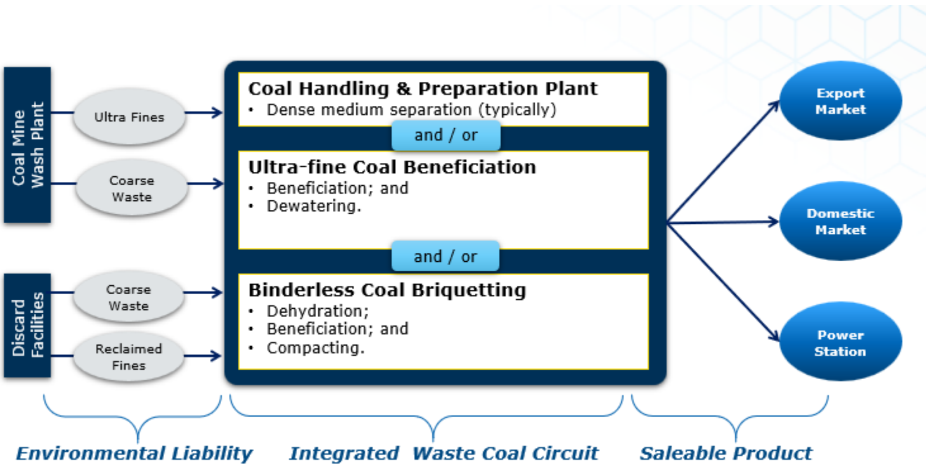

Fig.1. River Energy discard coal processing solutions.

exploration, mining, haulage, beneficiation, transportation, utilisation by the end user and eventual rehabilitation at the end of the life of the mine [29]. Each stage contributes varying degrees of environmental and health impacts [31, 32]. As illustrated in Figure 2, the River Energy waste processing solutions are designed to intercept and create value from waste coal to produce an energy product with a lower overall environmental impact.

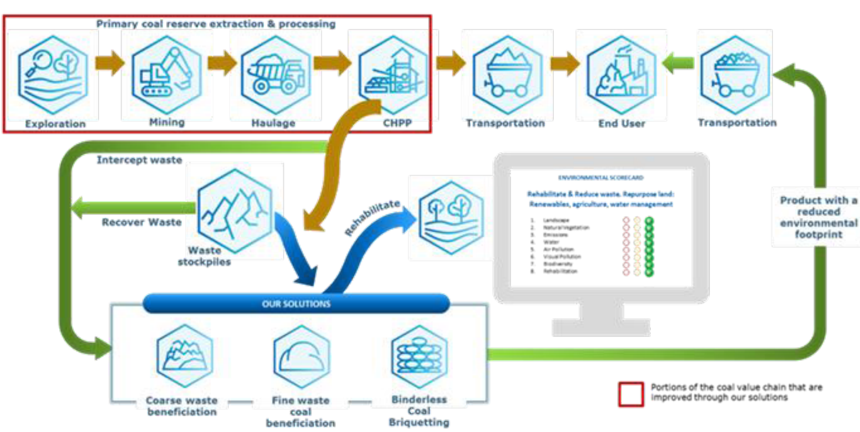

Fig.2. Life cycle of River Energy waste coal processing solutions.

2.1 Coarse waste beneficiation

River Energy is currently recovering and processing ~5 Mtpa of waste coal from historical coal discard dumps in the Emalahleni (Witbank) area in partnership with key sector participants to deliver products into the domestic and export markets. The waste coal is hauled from discard dumps to a coal handling and preparation plant (CHPP) where it is beneficiated by dense medium separation to yield a coarse washed product (-50mm+1 mm). The rejects (+50mm) are discarded into a main dump where further rehabilitation is undertaken. The fines (-1mm +200um) are de-slimed and sent to a spirals circuit with the balance of the fine material routed to a thickener for dewatering and thickening of solids before being sent to the filter press to produce filter cake (-200µm). The common practice in the coal industry is to discard this material as it is generally considered an unsaleable liability due to its high moisture and ash content, as well as the difficulty in handling and transporting the material [33, 34]. However, River Energy upgrades the filter cake through its proprietary fine coal beneficiation circuit, resulting in targeted yields in the range 40-60% with costs and liabilities reduced on these additional saleable volumes.

2.2 Fine and ultra-fine coal waste beneficiation

Typical fine and ultra-fine coal processing technologies in the coal processing industry include gravity separation, oil agglomeration, hydrocyclones, spirals and froth floatation methods [35, 36, 37]. However, the application of these technologies have proved to be too costly to operate in the local thermal coal markets, due to the challenges in efficiency, which result in high chemical and water consumption, yet low yields are achieved [38]. River Energy operates low operational cost screening and dewatering technologies for the recovery of historical and as-arising fine and ultra-fine coal. These technologies utilize static or high-frequency wet screening and have been proven globally for upgrading fine coal. The CHPP operation described in the preceding section is retrofitted with screening and centrifuge circuits to intercept the thickener feed or underflow slurry (-200µm arising fines) to produce a product (+50µm oversize product) and a waste (-50µm undersize).

2.3 Binderless coal briquetting

The beneficiated fines may be further processed through binderless coal briquetting depending on the required product specifications. River Energy`s Binderless Coal Briquetting (BCB) is a patented technology developed by a consortium led by the CSIRO in Australia over 20 years and refined and commercialised under an exclusive global licence. The BCB technology was developed to upgrade high-moisture, low-value coals through a low-cost process of dehydration and compaction. The binderless briquetting process is designed to handle feeds with high total moisture of up to 26% which are fed to a dryer for moisture removal at temperatures below 110°C. The dried coal is then fed to the briquetter, where it is briquetted and cooled to a safe storage temperature. The resultant briquettes are 50mm x 20 mm x 20mm in dimension [39]. Figure 3 illustrates the typical upgrade of raw discard that is achievable from high moisture arising fines and reclaimed fine coals found in the Witbank Coalfield resulting in the production of saleable, low moisture, export specification coarse product. Detailed quality upgrade that can be achieved are detailed in Sebola *et al* (2025) [39].

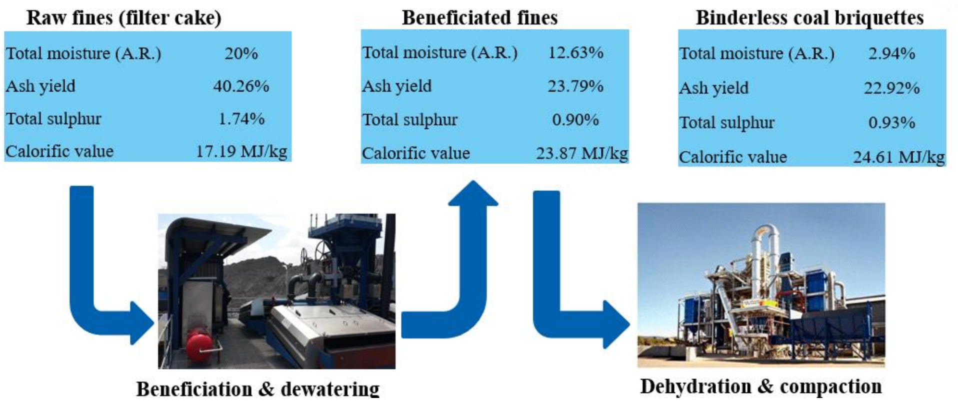

Fig.3. Typical upgrade qualities achieved on Witbank coal discard through fine coal beneficiation and binderless briquetting. Results on air dry basis unless otherwise indicated. A.R = As received basis.

3 Preliminary life cycle assessment of discard coal valorization

The life cycle of a product involves the utilisation of machinery, chemicals, energy and natural resources such as land, water and minerals, resulting in emissions to the air, water and soil, as well as waste generation [40]. The impact of these process inputs and outputs on the natural environment and society can be quantified using the Life Cycle Assessment (LCA) tool [41]. The LCA is an environmental management tool that is widely applied across different industries to assist organizations in identifying and quantifying the environmental and societal impacts of their value chains [42,43,44].

To this effect, River Energy is conducting a life cycle assessment through a third-party specialist environmental consulting firm (The Green House), on its current and proposed operations to quantify the life cycle impacts of its beneficiated discard-derived coal products in comparison to conventional run-of-mine (ROM) coal products burned in a local power station. The life cycle inventory data was primarily supplied by River Energy, and for all other inputs the Ecoinvent database [45], modified where relevant to better represent the geographical context. The LCA was conducted in SimaPro LCA software.

The functional unit (FU) in the study, which is the product or service unit against which environmental impacts are measured, is chosen as 1 kWh of thermal energy. The system boundary studied compares the following River Energy products:

- Coarse wash product from washing reclaimed discard (with co-production of beneficiated fines)
- A beneficiated fines product (FBC) with fines feed made up of fines sourced from washing reclaimed discard (66.6%) and reclaimed from a slimes dam (33.3%)
- A beneficiated fines product (FBC) with fines from ROM coal-washing
- A binderless coal briquette product (BCB) with briquettes made from beneficiated fines (66.6% from discard washing and 33.3% reclaimed from slimes dam), in a BCB plant using natural gas as the energy source.

The LCA follows the international standard on life cycle assessment [46]. As allowed under the ISO 14044 standard, system expansion (avoided production) is applied in this study to reflect the avoided mining (and beneficiation) of conventional coal substituted by the beneficiated discard/briquettes, that is, the benefits of no longer needing to produce the coal able to be replaced by the waste coal products are included in the system boundary of the study [46]. Life cycle impact assessment (LCIA) was modelled applying the 2016 ReCiPe method [47] which consolidates many impact categories into three areas of protection namely, damage to human health, damage to ecosystems and damage to resource availability (Figure 4). The potential damage to human health is expressed in Disability Adjusted Life Years (DALYs). The potential damage to ecosystem quality is expressed in species affected, and the potential impact on global non-renewable resources is expressed as increased extraction costs in USD [44]. Thus, the LCA provides a holistic consideration of multiple factors affecting environmental sustainability (including climate change), as well as impacts on human health and the future of resource availability, in contrast to traditional carbon foot printing which looks only at climate change factors [48].

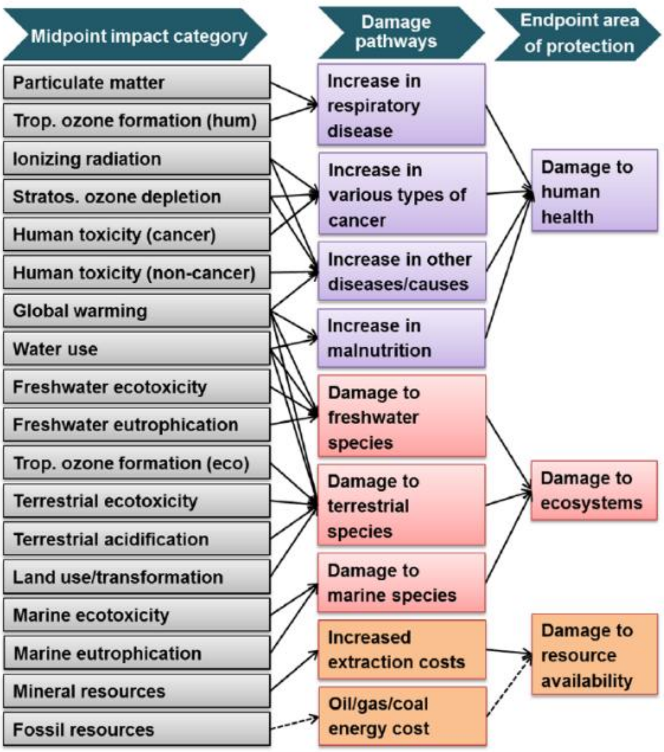

Fig.4. Summary of impact categories considered for the areas of protection in the ReCiPe2016 method [47].

The preliminary results of the LCA indicate discard-derived coal products have a net positive impact on human health and ecosystems, compared to conventional coal (Figure 5). That is, the positive effects associated with removing discard dumps and slimes dams outweigh the impacts that occur due to producing the waste coal products, which involves the use of fuel, electricity and water, etc. Overall, the avoided production results in 32 to 45% less potential damage to human health from electricity generated from BCBs and FBC products (compared to electricity generated from a comparative conventional coal product), and 30% to 38% less damage to ecosystem quality. The avoided human health damage associated with discard-derived coal products is primarily a result of avoided human carcinogenic toxicity, arising from avoiding the leaching of heavy metals that would otherwise have occurred from the discard dump [49]. The avoided damage to ecosystems is primarily a result of avoided ecotoxicity, as well as avoided freshwater eutrophication, similarly driven by avoided emissions from the discard dump [50]. Electricity production is associated with significant potential damage to human health and ecosystems, predominantly from coal combustion gases (SO_2, CO_2 and NO_x), waste dumps (heavy metals leaching from ash dumps), as well as high water use in power stations [51].

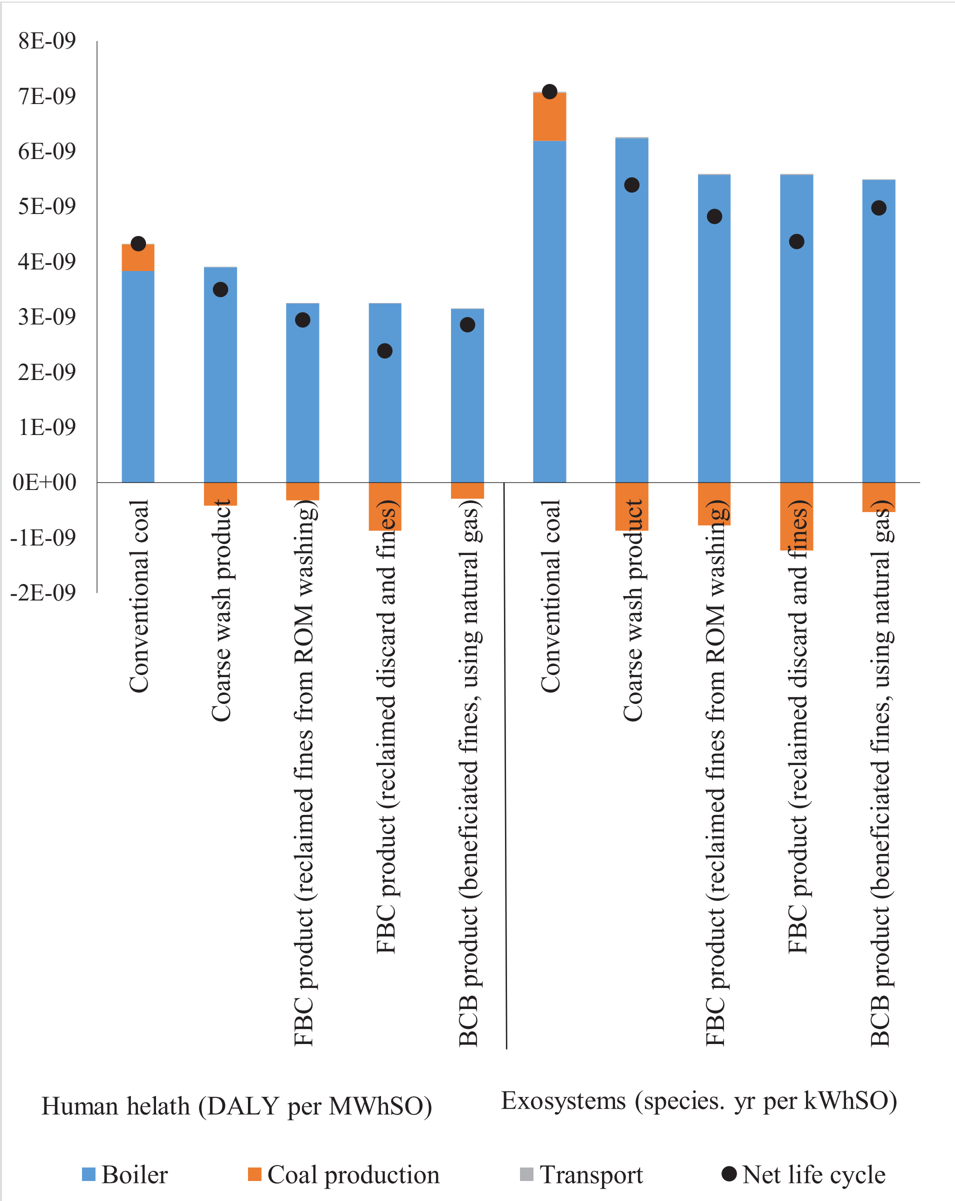

Fig.5. Potential damage to human health and ecosystems from use of coal products in a local power station, at point of electricity production with avoided coal production, compared to conventional coal.

Figure 6 illustrates that all the discard-derived coal products result in significantly lower damage to fossil resources compared to the life cycle of conventional coal i.e., the additional fossil fuel resources that are avoided by using the various discard-derived coal products to generate electricity substantially offsets resource scarcity. Although the production of waste coal products has an impact on resource scarcity, which is highest in those processes with high electricity and diesel use, such as electricity use in the coarse wash product, diesel use in discard reclamation and transport to the CHPP, as well as in the production of magnetite used in the washing process, this is substantially lower than the impact on resource scarcity from the mining and preparation of conventional coal. Therefore, the use of discard coal can be a significant catalyst towards reducing the depletion of non-renewable resources (fossil fuels and minerals) for future generations.

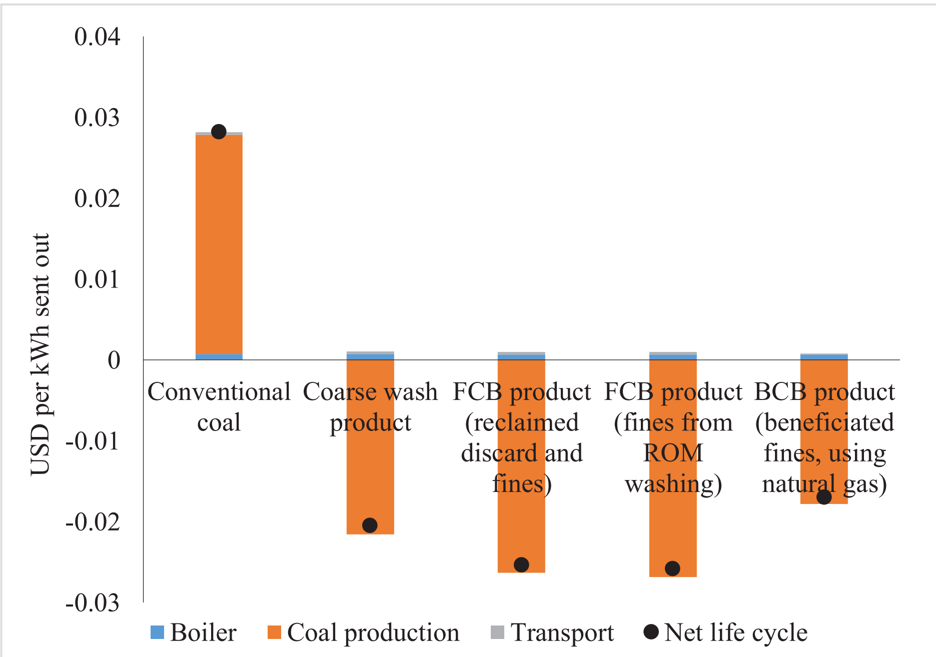

Fig.6. Potential damage to Resources from use of coal products in a local power station, at point of electricity production with avoided coal production, compared to conventional coal.

The carbon footprint (Figure 7) of the discard coal LCA scenarios shows that the avoided greenhouse gas emissions from conventional coal production can offset the net greenhouse gas emissions of the reclaimed discard and fines FBC product, the coarse wash product, and the reclaimed fines from ROM washing by 4.7%, 4.4% and 3.8%, respectively. The fact that the coal production stage accounts for a relatively small share (2.89%) of the life cycle carbon footprint of electricity generation is the reason that these percentages are relatively small when viewed across the coal-derived electricity life cycle. Nonetheless, replacing a conventional run-of-mine coal with a waste-derived coal product in an average South African coal-fired power plant (3155 MW) would reduce annual greenhouse gas emissions by around 1.1 million tonnes per year, assuming a load factor of 80%. These significant reductions demonstrate the above-mentioned RE products are ideal transition fuels, providing lower impact feedstock for coal-fired circuit applications.

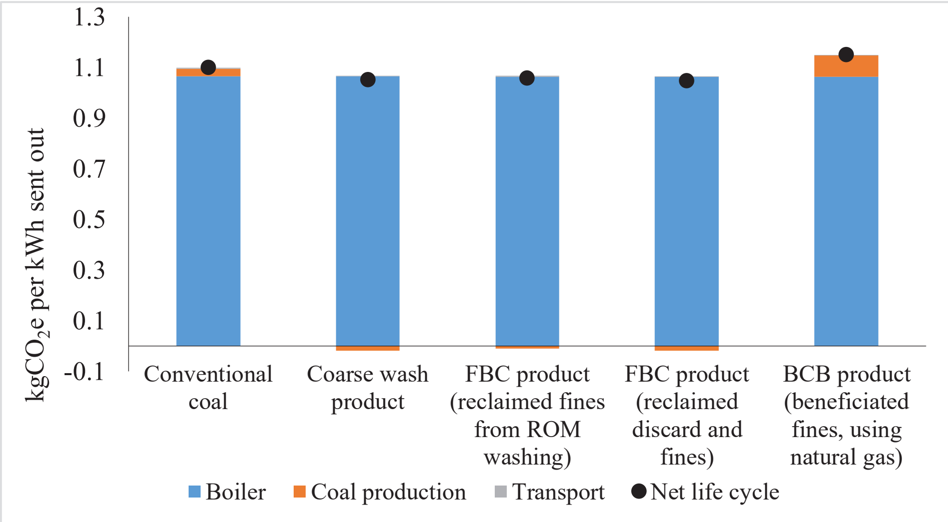

Fig.7. Global warming potential (carbon footprint) of the use of discard-derived coal products in a local power station, with avoided coal production, compared to conventional coal.

In contrast, the net life cycle emissions of the BCB product results in 4.7% higher greenhouse gas emissions relative to the conventional coal life cycle due to the additional processing stage (binderless briquetting) which consumes more inputs (fuel & electricity). It should however be noted that the full benefits of the BCB carbon footprint may be underestimated. For example, due to a lack of boiler efficiency data on the BCB product, an average boiler efficiency of 33.5% was applied for all coal products studied. Taking into consideration the improved quality characteristics of the BCB product, it is expected that the utilization of the BCB product in a boiler would result in a more consistent burn profile, forming less clinker, leading to a higher thermal efficiency and consequently lower CO_2 emissions per kWh. The only benefit modelled in the utilization phase of the BCB product compared to the conventional power station coal product, is a 25% decrease in milling energy based on test work performed with the BCB product being milled before injection into a pulverised fuel boiler. Therefore, further test work on the burn efficiency of the BCB product is necessary to determine how this might affect the boiler thermal efficiency.

Other limitations encountered in the LCA, include: (1) the magnitude of greenhouse gas emissions avoided by avoiding virgin coal production, which vary considerably across coal seams and geographies since methane emissions vary with mine depth, amongst other factors; (2) the Ecoinvent dataset for South African hard coal used in the life cycle model has a particularly low value for coal mine methane;. Therefore, the current iteration of the LCA does not fully capture all the benefits of using the discard derived products.

An LCA on coal pellet production from waste coal stored in impoundments in the United States of America showed a 7.93% decrease in global warming emissions when waste-derived coal pellets were produced and utilized in the steel making process [52]. It is expected that a similar net reduction in the carbon footprint of the BCB product life cycle can be achieved with similar data. Moreover, the integration of renewable energy sources such as solar PV, wind and biomass into the production stage of the various discard products would substantially decrease their climate change impacts.

4 Conclusions and recommendations

This study demonstrated the reclamation of historical and arising coarse and fine discard coal as a sustainable part of the solution for South Africa to complete its journey to a sustainable and just energy transition in the coal industry. This is supported by the preliminary LCA results, which show measurable benefits as to how the technological solutions offered by River Energy can significantly lower damages to human health and ecosystems through replacing conventional coal products with discard-derived coal products. Significantly lower damages to human health, ecosystem quality were found to be primarily a result of reductions in the amount of coal waste in discard dumps and slime dams, which have the potential to produce leachate and sterilise land. Moreover, the depletion of fossil resources avoided by using waste coal to generate electricity offsets the resources used in producing the waste coal products by a substantial degree. The net positive impact of the three areas of protection coupled with the improved carbon footprints of the discarded-derived products, warrants application in the South African coal industry.

Further iterations of the LCA will be conducted to include additional test work data, particularly into the performance of the BCB product, to understand the full benefits of the life cycle carbon footprint in the utilization stage of the value chain. It is recommended that greener electricity sources be integrated in the production stages of the discard coal product life cycles as the penetration of renewables into South Africa's grid electricity mix becomes more widely available.

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References

1. IEA. Coal 2024, IEA, Paris (2024), https://www.iea.org/reports/coal-2024, Licence: CC BY 4.0
2. CRSES. Visualisation of South African Energy Data. Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University (2024)
3. Minerals Council South Africa. 2023 Comprehensive facts and figures (2024)
4. T. Troszak. Why do we burn coal and trees to make solar panels. (Research Gate, 2019)
5. L. Schernikau, W.H. Smith, R. Falcon, Full Cost of Electricity FCOE and Energy Returns Eroi. J. Mgmt. & Sustainability. **12**, 96 (2022). https://doi.org/10.5539/jms.v12n1p96
6. Minister of Mineral Resources & Energy: Publication for comments: Integrated Resource Plan. Gazzette 49974 (2023)
7. J. Emblemsvåg, "Levelized Cost of Energy": A critical review and evaluation of the concept Energy. Res soc sci. **119**, 103897 (2025). https://doi.org/10.1016/j.erss.2024.103897
8. E.M. Urbano, K. Kampouropoulos, L. Romeral, Energy Crisis in Europe: The European Union's Objectives and Countries' Policy Trends—New Transition Paths? Energies. **16**, 5957 (2023). https://doi.org/10.3390/en16165957

9. F. Zhang, J. Lu, L. Chen,When green recovery fails to consider coal pushback: Exploring global coal rebounds, production, and policy retrenchment post Covid-19. Energy res soc sci. **101**, 103142 (2023). https://doi.org/10.1016/j.erss.2023.103142
10. The Presidency of the Republic of South Africa. South Africa`s Just Energy Transition Investment Plan (JET IP) for the initial period 2023–2023.
11. N.J. Wagner, The characterization of weathered discard coals and their behaviour during combustion. Fuel. **87**, 1687-1697 (2008). https://doi.org/10.1016/j.fuel.2007.09.009
12. P.J. Hancox, A. E. Götz, South Africa's coalfields — A 2014 perspective. Int. J. Coal Geol. **132**, 170-254 (2014). https://doi.org/10.1016/j.coal.2014.06.019
13. Department of Energy. National inventory discard and duff coal – 2001. Summary report. (2001)
14. J.F. Reddick, H. Von Blottnitz, B. Kothuis. A cleaner production assessment of the ultra-fine coal waste generated in South Africa. South. Afr. Inst. Min. Metall. **107**, 811-816 (2007). https://hdl.handle.net/10520/AJA0038223X_3309
15. M. Belaid, R. Falcon, P. Vainikka, K.V. Patsa. Potential and technical basis for utilising coal beneficiation discards in power generation by applying circulating fluidised bed boilers. In 2nd International Conference on Chemical, Ecology and Environmental Sciences, June 2013, 17-18 (2013)
16. B. North, A. Engelbrecht, B. Oboirien. South. Afr. Inst. Min. Metall. **115**, 573-580 (2015). https://doi.org/10.17159/2411-9717/2015/V115N7A3
17. S. Nyoni, M. Bwalya, N. Chimwani, Beneficiation potential of a low-grade coal from the Emalahleni (Witbank) coalfield. Physicochem. Probl. Miner. Process. **56** (2020). https://doi.org/10.37190/ppmp/126242
18. V. Crone, The goal of energy security must be economic development for all. S. Afr. J. Econ. **87**, 14-20 (2022). https://hdl.handle.net/10520/ejc-nagenda_v2022_n87_a8
19. P.A. Yanguas-Parra, N. Malz, P.Y. Oei, A. Furnaro, C. Hauenstein, G. Quiceno, F. Corral-Montoya, T. Mitterecker, J. Hanto, Perspective: How a short-term relapse to coal could put exporting countries and just transition processes at risk. Energy Res. Soc. Sci. **97**, 102989, (2023). https://doi.org/10.1016/j.erss.2023.102989
20. O.O. Babayomi, D.A. Dahoro, Z. Zhang, Affordable clean energy transition in developing countries: Pathways and technologies. Iscience. **25**, (2022). https://doi.org/10.1016/j.isci.2022.104178
21. V. Munnik, G. Hochmann, M. Hlabane, S. Law. The social and environmental consequences of coal mining in South Africa. Environmental monitoring, group, (2010)
22. R.N. Naidoo, Mining: South Africa's legacy and burden in the context of occupational respiratory diseases. Glob. Health Action. **6**, 20512 (2013). https://doi.org/10.3402/gha.v6i0.20512
23. B.N. Shongwe. The impact of coal mining on the environment and community quality of life: a case study investigation of the impacts and conflicts associated

with coal mining in the Mpumalanga Province, South Africa, Master Thesis, University of Cape Town, 2018

24. C. Strambo, J. Burton, A. Atteridge. The end of coal? Planning a "just transition" in South Africa. Stockholm: Stockholm Environment Institute (2019)
25. I. Dunmade, N. Madushele, P.A. Adedeji, E.T. Akinlabi, A streamlined life cycle assessment of a coal-fired power plant: the South African case study. Environ Sci Pollut, **26**, 18484-18492 (2019). https://doi.org/10.1007/s11356-019-05227-6
26. H.M. Stander, J.L. Broadhurst, Understanding the Opportunities, Barriers, and Enablers for the Commercialization and Transfer of Technologies for Mine Waste Valorization: A Case Study of Coal Processing Wastes in South Africa. Resources, **10**, (2021). https://doi.org/10.3390/resources10040035
27. T.P. Makhathini, J.K. Bwapwa, S. Mtsweni, Various Options for Mining and Metallurgical Waste in the Circular Economy: A Review. Sustainability, **15**, 2518 (2023). https://doi.org/10.3390/su15032518
28. F. Pavloudakis, C. Roumpos, P.M. Spanidis, Planning the Closure of Surface Coal Mines Based on Circular Economy Principles. Circ. Econ. Sustain, **4**, 75-96. (2024). https://doi.org/10.1007/s43615-023-00278-x
29. Minerals Council South Africa. The coal mining life cycle. 2022.
30. S.J. Mangena, A.C. Brent, Application of a Life Cycle Impact Assessment framework to evaluate and compare environmental performances with economic values of supplied coal products. J. Clean. Prod, **14**, 1071-1084 (2006). https://doi.org/10.1016/j.jclepro.2004.04.012
31. O. Ditsele, K. Awuah-Offei, Effect of mine characteristics on life cycle impacts of US surface coal mining. Int. J. Life Cycle Assess, **17**, 287-294 (2012). https://doi.org/10.1007/s11367-011-0354-y
32. G.J. De Korte, Coal preparation research in South Africa. South. Afr. Inst. Min. Metall, **110**, 361-364, (2010). https://www.scielo.org.za/pdf/jsaimm/v110n7/05.pdf
33. S. Tshikhudo, V. Shikwambana, The application of Baleen Filter microscreening technology at BECSA's South Export Plant. South. Afr. Inst. Min. Metall, **114**, 519-524 (2014). http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S2225-62532014000700008&lng=en&nrm=iso>
34. A. Noble, G.H. Luttrell, A review of state-of-the-art processing operations in coal preparation. Int. J. Min. Sci. Technol, **25**, 511-521 (2015). https://doi.org/10.1016/j.ijmst.2015.05.001
35. M. Ramudzwagi, N. Tshiongo-Makgwe, W. Nheta, Recent developments in beneficiation of fine and ultra-fine coal -review paper. J. Clean. Prod, **276**, 122693 (2020). https://doi.org/10.1016/j.jclepro.2020.122693
36. R. Q. Honaker, J. Kohmuench, E. Dohm, G H. Luttrell, The Coal Handbook, (Woodhead Publishing, 2023).

37. P.J. Bethell, Economic Factors Affecting Coal Preparation: Plant Design Worldwide and Case Studies Illustrating Economic Impact, The Coal Handbook. Second Edition, (Elsevier Ltd, 2023).
38. M.T. Sebola, D. McLean, M. Mphaphuli, Binderless briquetting of beneficiated fine discard coal from the Witbank Coalfield. The Southern African Coal Processing Society (SACPS) for the 21st International Coal Preparation Congress. Advancing sustainable coal preparation: innovations, challenges and best XXI ICPC practices, Sun City, North West Province, South Africa, 12-17 October 2025 (to be published).
39. D. Burchart-Korol, A. Fugiel, K. Czaplicka-Kolarz, M. Turek, Method for Assessing the Development of Underground Hard Coal Mines on a Regional Basis: The Concept of Measurement and Research Results. Sci. Total Environ, **15**, 562:61-72 (2016). https://doi.org/10.3390/en11061370
40. W. Klöpffer, B. Grahl, Life cycle assessment (LCA): a guide to best practice, (John Wiley & Sons, 2014).
41. P. Roy, D. Nei, T. Orikasa, Q. Xu, H. Okadome, N. Nakamura, T. Shiina. J, A review of life cycle assessment (LCA) on some food products. Food Eng, **90**, 1-10, (2009). https://doi.org/10.1016/j.jfoodeng.2008.06.016
42. O. Ditsele, Application of life cycle assessment to estimate environmental impacts of surface coal mining. Master Thesis, United States of America, 2010
43. M.A. Huijbregts, Z.J. Steinmann, P.M. Elshout, G.Stam, F. Verones, M.Vieira, R. van Zelm, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Ass, **22**, 138-147, (2017). https://doi.org/10.1007/s11367-016-1246-y
44. ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines.
45. G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (Part I): Overview and methodology. Int J Life Cycle Ass, 21(9), 1218–1230, (2016). https://link.springer.com/article/10.1007/s11367-016-1087-8
46. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework
47. ReCiPe. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterisation. RIVM Report 2016-0104a, National Institute for Public Health and the Environment (2016)
48. A. Laurent, M. Owsianiak, Potentials and limitations of footprints for gauging environmental sustainability. Curr. Opin. Environ. Sustain., 25, 20-27 (2017). https://doi.org/10.1016/j.cosust.2017.04.003
49. R.M. Mashishi; O.J. Okonkwo; T. Malehase, Selected trace element concentrations in runof-mine coal, discard, and coal product, and environmental implications. J. S. Afr. Inst. Min. Metall. **123**, 573-577 (2023). https://doi.org/10.17159/2411-9717/3114/2023
50. CSIR. Characterising the risk of human exposure and health impacts from acid mine drainage in South Africa (2013)

51. K.E. Langerman, & C. J. Pauw, A critical review of health risk assessments of exposure to emissions from coal-fired power stations in South Africa. Clean Air J. **28**, 68-79 (2018). https://doi.org/10.17159/2410-972X/2018/v28n2a19
52. D.P. Hanak. Environmental life-cycle assessment of waste-coal pellets production. Clean Energy. **6**, 1-14 (2022). https://doi.org/10.17159/2410-972X/2018/v28n2a19