Linking capital assets' Sunk CO_2 to transition risk.

– Evidence from Australian carbon-intensive industries

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Statement of Originality

This is to certify that to the best of my knowledge; the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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Glossary

Term	Definition
t	Year capital asset was created
n	Year capital asset was retired
ε	Current year
p	Projected year
k	Denotes a specific capital asset type
K	Denotes capital stocks of all asset types
$\mathbf{f}_t$	Direct GHG emission intensity
$\mathbf{A}_t$	Technical coefficients matrix
$\mathbf{I}$	Identity matrix
$\mathbf{Y}_t^k$	Monetary value of the invested assets *k* in year *t*
$\mathbf{E}_{t,\mathrm{INVEST}}^k$	The global supply chain-wide CO_2 emissions associated with the production $\mathbf{Y}_t^k$ of the assets based on year *t'*s inter-industry production networks and emission intensities.
$\mathbf{E}_{t,n,\mathrm{RETIRE}}^k$	Emissions embodied in capital assets *k* that were invested in year *t* and retired in year *n*
$\mathbf{R}_{t,n}^k$	The retirement of assets *k* in year *n≥t* after having been invested in year *t,* measured in monetary value of the investment year *t*.
$\mathbf{LEF}_\varepsilon^k$	Embodied GHG emissions in stock of capital assets *k* that remain operational in current year ε
$\mathbf{S}_\varepsilon^k$	GHG emission intensities of year ε's production activities owing to the reliance on the capital stock of asset *k*
τ	The minimum total direct carbon production-based emissions for an industry to be classified as a Carbon Intensive Industry
γ	The minimum direct carbon production-based intensity for an industry to be classified as a Carbon Intensive Industry
$\mathbf{LEF}_\varepsilon^\mathrm{K}$	The GHG footprint of final consumption owing to the capital stock of all assets that remain operational in year ε
$\mathbf{Y}_{2019}^\mathrm{C}$	A 9800x49 matrix expressing the monetary value of the final consumption of 49 countries/regions in 2019

Key terms

Term	Definition
Disorderly transition	Assumes that the introduction of climate policies is delayed, causing rapid emissions reduction to meet a temperature target, and resulting in higher transition risks (Aryanto 2022).
Fixed capital	Assets that were created in previous years but have been used as production inputs over multiple years (Xu, Zhang et al. 2023).
Stranded capital assets	"Assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities" (Caldecott 2013)
Capital endogenization	Method used in EE-IO analysis to attribute the emissions produced in capital formation to downstream production over multiple years.
Net Zero	Balancing consumption and production of global greenhouse gas emissions within a short timeframe (Loveday, Morrison et al. 2022).
Environmentally extended Input-Output (EE-IO)	An analysis technique that evaluates the relationship between economic activities and environmental impacts
Legacy Environmental Footprint (LEF)	"A measure of the historic environmental costs of the investments that created the current stock of manufactured assets".(Wang, Hertwich et al. 2023)
Sunk CO_2	LEF for the attribution of CO_2 in the context of a climate transition to Net Zero.
Carbon Intensive Industries (CII)	A subset of industries determined to be carbon intensive through a combination of carbon emission intensity and total emissions.
Production Based Accounting (PBA)	Attributing responsibility for carbon emissions to the sector and country that directly produced them.
Consumption Based Accounting (CBA)	Attributing responsibility for carbon emissions downstream to the sector and country that consumes the final product

Abstract

This thesis makes a unique contribution to the environmental economics literature by demonstrating a novel negative implication of future capital investment into Carbon Intensive Industries (CII). It has been well documented that a Net Zero disorderly transition results in CII stranded capital assets. This thesis builds on the literature by investigating the indirect implications of embodied greenhouse gas (GHG) emissions within capital assets at risk of stranding, referred to as 'Sunk CO_2'.

This thesis uses an Australian case study to illustrate the scale of CII Sunk CO_2 – a novel application of the Legacy Environmental Footprint (LEF) methodology from Wang et al (2023). It finds that CII including carbon-intensive electricity production and air transport have significant volumes of Sunk CO_2. Further, the long lifespan of these capital assets means any further capital investment within these sectors will likely cause an additional proportion of Sunk CO_2 to become stranded in a disorderly climate transition. Therefore, minimising future CII capital investment is necessary to avoid both the economic and environment consequences of asset stranding. To fully integrate the impacts of capital divestment and stranded capital assets into decarbonisation plans, measurements of Sunk CO_2 must be included. Incorporating measurements of Sunk CO_2 into sectoral divestments may in turn ultimately improve the effectiveness of Australia's plan to decarbonise by 2050.

1. Introduction

Optimising the global transition towards net zero greenhouse gas (GHG) emissions by 2050 (Net Zero) is critical in reducing economic and environmental impacts. There is broad agreement in literature that this requires a reduction in Carbon Intensive Industries' (CII) production (Mercure, Pollitt et al. 2018; Breitenstein 2019; Binsted, Iyer et al. 2020; Semieniuk, Holden et al. 2022). Subsequently, CII capital investment should be also minimised to reduce GHG emissions from future production. However, with global investment into capital assets approximately comprising a quarter of global GDP in 2021, any change to CII capital investment will have significant economic effects (World Bank 2023). One economic effect is causing stranded capital assets, defined as 'assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities' (Caldecott 2013).

If CII capital assets eventually become stranded due to a Net Zero transition, all subsequent implications should be incorporated in the capital investment decision. In turn, capital asset investment into CII should incorporate all implications of asset stranding due to a likely Net Zero transition. One implication that has not been explored is the embodied GHG emissions within CII capital assets (Referred to as Sunk CO_2), such as the GHG emissions generated in the initial formation of a coal factory. Sunk CO_2 is distinct from potential future direct GHG emissions of the CII capital assets, such as the GHG emissions produced by a coal factory overtime, which is well documented (Xu, Zhang et al. 2023). Aggregate measures of Sunk CO_2 indicate that the size of CII Sunk CO_2 is large – in 2019, embodied emissions within capital assets, such as in the creation of electrical structures or aircraft, were five times the size of annual direct emissions (Wang, Hertwich et al. 2023). Despite this, the size of Sunk CO_2 within CII capital assets is not incorporated into capital asset investment decisions.

To incorporate Sunk CO_2 into capital asset investment decisions, subsequent responsibility for the embodied emissions must be attributed. Conventional approaches allocate emissions required to produce capital assets based on the year and country of formation. This does not consider the responsibility of countries that either directly use the capital or the capital-consuming sector's output. To be able to determine these responsibilities, countries involved in the CII supply chain must be identified in a systematic way. This includes thorough analysis of upstream capital asset production, which is reliant on global supply chains and international trade (Sodersten, Wood et al. 2018). Determining the allocation of CII Sunk CO_2 over time can inform ongoing debates on assessing equity of CO_2 emissions across generations, due to the long average lifespan of capital assets (Ye, Krol et al. 2023). This has implications for government policies in determining the degree that different generations should be responsible for financing a Net Zero transition (Budolfson, Dennig et al. 2017), as well as determining responsibilities between countries.

This thesis will use an Australian case study to illustrate the scale of CII Sunk CO_2. Australia is highly reliant on CII such as electricity by coal, thus it has a large portion of CII capital assets at risk of stranding (Edwards, Cui et al. 2022). Further, this thesis will isolate the countries that are part of the CII supply chain, as well as in the formation of the CII capital assets. This will assist policy makers in evaluating the risks in making further capital asset investments into Australian CII.

2. Background

2.1. Determining national responsibilities for a Net Zero economic transition

Near-term actions that limit global warming to 1.5 degrees Celsius would significantly reduce economic, environmental and social damages compared to scenario projections with higher temperature limits (Hoegh-Guldberg, Jacob et al. 2019). This transition to Net Zero requires a mass economic and societal transition, leading to trade-offs between economic and environmental objectives in the short, medium, and long term (Qingchen and Aiqing 2018). Characterising these trade-offs and their relative costs and benefits is necessary to optimise the transition, requiring rigorous scientific and systematic carbon accounting methodology. In turn, this relies on characterising how responsibility for emissions should be determined between nations (Xu, Zhang et al. 2022). The carbon accounting system has evolved from production-based accounting (PBA) measuring territorial emissions to consumption-based accounting (CBA), as well as improving the granularity of the industries and economic regions included (Xu, Zhang et al. 2023).

PBA infers that emissions are seen as the responsibility of countries who operate economic processes that produce emissions. At a country level, government environmental agencies typically report domestic emissions on the basis of international carbon accounting systems and climate treaties such as the Paris Agreement (Tukker, Pollitt et al. 2020). The primary disadvantages of PBA include the implications of fragmentation of supply chains and offshoring (Davis and Caldeira 2010; Zhong, Goh et al. 2022). Under this reporting methodology, importing countries are incentivised to transfer their share of abatement obligations to foreign countries by outsourcing carbon-intensive industries and importing related products (Lin, Hu et al. 2015; Hu, Lin et al. 2016; Franzen and Mader 2018; Kim and Tromp 2021). For instance, from 1991 to 2004 the territorial emissions of the UK diminished while the carbon footprint of UK consumption simultaneously increased (Wiedmann, Wood et al. 2010).

Therefore, evaluating emissions mitigation responsibilities through PBA does not fully consider how consumption of products in a country drives environmental impacts globally (Tukker, Pollitt et al. 2020). CBA assesses the life cycle emissions and resources involved in satisfying final consumption and complements PBA. This approach reflects the user pays principle, which calls upon the final user of embodied emissions to compensate for indirect costs (Tukker, Pollitt et al. 2020). By sharing responsibility for emissions between producers and consumers, a more equitable inter-national agreement on global climate policy could be facilitated (Steininger, Lininger et al. 2014; Sodersten, Wood et al. 2018).

Determining responsibilities of a global Net Zero transition through PBA or CBA has different implications for national Net Zero transitions. A global transition to Net Zero has been estimated to require 2-5% of global GDP in annual investment into energy capital assets (Masson-Delmotte 2018), so even small adjustments to global allocations can have significant implications for national Net Zero transition pathways.

2.2. The emergence of stranded capital assets

More accurately capturing the impact of stranded capital assets facilitates a more informed route to Net Zero and better allocation of responsibility. The scale and severity of stranded capital assets primarily depends on the Net Zero transition pathway chosen at the national and international levels, which can be broadly characterised as 'orderly' or 'disorderly'. Orderly scenarios assume climate policies are introduced early and become gradually more stringent. Disorderly scenarios explore higher transition risk due to policies being delayed or divergent across countries and industries (NGFS 2019). These scenarios are discussed in greater detail in Section S2.

A large proportion of the literature on Net Zero transitions considers orderly scenarios, which have informed international treaties and agreements, including the 2016 Paris Agreement (Schleussner, Rogelj et al. 2016). Within these scenarios, ceiling limits of the quantity of emissions are used to demonstrate multiple sources of emissions must be eliminated within decades to reach a specific warming scenario outcome (Rogelj, Popp et al. 2018) (Meinshausen, Meinshausen et al. 2009) (McGlade and Ekins 2015) (Migliorelli 2019). These ceiling limits can lead to stranded capital assets due to the pre-existing capital assets within industries that prominently produce the emissions with ceiling limits. Modelling suggests an 'optimal' orderly transition requires a sharp and early mitigation effort (Valentini and Vitale 2017) (Vogt-Schilb, Meunier et al. 2018). In these orderly scenarios, policy responses such as a carbon price may drive premature retirement of existing CII capital assets, generating significant private costs in the form of stranded capital assets (Rozenberg, Vogt-Schilb et al. 2020).

The scale and probability of CII capital asset stranding would increase in a disorderly climate transition (Bebbington, Schneider et al. 2020). Circumstances where disorderly transitions can occur include unexpected increases in carbon prices or productivity shocks (Allen 2020). Further, International Monetary Fund research suggests that the world is not currently on track for Net Zero, raising the risk of disorderly scenarios manifesting and stranded capital assets becoming more common (IMF 2021). In turn, the longer the global transition stays off a Net Zero trajectory, the more disorderly – and thus costly – the transition will be.

2.3. Characterising the impact of stranded capital assets

Systematically and comprehensively measuring and capturing the consequences of stranded capital assets is essential for creating Net Zero transition projections and informing policy. Most consequences including changes in potential direct emissions or socio-economic effects are proportional to the scale of stranded capital assets. Some estimates of the scale of global stranded capital assets exceed US$1 trillion in costs, primarily comprised of future lost corporate profits (Semieniuk, Holden et al. 2022) Mercure, Pollitt et al. 2018). Projected capital asset stranding disproportionately affects the geographical regions of Southeast Asia, South America, and Europe (Breitenstein 2019; Binsted, Iyer et al. 2020), with the potential to cause detrimental flow-on effects to employment and other socio-economic outcomes (Auger, Trüby et al. 2021). Conversely, mitigating additional coal capital asset investments could reduce stranded capital assets by $520 billion in a 1.5 °C degree environment (Edwards, Cui et al. 2022).

A variety of methods have been utilised to integrate stranded capital asset considerations into climate policy, without incorporating Sunk CO_2. Löffler, Burandt et al. (2019) calculate the size of stranded capital assets depending on the effectiveness of a long-term Net Zero economic transition. Mo, Cui et al. (2021) and Vogt-Schilb, Meunier et al. (2018) use a varying carbon price to analyse economic impacts on a Net Zero transition, including stranded capital assets. Heerma van Voss and Rafaty (2022) and Worrall (2018) instead evaluate the effectiveness of national level government interventions attempting to minimise stranded capital assets. These efforts are often constrained by political factors, such as from the short-term effects on employment affecting communities (Rozenberg, Vogt-Schilb et al. 2020).

Indirect impacts include impacts on local communities (Hodges 2019; Burke and Fishel 2020), downstream supply chains (Cahen-Fourot, Campiglio et al. 2021) and the financial industry (Battiston, Mandel et al. 2017). More accurate and comprehensive stranded capital asset calculations can help inform decision-making on different decarbonization policy choices, and how strategies for future capital investment should be consistent with global climate goals (Breitenstein 2019). Past approaches have not considered the Sunk CO_2 within stranded capital assets in determining policy choices around decarbonisation. Therefore, current methodologies are incomplete and thus their utility in informing strategies are suboptimal. The size of this Sunk CO_2 will also likely continue to size in size, as aggregate measures suggest that grows faster than GDP and population growth (Wang, Hertwich et al. 2023). Quantification of indirect emissions is essential as these emissions can have an influence on decarbonisation pathways, as McDowall, Solano Rodriguez et al. (2018) has previously shown for the European Energy System.

2.4. The significance of stranded capital assets' Sunk CO_2

Given the significant size of Sunk CO_2 across all capital assets (Wang, Hertwich et al. 2023), the scale of Sunk CO_2 within the stranded capital assets should be estimated. The practical application of Sunk CO_2 within stranded capital assets is more nuanced than the potential direct emissions of the capital assets. The Sunk CO_2 represent legacy investments in capital formation from previous years which cannot be undone. However, if global consumption continues at current levels until a disorderly climate transition, then the Sunk CO_2 is an indicator of what Business as Usual (BAU) capital investment would cause. In a simplified BAU scenario, future capital investments into these industries would maintain the current Sunk CO_2 for future years. This is due to a disorderly climate transition usually incorporating a lag before a rapid divestment away from carbon-intensive industries occurs (NGFS 2019). A global disorderly transition is supported by the current positive growth trends of coal and other carbon-intensive products (Aguirre-Villegas and Benson 2022).

While the past investments that form the current Sunk CO_2 in these industries are sunk costs, the Sunk CO_2 embodied in future investment is not. Since a disorderly transition causes the value of stranded capital assets to diminish, so does the Sunk CO_2. Therefore, if future investments are impacted by the anticipated diminished future value of a capital asset, the contribution of future investments into a Sunk CO_2 should also be considered.

Practical applications of the Sunk CO_2 within stranded capital assets are consistent with broader considerations around CII investments, such as the cost and indirect implications described above. These include adjusting industry support between incumbent CIIs and emerging renewable industries, through subsidies, incentives or tax breaks. This can also be integrated into decarbonisation scenarios to ensure that the impacts of future investment into carbon-intensive industries are comprehensive. More broadly, domestic policy makers alongside other countries and multilateral bodies need to determine responsibility for mitigation for emissions, depending on a variety of factors including origin and final destination.

The implications of using PBA or CBA in the context of Sunk CO_2 would likely significantly alter how these responsibilities are determined. The Sunk CO_2 can originate in a trading partner country, be embodied as in input in an Australian CII, and in turn embodied in a final destination product to a different trading partner. Linking emissions through this process has not been demonstrated before, despite the possible shifts in emission mitigation responsibility that it entails.

Australia was chosen as the case study for this thesis due to the high levels of assets at risk of stranding and existing Net Zero transition commitments. Studies suggest Australia will be disproportionately exposed to climate transitions away from CII due to its relatively high level of CII capital capacity and output (Auger, Trüby et al. 2021) (McGlade and Ekins 2015). In addition, Australia had the highest emissions embodied in capital assets per capita in 2019 (Ranran, 2023). The economic benefits of these existing capital stocks and future investment within Australian CII will increasingly be evaluated against the environmental impact (Lopez, Pastén et al. 2022).

Australia has committed to economic transitions away from CII in both domestic and international agreements. In 2022, Australia set an emissions reduction target of 43 per cent by 2030 and Net Zero emissions by 2050 (DISER 2021). In addition, Australia signed a bilateral Green Economy Agreement (GEA) with Singapore, a major East Asian trading partner (DFAT 2022). This agreement includes sections on bilateral trade and transition finance to support each country's Net Zero economic transition. Integrating Sunk CO_2 into the execution of these domestic and international commitments improves the evaluation of the negative impacts of future Australian CII capital asset investment.

2.5. Estimating stranded capital assets Sunk CO_2

2.5.1. Origin

Determining the origin country of the CII Sunk CO_2 requires Environmentally Extended Input Output Analysis (EE-IO), an analysis technique that evaluates the relationship between economic activities and environmental impacts (See Section S1). Capital endogenization is a method used in EE-IO analysis to attribute the emissions produced in capital formation to downstream production. Historically, EE-IO analysis has treated capital investment as exogenous to the inter-industry system. This fails to incorporate how capital goods are used further in production processes (Sodersten, Wood et al. 2018).

Capital endogenization requires integrating two capital asset metrics: the Gross Fixed Capital Formation (GFCF) and the Consumption of Fixed Capital (CFC). Although both concepts measure a quantity of fixed assets, they represent different measures of capital. The GFCF represents the annual net change in fixed assets, accounting for acquisitions minus disposals, within a given financial period. It signifies a continuous stream of long-term investments aimed at either expanding or sustaining production capacity. On the other hand, the CFC reflects the anticipated decrease in the present value of the fixed asset inventory over the accounting period due to factors such as physical wear and tear, standard obsolescence, and typical accidental damage. (Sodersten, Wood et al. 2018).

In addition, the capital flows from an initial capital formation can continue for decades, in that capital endogenization requires connecting GFCF to future CFC from multiple years. The capital asset stock's lifetime determines how many goods they can produce and how fast they can be replaced by new, more efficient facilities. In turn, the capital efficiency determines the relationship between total output and energy and material throughput in the production process (Pauliuk, Wood et al. 2015). The increasing efficiency of capital formation means that capital stock is not homogeneous. Further, CFC is not uniform between different years of capital formation. Incorporating different years of capital formation into capital endogenization is referred to as dynamic capital endogenization.

Most literature analysing emissions embodied in capital focuses on capital flows (Miller, Berrill et al. 2019; Södersten and Lenzen 2020), looking instead at the emissions embodied within capital asset stock has a key advantage in the context of stranded capital assets. Capital flows in a single year are significantly less than the underlying capital stock. Yet asset stranding is likely to be permanent in the context of a Net Zero transition, and therefore the emissions embodied within the capital assets flows to the year they are stranded would underestimate the full scale of stranding for a point in time estimation.

Wang, Hertwich et al. (2023) developed a model that examines asset, industry, and country specific LEFs in the global value chain from 1970 to 2019, by aggregating emissions embodied in a dynamic capital asset stock determined by previous GFCF. Country and industry level LEF disaggregation are useful for determining emission responsibilities at a more granular level, as also shown in Ye, Krol et al. (2023). This will be used for this thesis to determine the origin of Australian CII Sunk CO_2, which is a novel use of the LEF methodology.

2.5.2. Destination

As capital endogenization has become more advanced, literature has also begun analysing how to allocate CO_2-emission responsibilities of capital asset activities (Lenzen and Treloar 2004; Sodersten, Wood et al. 2018; Södersten and Lenzen 2020; Ye, Krol et al. 2023). Depending on the method, the emissions could be allocated towards producers, or to users, or to final consumers of products that are produced by using associated capital assets. The attribution method substantially alters CO_2 emission accounting at both regional and sectoral levels. Ye, Krol et al. (2023) shows that allocating CO_2 emissions embodied in capital assets over time relieves emission responsibility for the year of formation, with 25–46% reductions from conventional emission accounts. This temporal allocation also broadly leads to a delay in carbon mitigation, with emissions being distributed away from the year of formation. In turn, the changes in sectoral allocations shift the emission responsibilities towards the capital-intensive sectors. This thesis will build on this distribution of responsibility from Ye, Krol et al. (2023) by instead looking at the destination of CII Sunk CO_2. While Ye, Krol et al. (2023) utilises capital flows to determine the final destination, this thesis will use the LEF method developed in Wang, Hertwich et al. (2023). As with estimating the origin of the Sunk CO_2, this will help better determine the point in time impacts arising from the CII capital assets becoming stranded. This is also a unique contribution to literature, with the intersection of the final destination of products.

3. Aims

The aim of this thesis is twofold:

1. Determining how future capital investments in Australian CII could be affected by CII Sunk CO_2.
2. Calculating the upstream primary countries of origin for the Australian CII Sunk CO_2, as well as the downstream destination of the Australian CII Sunk CO_2, to initiate further research into how responsibilities for the embodied emissions should be allocated.

This paper is the first of its kind to look at the Sunk CO_2 of stranded capital assets. It can serve as a cornerstone into further research into linking stranded capital assets, capital endogenization and disorderly economic transitions.

4. Method

There are three steps to finding the Sunk CO_2 within assets at risk of being stranded, as summarised in Figure 1.

1. Firstly, determining which industries are at risk of causing capital asset stranding (CII), through isolating industries that have a high carbon intensity S_i and total gross emissions F_i (Section 4.1).
2. Secondly, estimating the CII Sunk CO_2 origin by formation country and year, through estimating the embodied emissions within dynamic capital stock (Section 4.2).
3. Finally, estimating the CII Sunk CO_2 origin by destination country, by attributing the CII Sunk CO_2 to final demands (Section 4.3).

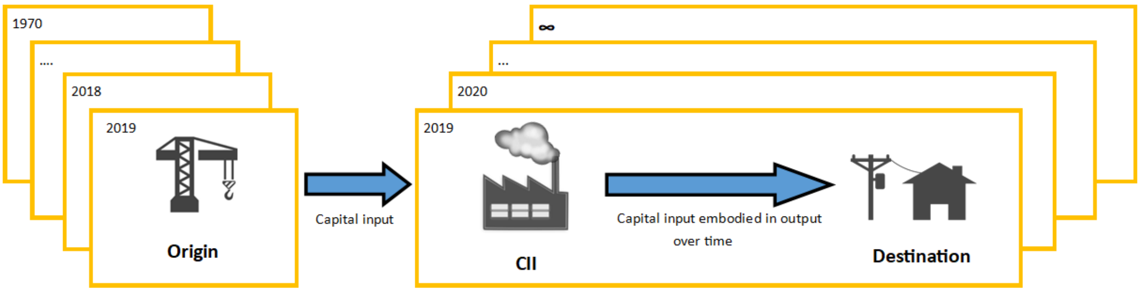

Figure 1: Diagram of the flow of historical capital inputs into future production and consumption. Left hand side shows historical capital asset formation from country of origin, right hand side shows how the CII utilised capital assets are attributed to final consumption over all future years.

4.1. Determining industries at risk of causing capital asset stranding

CII is determined by the set of industries are carbon-intensive $\boldsymbol{C}$, with the dimensions $m \times 1$. This is set by industries that fulfil two criteria. Firstly, $F_i > \tau$, where τ is a minimum direct emission that is determined to be carbon-intensive. Secondly, the industries are also assumed to have a minimum level of carbon intensity $S_i > \gamma$,where γ is the minimum carbon intensity to be determined as carbon-intensive. This excludes industries that are high carbon emitters primarily due to the size of their output. The use of both measurements is due to previous literature detailing industries at risk of being stranded due to carbon intensity, such as electricity by coal (Caldecott 2016).

4.2. Estimating CII Sunk CO_2 origin

The model used here is an application of Wang, Hertwich et al. (2023), which traces CO_2 emissions caused by the capital formation in 49 regions/countries from 1970 to 2019 to the building up of capital stock in the same period. The data from 1970 to 1994 are used to quantify historical CO_2 emissions embodied in capital stock used from 1995 onwards.

More specifically, this is achieved through three steps:

1. For asset type *k* (e.g., machinery, transport equipment, and buildings) invested by industries and countries in year *t*, obtain the global supply chain-wide CO_2 emissions associated with the production $\mathbf{Y}_t^k$ of the assets based on year *t's* inter-industry production networks and emission intensities $\mathbf{E}_{t,\mathrm{INVEST}}^k$.

$$\mathbf{E}_{t,\mathbf{INVEST}}^{k} = \mathbf{f}_t(\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{Y}_t^k \quad \text{(Eq.1)}$$

f_t is a row vector (1x9800) specifying the direct GHG emission intensity of 200 product types in 49 countries/regions (44 individual sovereignties and 5 rest of the world regions). $(\mathbf{I} - \mathbf{A}_t)^{-1}$ is a Leontief inverse matrix (9800x9800), where $\mathbf{A}_t$ is the multi-regional matrix of technical coefficients (9800x9800) and $\mathbf{I}$ the identity matrix (9800x9800). Each column of the Leontief inverse matrix shows the total, both direct and indirect, input requirements across the global supply chains due to one unit output of a given product-country pair. In the following, we use the index *t* for denoting the year of asset investment and thus mostly looking retrospectively at past years, the index *n* for tracking each year of asset retirement since year *t*, and index ε to refer to the current year. $\mathbf{Y}_t^k$ is a matrix (9800x9800) expressing the monetary value of the invested assets *k* in year *t*; the capital products and their investing (using) industries are aligned by rows and columns, respectively.

2. We now determine the emissions $\mathbf{E}_{t,n,\mathrm{RETIRE}}^k$ embodied in capital assets *k* that were invested in year *t*, and retired in year *n* as:

$$\mathbf{E}_{t,n,\mathbf{RETIRE}}^{k} = \mathbf{f}_t(\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{R}_{t,n}^k \quad \text{(Eq.2)}$$

$\mathbf{R}_{t,n}^k$ (9800x9800) is a matrix that captures the amount of assets *k* that was invested in year *t* and retired at year *n* (*n≥t*), measured in monetary value of the investment year *t*. $\mathbf{R}$ has elements R_{ij}, where *i* (rows) and *j* (columns) count the asset products and their investing (consuming) industries, respectively.

3. Establish the stock of capital assets *k* that remain operational in current year *ε*, and the embodied CO_2 emissions generated in year *1, 2, …, t* (*t≤ε*) based on the inflows (capital formation) and the outflows (we trace capital retirement at each year *n*, through year of investment *t* to current year *ε*) obtained above. This is constrained to CII, only including industries that correspond to $C_i = 1$

$$\mathbf{LEF}_\varepsilon^k = \sum_{t=1970}^{\varepsilon} \mathbf{EP}_{t,\mathrm{INVEST}}^k - \sum_{t=1970}^{\varepsilon}\sum_{n=t}^{\varepsilon} \mathbf{E}_{t,n,\mathrm{RETIRE}}^k \quad \text{(Eq.3)}$$

Equation 3 entails that for such capital that is completely retired by year infinity (∞), $\mathbf{LEF}_\infty^k = 0$. For such capital that by year *ε* is not completely retired, $\sum_{t=1970}^{\varepsilon}\sum_{n=t}^{\varepsilon} \mathbf{LEF}_{t,n,\mathrm{RETIRE}}^k < \sum_{t=1970}^{\varepsilon} \mathbf{LEF}_{t,INVEST}^k$, and therefore $\mathbf{LEF}_\varepsilon^k > 0$. Based on Eq. 2 and Eq. 3, we can write Eq. 4 as the following:

$$\mathbf{LEF}_\varepsilon^k = \sum_{t=1970}^{\varepsilon} \mathbf{f}_t(\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{Y}_t^k - \sum_{t=1970}^{\varepsilon}\sum_{n=t}^{\varepsilon} \mathbf{f}_t(\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{R}_{t,n}^k$$

$$\mathbf{LEF}_{\varepsilon}^{k} = \sum_{t=1970}^{\varepsilon} \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\mathbf{Y}_t^k - \sum_{t=1970}^{\varepsilon} \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\sum_{n=t}^{\varepsilon}\mathbf{R}_{t,n}^k$$

$$\lim_{\varepsilon\to\infty}\mathbf{LEF}_{\varepsilon}^{k} = \sum_{t=1970}^{\infty} \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\mathbf{Y}_t^k - \sum_{t=1970}^{\infty} \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\sum_{n=t}^{\infty}\mathbf{R}_{t,n}^k$$

$$\lim_{\varepsilon\to\infty}\mathbf{LEF}_{\varepsilon}^{k} = \sum_{t=1970}^{\infty} \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\mathbf{Y}_t^k - \sum_{t=1970}^{\infty} \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\mathbf{Y}_t^k = 0 \qquad \text{(Eq.4)}$$

CII LEF is also projected $\mathbf{EP}_{\varepsilon+p}^{k}$,for the emissions embodied in current capital stock $\mathbf{EP}_{\varepsilon}^{k}$ across future years p. This is shown in Equation 5:

$$\mathbf{LEF}_{\varepsilon+p}^{k} = \sum_{t=1970}^{\varepsilon} \mathbf{E}_{t,\mathbf{INVEST}}^{k} - \sum_{t=1970}^{\varepsilon+p}\sum_{n=t}^{\varepsilon+p} \mathbf{E}_{t,n,\mathbf{RETIRE}}^{k} \qquad \text{(Eq.5)}$$

This is referred to as the 'no further investment' scenario, which is used to compare against a 'Business as Usual' (BAU) scenario for each CII over future years p. The BAU scenario $\overline{\mathbf{LEF}}_{2019+p}^{k}$ uses the simplifying assumption that Sunk CO_2 remains constant over p future years, $\overline{\mathbf{LEF}}_{2019+p}^{k} = \mathbf{LEF}_{\varepsilon}^{k}$. This in turn assumes that the rate of retirement of capital assets is approximately equal to the rate of future annual investment into capital assets. The difference between the BAU scenario and no further investment scenario $\ddot{\mathbf{LEF}}_{2019+p}^{k} = \overline{\mathbf{LEF}}_{2019+p}^{k} - \mathbf{LEF}_{2019+p}^{k}$ is used as a simple projection indicator of the embodied emissions within stranded capital assets caused by continued investment for any future year.

4.3. Estimating CII Sunk CO_2 destination

To find the supply chain GHG emissions that became embodied in the potentially stranded capital stock of asset *k*, which are accumulated from 1970 to year the current year ε (i.e., $\mathbf{EP}_{\varepsilon}^{k}$, 1x9800), are attributed to the current year ε's total output of the asset investing (using) industries ($\mathbf{x}_{\varepsilon}$). 2019 is used as the current year (ε) for this paper.

$$\mathbf{S}_{2019}^{k} = \mathbf{LEF}_{2019}^{k}\hat{\mathbf{x}}_{2019}^{-1} \qquad \text{(Eq.6)}$$

where the hat symbol denotes diagonalisation. $\mathbf{S}_{\varepsilon}^{k}$ (1x9800) can be considered a vector of GHG emission intensities of the current year ε's production activities owing to the reliance on the potentially stranded capital stock of asset *k* accumulated by year ε. By adding up $\mathbf{S}_{\varepsilon}^{k}$ modeled for all asset types, we obtain the total CO_2 emission intensities of the current year ε's production activities owing to the reliance on the potentially stranded capital stock K of all assets accumulated since 1970 ($\mathbf{S}_{\varepsilon}^{\mathrm{K}}$, 1x9800):

$$\mathbf{S}_{2019}^{\mathrm{K}} = \sum_k \mathbf{S}_{2019}^{k} \qquad \text{(Eq.7)}$$

Thus, the CO_2 footprint of final consumption in the current year ε owing to the accumulated capital stock of all potentially stranded capital assets, separated by type of destination country can be expressed as $\mathbf{LEF}_{2019}^{\mathrm{K}}$, shown in Equation 8:

$$\mathbf{LEF}_{2019}^{\mathrm{K}} = \mathbf{S}_{2019}^{\mathrm{K}}(\mathbf{I} - \mathbf{A}_{2019})^{-1}\mathbf{Y}_{2019}^{\mathrm{C}} \qquad \text{(Eq.8)}$$

where $\mathbf{Y}_{2019}^{\mathrm{C}}$ is a 9800x49 matrix expressing the monetary value of the final consumption of 49 countries/regions in 2019.

5. Data

The final demand, $\mathbf{Y}_{2019}^{C}$, coefficient $\mathbf{A}_t$, and satellite account $\mathbf{f}_t$ matrices from 4.2-4.3 will be estimated using data from EXIOBASE 3, an EE-MRIO database consistent with the System of Environmental-Economic Accounting (Stadler, Wood et al. 2018). It has a high industrial detail matched with multiple social and environmental satellite accounts. The data ranges from 1995 to 2019 for 44 countries (28 EU member plus 16 major economies) and five rest of the world regions (shown in Appendix B). The dataset has 200 product variables, with 15 product groups that are further dis-aggregated into 12 more groups (shown in Appendix A). Energy commodities are likewise detailed in EXIOBASE, with 69 types of energy carriers distinguished, based on International Energy Agency (IEA) energy balances, and including the disaggregation of the electricity generation industry into 12 types of electricity producers (Stadler, Wood et al. 2018). Further detail is included in the mining industry, with 11 types of ores and quarrying. This disaggregation of energy and mining enables more granular estimations of CII, assisting policy makers in developing policy responses to reduce transition risk. To determine CII, EXIOBASE 3 data from 2015-2019 was averaged, ensuring that the industries captured were consistently carbon-intensive, instead of due to data variation.

The construction of $\mathbf{Y}_t^k$ is described in detail in Ye, Hertwich et al. (2021). Retirement functions $\mathbf{R}_{t,n}^k$ for Australian capital assets will be calculated using global proxies, as described in detail in Wang, Hertwich et al. (2023), as suitable national indicators are not available. The closest national indicator is the GFCF calculation from the Australian national accounts, which utilises data from “Estimates of Depreciation and Capital Stock, Australia” (Walters and Dipplesmann, 1985). This dataset is based on tax lives rather than asset lives, which are consistently larger than the physical lifespan, and therefore avoid underestimating the lifespan of CII stranded capital assets.

6. Results and discussion

This section uses an Australian case study to demonstrate the applications of the Sunk CO_2 methodology described in Section 4 with the data from Section 5. Firstly, the CII from Section 4.1 will be estimated in Section 6.1, using a carbon intensity S_i minimum γ of 1 kt/€5m and a gross direct emission F_i minimum τ of 4Mmt. These CII will be used calculate the Sunk CO_2 in Section 6.2, disaggregating the Sunk CO_2 by type of asset, using Equation 3. Section 6.2 will also use Equation 5 to compare the level of CII Sunk CO_2 projected over time in a BAU capital investment scenario against a no further capital investment scenario. Section 6.3 instead disaggregates the current Australian CII Sunk CO_2 by type of origin country using Equation 3, as well as type of destination country using Equation 8 (as shown graphically in Figure 1). Section 6.4 further discusses the destination of Sunk CO_2 by instead disaggregating by destination industry. Section 6 concludes with brief qualifications for the results and methodology.

6.1. Estimating CII by production-based direct emissions

CII are primarily comprised of non-renewable electricity generation, resource extraction and resource refinement industries (Figure 2). Generation of electricity using carbon-intensive fuels has both a high intensity and gross emissions, making the industries highly exposed to a disorderly climate transition. The high gross direct emissions for electricity by coal is also due to the sector accounting for about 60 per cent of Australia's electricity generation (Cronshaw 2015). This is supported by literature, with Löffler, Burandt et al. (2019) finding that the prominent European sectors at risk of stranding were power generation by coal and gas, based on GCAM modelling. This is supported by Pfeiffer, Hepburn et al. (2018) and Vogl, Olsson et al. (2021) which argue that both natural gas and coal-based power generation have to be globally phased out to limit global warming.

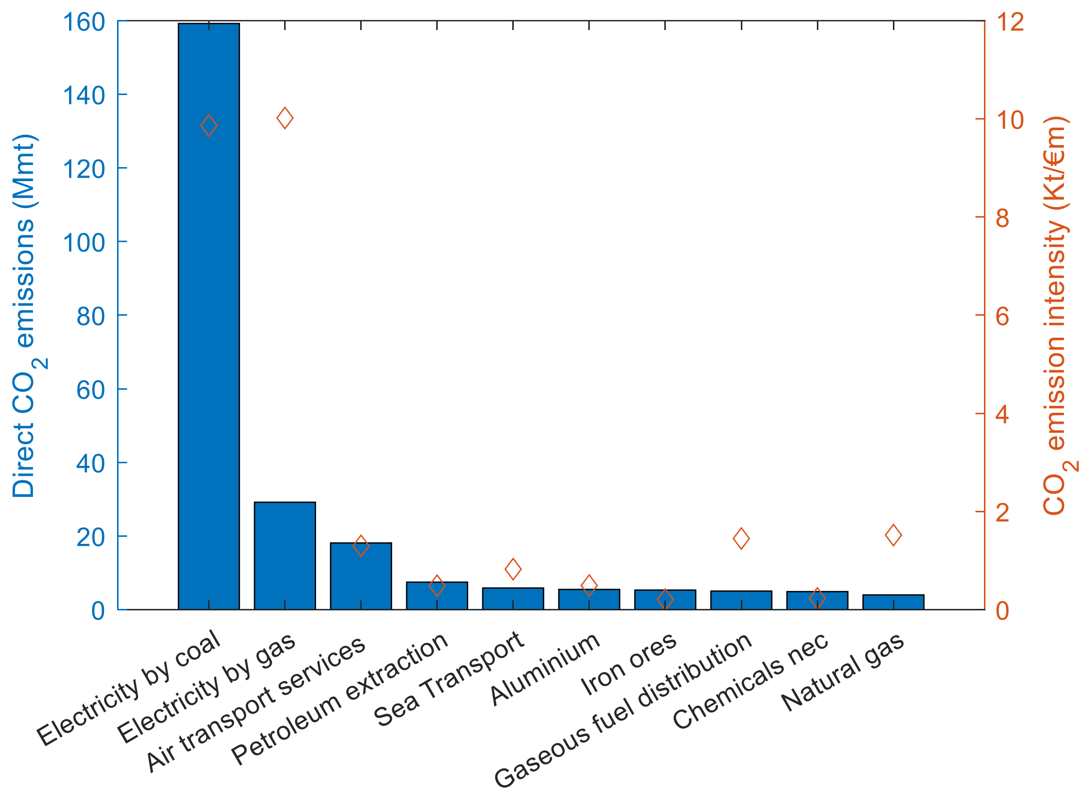

Figure 2: Estimating Australian CII in 2019 by highest direct emissions. CII are determined through the total production-based emissions $\mathbf{F}_{2019} > 4\text{Mmt}$ and emission intensity $\mathbf{S}_{2019} > 1\ kt/€5m$. The emission intensity is denoted by the orange diamonds with the right (orange) axis, whereas the direct CO_2 emissions are denoted by the blue columns with the left (blue) axis. Section S1 shows CII estimation without applying the minimum carbon intensity $\mathbf{S}_{2019} > 1\ kt/€5m$.

The results also indicate that transportation sectors are exposed to disorderly climate transitions with both air and sea transportation services having high environmental intensities and total emissions. Both sectors' emissions primarily come from high fuel usage. This is significant given that the United Nations' International Civil Aviation Organization expects aviation emissions to approximately triple by 2050, when aircraft is projected to also account for a quarter of the global carbon budget (ICAO 2018). Hu, Lin et al. (2016) also estimates high emissions for the transportation sectors in Sweden and suggests that the policy responses in these sectors should be considered for emission reduction. While transportation services are not sectors that are primarily discussed in the context of stranded capital assets, literature suggests that phasing out carbon-intensive methods of air and sea transportation is necessary for a Net Zero transition (Dray, Schäfer et al. 2022; Bergero, Gosnell et al. 2023). A disorderly phase out of carbon-intensive methods would in turn likely cause stranded capital assets.

The remaining sectors are mostly split between primary sectors relating to energy and metal ore extraction, and secondary sectors relating to production or refinement. The primary sector CII encompasses petroleum extraction, iron ores and natural gas extraction. Petroleum extraction is notable given that several of the downstream uses of petroleum are more carbon-intensive, particularly when it is used as a fuel. However, the underlying size of the extraction sector determines it to be a CII instead of the downstream sectors, despite a comparatively lower carbon intensity. Iron ores has the lowest CII carbon emission intensity and has high carbon emissions instead due to the underlying size of the sector.

Australia has the world's largest estimated reserves of iron ore, and is their single largest commodity export (Yellishetty, Werner et al. 2022). Forecasts suggest that Australia will earn around A$700 billion between 2021-26 from iron ore exports. Simultaneously, downstream processes such as iron and steel production are responsible for 7 per cent of global GHG emissions. Due to this, Vogl, Olsson et al. (2021) suggests that types of steel and iron production equipment should be phased out, which could also have an additional upstream impact to Australian iron ore extraction.

Natural gas could similarly pose compounding transition risks, given that both natural gas extraction and electricity by natural gas are emission intensive. This is notable given that the EU taxonomy for sustainable finance currently defines natural gas as a transition sector, meaning that it is intended be used to quickly transition away from fossil fuels such as coal. The EU taxonomy is a classification system that defines criteria for economic activities that are aligned with a Net Zero trajectory by 2050 and the broader environmental goals other than climate.

For the secondary sector CII, meaning CII that produce products derived from primary sectors, both have comparatively low carbon intensities, and instead have a large total carbon footprint due to their size. This is shown by how Australia is the largest exporter of both alumina and bauxite, the two primary aluminium production outputs. Further, aluminium production forms approximately 3 per cent of the world's direct industrial CO_2 emissions. These estimates will likely grow over time, with global annual demand for aluminium projected to triple by 2050 (Gautam, Pandey et al. 2018). The carbon intensity of aluminium result from the carbon-intensive smelting process. The second secondary sector CII, Gaseous fuel distribution, encompasses connecting to a consumer through a system of mains. The separate operation of gas pipelines, connecting producers with distributors of gas, is instead included in other categories. The relatively high total carbon footprint is also due to the size of the industry, with 70 per cent of Australian homes using mains or bottled gas for heating, cooking and hot water, according to an Energy Networks Australia report in 2020.

The EXIOBASE category "chemicals not elsewhere classified (n.e.c)" is an aggregate of the chemical and pharmaceutical industry sectors. The finding that the sector has high gross carbon emissions is consistent with literature and is partly due to half of the chemical sector's energy input being consumed as a raw material input rather than as a source of energy (IEA 2022).

One sector discussed in literature as being at risk of stranding that is not included in CII is agriculture (Caldecott 2013; Bos and Gupta 2019). This is due to the comparatively high disaggregation of agriculture within EXIOBASE compared to mining or other secondary industries. A CBA method of determining CII is shown further in Section S4 but is excluded from the remaining analysis. This is due to consumption-based accounting being an unrealistic method of determining industries that would be rapidly divested from in climate transitions. Economic policy around mitigating emissions is primarily based instead on production-based estimations (Tukker, Pollitt et al. 2020). Further, the downstream effects of the CII converge with industries that have high embodied emissions through consumption-based accounting (discussed further in Section S8).

6.2. CII Sunk CO_2

Figure 3a shows the CII Sunk CO_2, as these industries are assumed to be most likely to cause stranded capital assets with a disorderly transition towards Net Zero emissions. Comparing this to Figure 2 indicates the relative size of the Sunk CO_2, with most CII having a larger Sunk CO_2 than annual direct emissions. While the Sunk CO_2 has been accumulated over gradual capital investment, it nevertheless is an indication of the potential impact of a disorderly climate transition of continuing CII capital investment. These impacts are particularly large within the 'non-residential structures' capital type, which encompasses a range of industry specific structures that may be difficult to reappropriate.

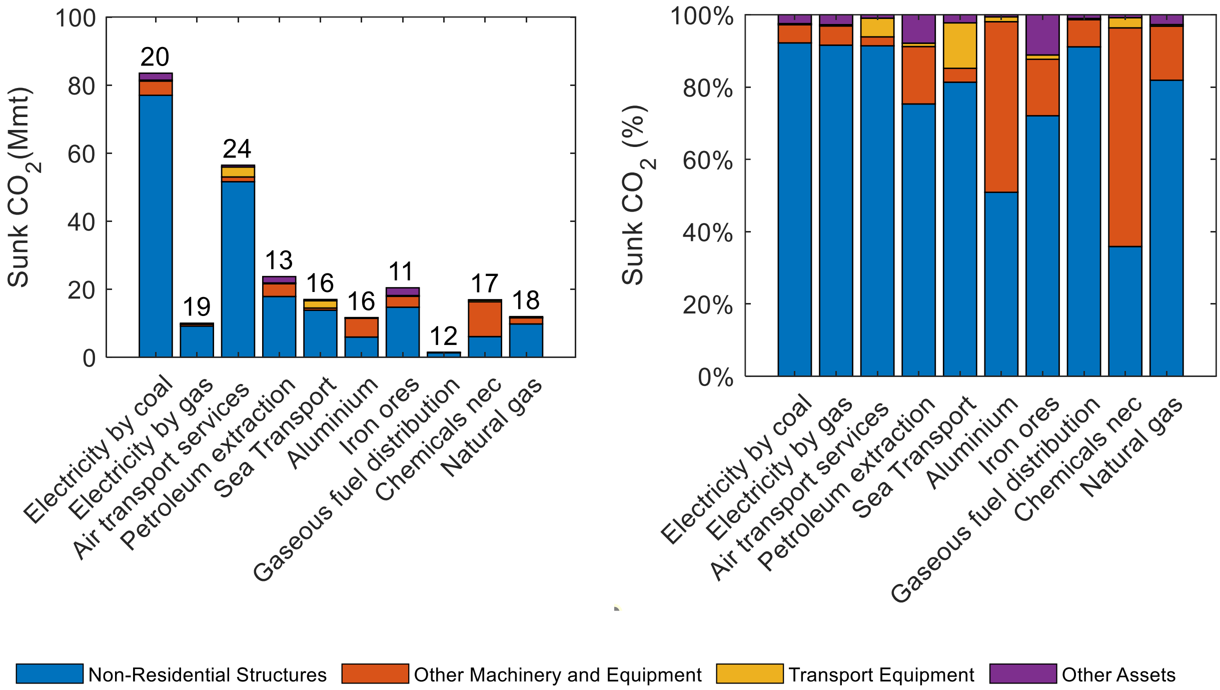

Figure 3: Shows the 2019 Australian CII Sunk CO_2 for each CII by asset type, arranged by the previous ranking of direct carbon emissions rather than Sunk CO_2. Left hand side (a) shows the total 2019 Australian Sunk CO_2 disaggregated by asset type for each CII (average age of asset shown above column), whereas right hand side (b) shows the percentage of each asset type comprising 2019 Australian CII Sunk CO_2 for each CII. Both Figures 3a and 3b were calculated using Equation 5 from Section 4.

On a sectoral level, electricity by coal also has the highest CII Sunk CO_2. The two CII Sunk CO_2 from electricity industries shown in Figure 2 have most of their emissions within non-residential structure investment. This is due to the electric and other power structures subdivisions, which have previously been shown to have a high carbon intensity (Wu, Guo et al. 2018). In turn, the relative proportions between electricity by coal and electricity by gas from Figure 2 is approximately consistent. This is likely due to the similar types of capital required for each sector, leading to a similar Sunk CO_2 per output. The relative size of most other sectors' Sunk CO_2 compared to Figure 2 is also significantly larger than the electricity generating CII. This is due to the comparatively high direct carbon emission intensity of the electricity generating CII being independent to the Sunk CO_2 shown in Figure 2. This is supported by Södersten and Lenzen (2020), which found that capital flows endogenization within electricity by coal final demand was one of the few sectors that did not significantly increase its carbon footprint. The exception to this is gaseous fuel distributions which, as discussed in Section 6.1, does not include long distance gas distribution from production to mains, contributing to a comparatively low Sunk CO_2.

The two transport CII are the only CII that have a significant Sunk CO_2 within transport equipment, although neither are above 20 per cent. Instead, the primary Sunk CO_2 for both is also within non-residential structures. This likely due to the 'Transit buildings; air' and 'Transit buildings; land' subdivisions within non-residential structures contributing the majority of the Sunk CO_2. Further, air transport also has the longest lifespan of all CII capital, likely due to the long lifespan of the transit buildings. These transit buildings also contribute to air transport services having the largest Sunk CO_2 across CII compared to each industry's respective direct emissions. The lifespan of the sea transport capital is average, suggesting a lower lifespan for sea transit structures. The two primary industries 'Iron ore' and 'Petroleum extraction' also have most emissions within non-residential structures. This would likely correspond to the asset subcategories 'Mining structures' and 'Petroleum and natural gas' respectively. There is also a significant percentage attributed towards other machinery and equipment, which would be primary comprised of 'Mining and oilfield machinery'. The comparatively high level of Sunk CO_2 in these sectors compared to their direct emissions is supported by a similar analysis for U.S oil and gas extraction capital, where the inclusion of embodied capital emissions led to a significant increase in carbon footprint (Miller, Berrill et al. 2019). The two secondary industry CII are the only CII to have most of its Sunk CO_2 not being within non-residential structures. Instead, both have the most Sunk CO_2 within other machinery and equipment. This is likely due to the high requirements for machinery within secondary industries, relative to primary industries such as iron ore or petroleum extraction. This encompasses several 'machinery and other equipment' asset type subcategories, including 'Fabricated metal products', 'Metalworking machinery', and 'General industrial equipment'.

In a projected future disorderly climate transition, the total Sunk CO_2 will be stranded. Incorporating that potential stranding into current policy making has implications for CII capital investment. While previous capital investment cannot be changed, CII capital investment between the current year and a disorderly climate transition will increase the stranded Sunk CO_2. Figure 4 simplifies the policy maker's choice when anticipating this disorderly climate transition into two scenarios, as shown in Equation 5. Firstly, the policy maker can facilitate the BAU capital investment maintaining the level of Sunk CO_2 in the CII industry $\overline{\mathbf{E}_{2019+p}^{k}}$(shown in orange), or to stop/dis-incentivise further investment into CII capital $\dddot{\mathbf{E}}_{2019+p}^{k}$ (shown in blue). This is broadly consistent with Ye, Krol et al. (2023), which designed China's future capital investment pathways by a BAU scenario and two alternative capital-oriented scenarios. However, this section is intended to instead demonstrate of when capital formed from future investments into CII are do not reach their average asset age due to asset stranding. This contrasts with Ye, Krol et al. (2023), which distributes the emissions embodied within the capital assets through their full expected physical lifespan.

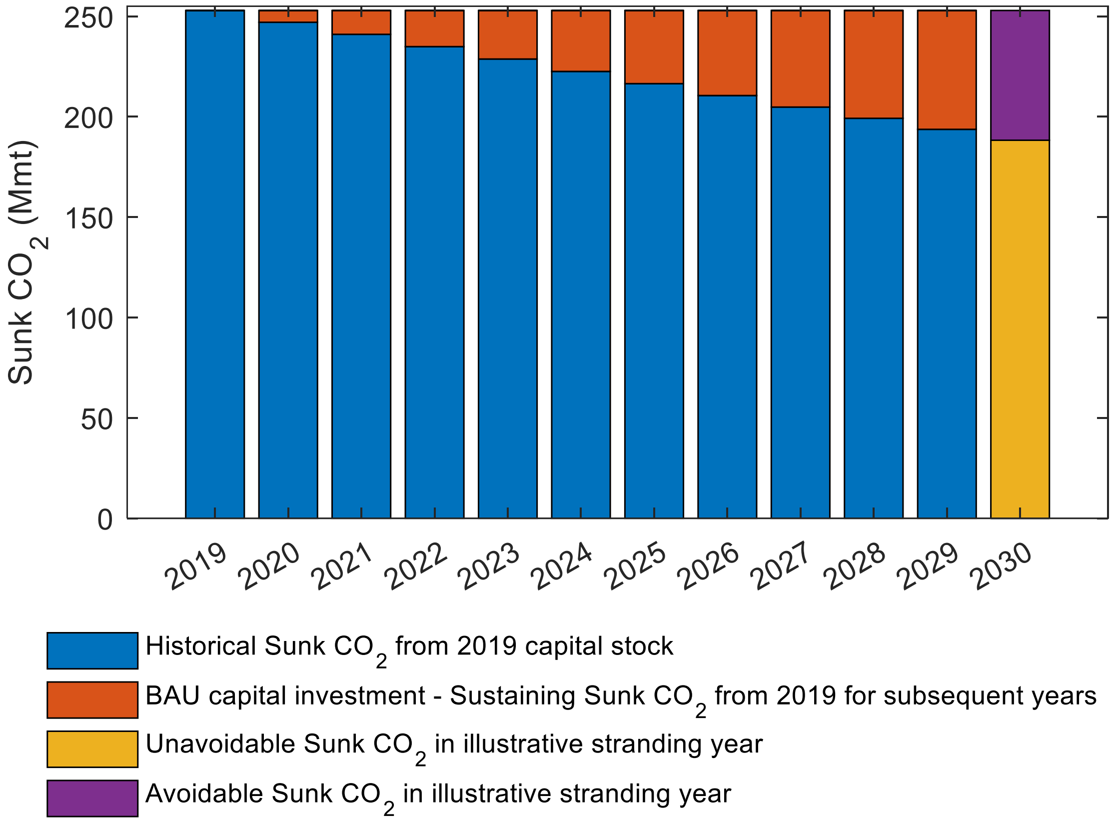

Figure 4: CII Sunk CO_2 stranded in illustrative 2030 disorderly climate transition. The Sunk CO_2 from capital produced by year n decreases over time proportional to the physical retirement rate of the capital assets. The BAU capital investment is assumed to maintain the Sunk CO_2 levels from the current year 2019.

The stranding year is assumed to be 2030 for illustrative purposes, to be broadly consistent with the NGFS disorderly transition scenario, as well as the Ye, Krol et al. (2023) scenario for capital investment. This would cause at least 188Mmt of Sunk CO_2 (yellow bar) to be stranded. The Australian policy makers CII investment decision in the current and subsequent years affects the size of the additional Sunk CO_2 that would be stranded. BAU capital investment (purple bar) would cause this to be 64Mmt of additional Sunk CO_2. The average lifespan of the most carbon-intensive CII, ‘electricity by coal’ is 24 years, indicating that even if the stranding year is assumed to be as late as 2040 or 2050, CII BAU capital investment in the short term still leads to a significant portion of stranded Sunk CO_2.

The degree of Sunk CO_2 would also depend on the type of asset that becomes stranded. Literature around stranded capital assets typically focus on capital categorised within ‘non-residential structures’, particularly on coal electricity production facilities (Caldecott 2016; Rozenberg, Vogt-Schilb et al. 2020; Edwards, Cui et al. 2022). As Section S6.2 shows, the long lifespans of non-residential structures would have a higher risk of becoming stranded than software or communication equipment. In addition, the later that the capital is produced, the longer total lifespan it is expected to have due to improvements in technology, as shown further in Section S6.3. Therefore, a decision by Australian policy makers to continue BAU capital investment into CII such as coal electricity production facilities would likely lead to a significant portion of the Sunk CO_2 becoming stranded in a future disorderly transition.

Choosing between these scenarios is relevant for policy makers when a stranded event is expected to occur, shown in orange and blue. This causes both the yellow and purple Sunk CO_2 to be unutilised. However, while the yellow cannot have been avoided, the purple could have been. Therefore, a policy maker needs to incorporate both the BAU capital investment with CII Sunk CO_2 and expected transition periods into optimising decarbonisation scenarios.

Assuming that the significant portion of the Sunk CO_2 arising from future investment will become stranded, the question arises on how these emissions should be allocated between generations and countries involved in the supply chain. Ye, Krol et al. (2023) allocated the emissions embodied in carbon emissions from year of formation to subsequent years of consumption, across the expected lifespan of the capital asset. However, if the capital asset will not be used across the expected lifespan, literature has not determined how these emissions should be allocated. If the method from Ye, Krol et al. (2023) was used for these assets, future generations that already transitioned away from CII would continue be partly responsible for the CII sunk cost. While further research would be required to determine the allocations of these emissions, this thesis would suggest proportionally attributing emissions against the usage of the CII capital assets, which differs from the total physical lifespan. This ensures that the CBA principles are maintained, where the final consumers of embodied emissions are ultimately allocated responsibility.

6.3. Origin and destination of CII Sunk CO_2 by country

Figure 5a shows the upstream origin of the CII Sunk CO_2 from Figure 3. It shows that an average of 38 per cent of CII Sunk CO_2 originated outside of Australia. This is relatively consistent between industry types, between 30 per cent for ‘Air transport services’ and 60 per cent for ‘Chemicals n.e.c’. However, the proportions vary between asset types, depending on the relative ease of capital production in Australia. For example, 97 per cent of computing equipment and 16 per cent of transport for overall Australian Sunk CO_2 capital originates outside of Australia. In contrast, only 25 per cent of both residential and non-residential structures Sunk CO_2 originates outside of Australia.

Disaggregating the foreign ownership by country shows that Asia-Pacific countries have a high proportion of the Sunk CO_2 origin, with an average of 60 per cent of the foreign origin Sunk CO_2. The high proportion of the Asia-Pacific is primarily driven by China, with over a third of CII foreign capital formation. This indicates the strong reliance of Australian sectors on Asia-Pacific capital formation. In turn, this demonstrates that reducing additional investment into CII would have trade implications with Asia-Pacific countries, particularly China.

Figure 5b shows the downstream final demand attributions of the CII Sunk CO_2 from Figure 3. It shows that an average of 21 per cent of Sunk CO_2 will be attributed to final demands outside of Australia. This also shows that Asia-Pacific countries, particularly China and Japan, have a high proportion of the Sunk CO_2 destination, with an average of 62 per cent of the foreign origin Sunk CO_2. This indicates the downstream implications of CII divestment and suggests that Net Zero transitions for both countries should take into consideration the impacts of continued investment into CII. The downstream impacts also have significantly more variances than Sunk CO_2 origin for foreign percentage, ranging between 0 per cent for ‘Natural gas’ and 92 per cent for ‘Iron ore’. This demonstrates how the downstream impacts of changes to CII capital investment are highly sector dependent, and that policy responses will need to be made individually for each sector.

The three primary production CII share a high proportion of downstream demand being from Asia-Pacific countries. The downstream implications caused by changes to Australian iron ore capital investment will primarily be to Chinese final demands, which is consistent with international trade volumes (DFAT 2022). Petroleum impacts instead have a larger proportion of other Asia-Pacific countries final demands, including from Japan, Singapore and Indonesia. This is also consistent with international trade volumes, with Singapore being the largest importer of Australian refined petroleum (DFAT 2022). This would indicate that any policy changes to capital investment within production-based CII should be in conjunction with Asia-Pacific countries.

The low foreign percentage of CII such as electricity production reflect that a high proportion is directly consumed by Australian final demands, or indirectly through the products they subsequently produce. The overall low foreign percentage from natural gas is due to the sector being almost entirely directly attributed to domestic final demand, as opposed to the natural gas liquid sector, which is instead mostly exported as an intermediary product. Therefore, policy around CII capital investment is comparatively less influenced by overseas impacts and should focus on domestic impacts.

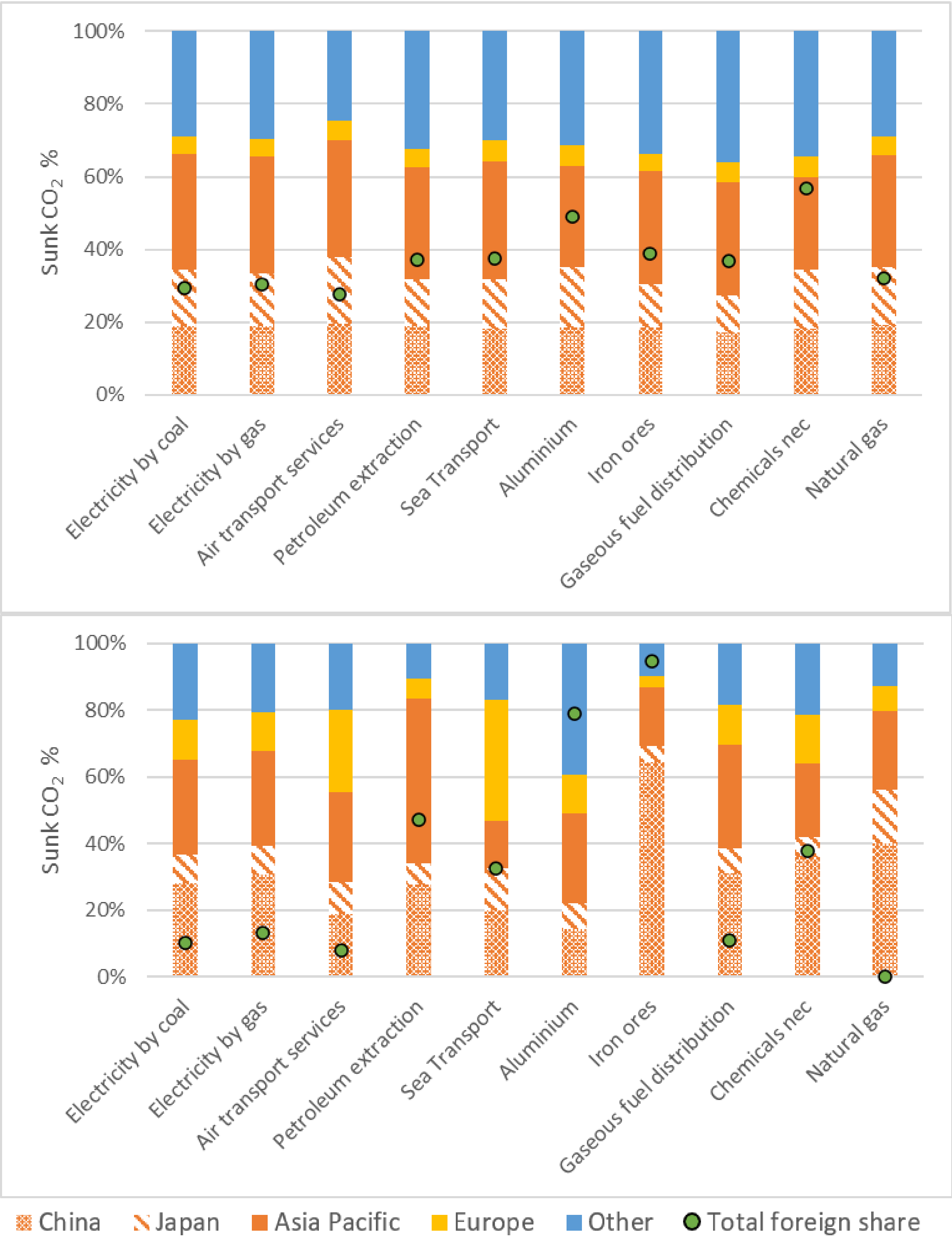

Figure 5: Shows primary countries where the previously produced Sunk CO_2 will likely originate from (top, (a)) or be ultimately attributed to (bottom, (b)) for each CII. Top figure (a) shows the total 2019 Australian Sunk CO_2 disaggregated by origin country for each CII, whereas bottom figure (b) shows the total 2019 Australian Sunk CO_2 disaggregated by final destination country for each CII. This assumes that these distributions are consistent over time. X axis is arranged by level of direct emissions, as shown in Figure 2. The green dot represents the proportion of Sunk CO_2 that originated or finished in non-domestic countries (not Australia). The foreign origination share is disaggregated further by region in the stacked bars. The orange components in the stacked bars represent Asian Pacific countries, which is further disaggregated for Japan and China.

6.4. Destination of CII CO_2 emissions by sector

Table 1 shows how the CII CO_2 would be attributed downstream, disaggregated by final industry. Most industries' direct final demand is the largest downstream industry, indicating that the primary impact of the changes to the CII capital investment would be to household final demand, as shown in Section S8. This would suggest that policy around CII capital investment should incorporate the consequences experienced by households, including the availability of substitutes.

The only sectors that do not have direct final demand as their largest sector are petroleum extraction, aluminium, and iron ores. These commodity-based industries are prominently upstream and have large downstream impacts, as shown further in Section S7. These sectors are used as an intermediate good for a variety of sectors, particularly in further capital formation. Therefore, policy makers considering changes to investment in CII should also consider the additional effects that a reduction in further downstream capital formation would cause. This would require capital flow endogenization to see the full impacts, which is a possible extension of this research.

It is notable that service-based sectors are disproportionately affected in CII downstream impacts, with 80 per cent of the second and third largest proportions of each CII. This due to service sectors being primarily downstream, with the CII sector intermediary inputs being embodied in their final output. Further, the construction industry is a primary downstream affected industry in all sectors. This is due to both the size and wide range of inputs required for construction, as well as that most of the CII are either primary or secondary industries, both of which are major inputs into construction.

Table 1: 2019 Australian CII CO_2 by FD industry (%).

CII	Downstream sector by size (%)		
	First	Second	Third
Electricity by coal	Electricity by coal 58%	Construction work 9%	Hotels and restaurants 5%
Electricity by gas	Electricity by gas 48%	Construction work 9%	Hotels and restaurants 6%
Air transport services	Air transport services 54%	Public Administration 8%	Other business services 5%
Petroleum extraction	Motor Gasoline 35%	Construction work 20%	Petroleum extraction 7%
Sea Transport	Sea Transport 60%	Construction work 7%	Public administration 4%
Aluminium	Construction work 18%	Machinery and equipment n.e.c. 15%	Motor vehicles, trailers and semi-trailers 11%
Iron ores	Construction work 37%	Machinery and equipment n.e.c. 14%	Motor vehicles, trailers and semi-trailers 9%
Gaseous fuel distribution	Gaseous fuel distribution 35%	Construction work 20%	Health and social work 7%
Chemicals nec	Chemicals nec 36%	Health and social work 14%	Construction work 11%
Natural gas	Natural gas 100%	Construction work 0%	Furniture; other manufactured goods n.e.c. 0%

6.5. Qualifications

This research has several limitations which further research could seek to address. As with all IO analysis, sector aggregation means that some results should be treated with caution. The retirement function of the Sunk CO_2 was primarily based on the KLEMS 32 industries, meaning that industries such as electricity by coal, electricity by gas, and other gas industries are based on the same retirement function. Therefore, the similarity of Sunk CO_2 trends within these sector groupings are likely to be due to the measurement method rather than the embodied emissions within the sector's capital being analogous. This research could be extended by estimating the Sunk CO_2 retirement functions to the EXIOBASE 200 industry level of granularity, enabling greater comparison between CII.

The Sunk CO_2 estimations in Figure 4 has several simplifying characteristics. For example, the BAU scenario assumes that Sunk CO_2 is maintained over time. An area of extension would be to instead assume that the same level of capital stock is maintained over time, incorporating projected changes in the carbon intensity of capital formation. Further scenarios could also be developed, with partial divestment away from CII capital stock.

7. Conclusion

7.1. Overall

Comprehensively determining the impacts of CII future capital investment is a critical component within the optimisation of a global Net Zero emission economic transition. This thesis has made a novel contribution to the impacts of CII capital investment by analysing the Sunk CO_2 emissions within stranded capital assets. Integrating Sunk CO_2 emissions would prevent avoidable emissions embodied in CII capital investment in a future disorderly economic transition towards Net Zero. Further, it improves the accuracy of carbon accounting and, in turn, serves to determine more equitable mitigation responsibility and inform public policy.

The Australian case study estimated the scale of CII Sunk CO_2 over time, separated by type of asset and industry. It showed that CII such as carbon-intensive electricity production and air transport have a significant Sunk CO_2, due to the respective use of electrical and transit structures. This thesis has determined that the average lifespan of these sectors Sunk CO_2 ranges between 15-25 years, suggesting that continued capital investment in these sectors would lead to a high Sunk CO_2 in the event of a disorderly climate transition.

Attributing responsibility for these Sunk CO_2 has not been discussed in literature. Given the significant size of these emissions, with this thesis estimating that these emissions exceeded 250Mt CO_2 across all Australian CII in 2019, determining these responsibilities becomes important in a disorderly Net Zero transition. Determining responsibilities must consider the year and origin country of formation, usage in subsequent future consumption, and the final destination of embodied emissions.

Methods from past literature of allocating responsibility to future generations has not considered the likelihood of CII asset stranding. This thesis has demonstrated the merits of proportionately attributing emissions against the usage of the CII capital assets, instead of attributing them proportional to the physical retirement rate. This facilitates the inter-generational attribution of emissions embodied in CII capital assets, as well as between countries and sectors involved in the CIIs' supply chains. In turn, anticipating these responsibilities before the capital assets become stranded may change domestic climate policy. The Australian case study shows that the foreign production of these capital assets is primarily comprised of Asia-Pacific countries, particularly China. The total foreign share of capital asset production was estimated to range between 20-50 per cent. This is broadly consistent with the final destination of the CII outputs with Asia-Pacific countries, including Singapore and Japan, also being the dominant foreign recipients. The total foreign share of CII output destination widely varies, suggesting that the implications for Sunk CO_2 are heavily industry dependent.

7.2. Domestic policy applications

There are a range of applications for Australian policy makers from these results. The proposed Australian Government Net Zero plan currently includes sectoral decarbonisation plans for sectors including electricity and energy, industry and transport. These sectoral decarbonisation plans include capital divestment and the consideration of stranded capital assets. To fully integrate the impacts of capital divestment and stranded capital assets into decarbonisation plans, measurements of Sunk CO_2 should be included. The Sunk CO_2 varies by CII, with electricity by coal and air transport services having significantly higher Sunk CO_2 than other CII. Further, sectors such as natural gas have significantly higher downstream domestic impacts compared against sectors such as iron ore.

Therefore, the attribution of CII Sunk CO_2 will have varying downstream impacts depending on the sector. Incorporating this sectoral heterogeneity into the implications of sector divestments may ultimately improve the effectiveness of the Net Zero by 2050 plan.

7.3. International policy applications

The applications of Sunk CO_2 to Australian international policy can be split into bilateral and multilateral agreements. The Australia GEA agreement with Singapore includes sections on development of electricity production, which would require capital asset investment. Execution of this agreement should consider all ramifications of capital asset investment. This includes the Sunk CO_2 in capital asset investments into capital intensive sectors, and the subsequent implications for the GEA. Given that East Asian countries like Singapore are dependent on the output from Australian CII, this could have substantial impacts to the GEA. For example, Singapore's status as the primary importer of Australian refined petroleum means that embodied emissions within Australian refined petroleum are ultimately attributed to them. In turn, a disorderly transition means that Sunk CO_2 within Australian refined petroleum capital would be attributed towards Singapore. Bilateral agreements should incorporate this understanding that the capital investment within this refined petroleum is therefore a shared responsibility, including the Sunk CO_2 embodied with the capital.

Similarly, the GEA could be altered when the Sunk CO_2 embodied within CII capital is incorporated. For example, given that China is a major trading partner of Australia, it is possible that an additional GEA could be signed with China. Incorporating Sunk CO_2 into the agreement would likely have impacts on the Australian iron ore sector. As with Singapore and refined petroleum, China's status as the primary importer of Australian iron ore means that they would share responsibility for continued capital investment within the sector, including the Sunk CO_2.

Australia was a signatory to the multilateral Paris Agreement (the Agreement) in 2015 to accelerate the actions and investments needed for a Net Zero economic transition. The Agreement included collaborating with developing countries to mitigate their emissions, which included those embodied in capital formation. Given that Sunk CO_2 incorporates both the origin country, the carbon-intensive industry country, and the destination country, policy around this requires multilateral coordination. Partnering with capital origin countries like China, as well as destination countries like Singapore, will more effectively allocate responsibility for reducing investment in capital intensive sectors. Following consumption-based accounting frameworks, this could shift responsibility away from the origin country and towards the destination country.

7.4. Extensions

A primary contribution of this thesis is to facilitate further research into the previously unexplored area of Sunk CO_2. One primary avenue of extension within this research is to integrate CII Sunk CO_2 indicators into broader optimisations of energy transitions, such as Global Integrated Assessment Models (GIAMs). Estimations of the impacts of stranded capital assets have used GIAMs (Edwards, Cui et al. 2022) (Binsted, Iyer et al. 2020) (Semieniuk, Holden et al. 2022) (Auger, Trüby et al. 2021) Malik, Bertram et al. (2020). Using Sunk CO_2 within these models would likely improve evaluations by policy makers as to the impact of future CII capital asset investments. In turn, it would likely increase the costs of CII BAU capital investment, which would further strengthen the case for an early and sharp mitigation effort towards Net Zero.

An alternative method of integrating the CII Sunk CO_2 is through policy-based optimisations around reducing the impact of stranded capital assets. Previous research such as (Löffler, Burandt et al. 2019), Coulomb, Lecuyer et al. (2018), and Zhang, Da et al. (2021) on characterising these policy optimisations focus on the economic implications. This paper's analysis provides a complementary environmental perspective, providing a more comprehensive understanding of the long-term environmental effects of CII capital investments.

Overall, this thesis demonstrates that future avenues of research within stranded capital assets should incorporate Sunk CO_2 into optimisation decisions. These include policy making decisions around CII capital investment, as well as broader energy transition optimisations.

Supplementary Information

The sections in the supplementary information are structured in the following way: Section S1 is a high-level overview of EE-IO analysis, including the theoretical basis and algebraic notation. Section S2 expands on the discussion from Section 2.3 on climate scenarios, expanding on key terms such as "disorderly" and "orderly" climate transition and the subsequent economic impacts. Section S3 estimates the CII without having the second CII criteria relating to carbon intensity and discusses the subsequent changes in captured industries. Section S4 estimates CII using a CBA method instead of PBA to determine both the total sectoral emissions and emissions intensity. Section S5 shows how each aggregate capital data type was constructed, linking back to the CII estimated in Section 6.1. Section S6 shows the overall Sunk CO_2 trends in Australia across all sectors, including how the trends are heterogenous between capital types, trading partner, and year of capital formation. This is also compared against the equivalent CII trends discussed in Section 6.2. Section S7 shows the downstream effects of CII production, discussing the possible implications in the context of asset stranding. S8 disaggregates the final destination of CII output by type of final demand, instead of by sector as in 6.4.

S.1. An Overview of Environmentally Extended Input Output (EE-IO) analysis

IO analysis is a modelling technique that divides the economy into final demand and production and accounts for the direct and indirect interdependencies among different sectors (van Leeuwen, Nijkamp et al. 2005). This details how goods and services are used as inputs for production of other goods and services, shown in quadrant T in Figure S1. Because of the assumption that any one industry produces one product, there is an equal number of industries and products.

The bottom left quadrant of Figure S1, primary inputs to production (v), are elements of production that are treated as exogenous to the framework of the economic production being analysed. Primary inputs have not been produced by any production process of the economy being analysed, including labour input provided by domestic households, capital, and government inputs.

Final demand (y) in the top right quadrant of Figure S1 refers to elements of consumption that do not relate to the production process but to the products or services in their final form and for final use within the economy being analysed. Final demand includes consumption by households and government, as well as capital formation and exports.

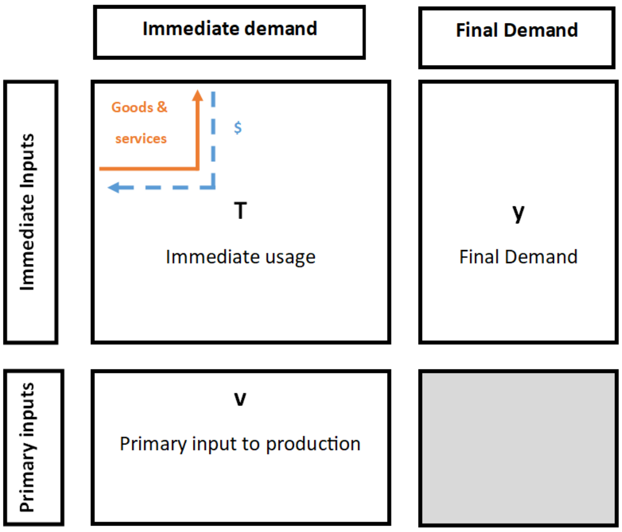

Figure S1: IO analysis diagram showing the division of the economy into final demand and production and accounting for the direct and indirect interdependencies among different sectors.

Supply and demand must balance which means that the total outputs must be equal in monetary terms to the total inputs $\mathbf{T}+\mathbf{y}=\mathbf{T}+\mathbf{v}=\boldsymbol{x}$ which represents the gross output by a production activity. The coefficient matrix $\mathbf{A}$ is a representation of the proportion required of each input in the production of a unit of production $\mathbf{A}=\frac{\mathrm{T}_{ij}}{x_i}$

To show Figure S1 algebraically, $\boldsymbol{x}$ is a $m \times 1$ vector, where m is the number of industries and products, the inter-industry input $\boldsymbol{A}$ is a $m \times m$ matrix, and the $m \times 1$ vector $\boldsymbol{y}$ specifies annual final demand by m products.

$$\mathbf{x}=\mathbf{A}\mathbf{x}+\mathbf{y} \qquad \text{(Eq. S1)}$$

Solving Equation S1 for total output $\mathbf{x}$ yields Equation S2:

$$\mathbf{x}=(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y} \qquad \text{(Eq. S2)}$$

$\mathbf{I}$ is the identity matrix $(m \times m)$, and $(\mathbf{I}-\mathbf{A})^{-1}$ is the matrix of total requirements $(m \times m)$, often referred to as the Leontief inverse $\mathbf{L}$. The alternative method of aggregating inter-industry inputs, the Ghosh Model, is shown in Section S7. Each element of the inter-industry requirement matrix A_{ij} indicates the direct intermediate requirements of activity i in producing one unit output of activity j. Each element of the Leontief inverse L_{ij} shows the total (i.e., the direct and indirect) intermediate requirements of activity i in producing one unit of output of activity j (Schaffartzik, Eisenmenger et al. 2013).

Extending IO analysis to evaluate the interlinkages of carbon emissions requires an estimate of the total environmental impact caused by the demand for each output $\mathbf{E}$ $(1 \times m)$. E_{ij} refers to the total environmental total inputs of j into activity i. This is estimated using a direct environmental inputs intensity $\mathbf{f}$ $(1 \times m)$ matrix, with each element $f_{mi}=\frac{E_{ij}}{x_i}$ showing the direct environmental inputs of *j* per unit output of activity *i*. The term $\mathbf{f}(\mathbf{I}-\mathbf{A})^{-1}$ is also called the total environmental multiplier, capturing the direct and indirect environmental inputs per unit output by production activity. This method of estimating the total environmental impact $\mathbf{E}$ can be seen below in Equation S3.

$$\mathbf{E} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \qquad \text{(Eq. S3)}$$

Extending the single country IO table example in Figure S1 to a multiregional IO table (MRIO) is shown in Figure S2, which usually require that all countries included have a uniform sectoral structure. The compilation of data to build an MRIO table must also address the fact that row and column totals are usually not equal. Therefore, different balancing techniques can be applied. For an MRIO table to map the entire world, countries that are not explicitly covered are usually included in one or more residual regions (e.g., Rest of World Account, or "RoW"). The RoW aggregations in this thesis are shown in Appendix B.

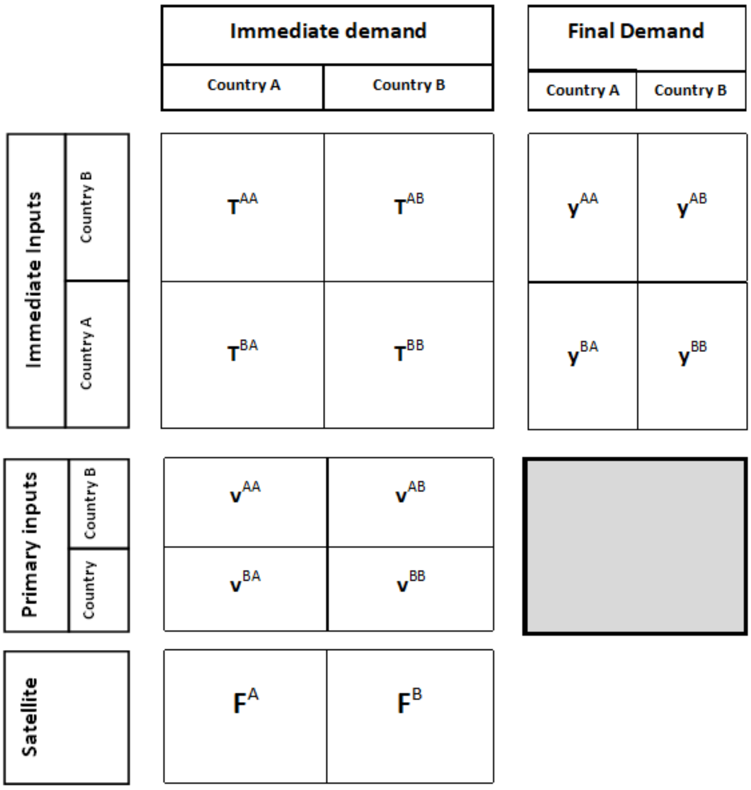

Figure S2: Diagram extending the Figure S1 IO analysis diagram to mutliple economies and envronmental inputs using the satelite accounts, defined as a EE-MRIO analysis.

S.2. Overview of climate scenarios- NGFS example

At the 2017 "One Planet Summit", a group of central banks and supervisors established the Network of Central Banks and Supervisors for Greening the Financial System (NGFS). They have continued to update a set of hypothetical climate scenarios that provide a common reference point for understanding how climate change and climate policy and technology trends could evolve in different futures. The collection of scenarios is intended to show a broad spectrum of risk outcomes, primarily dependent on policy responses (Bertram, Hilaire et al. 2020). This project stems from the evidence that current country policies are not yet sufficient to achieve official commitments and targets. The possible consequences of the policy responses are categorised by two risk metrics. Firstly, transition risk, which covers the potential costs to society of progressing to a low carbon economy to mitigate the impacts of climate change. This includes changes to financial, policy, regulatory and geopolitical outcomes. Secondly, physical risk covers impacts of climate change including extreme weather events, rising sea-levels, biodiversity loss, and many other consequences. A brief overview of the different ways that governments respond to this current deficit is discussed below:

In orderly scenarios, it is assumed that climate policies are implemented at an early stage and progressively become more rigorous, resulting in relatively low levels of both physical and transition risks. This is shown in the lower left quadrant of Figure S3. In disorderly scenarios, transition risk increases due to delayed or inconsistent policy implementation across countries and sectors. This inefficiency leads to carbon prices and other policy responses being more severe to maintain the same temperature in 2050 as orderly scenarios (Bertram, Hilaire et al. 2020). This is shown in the upper left quadrant of Figure S3.

In hot house world scenarios, it is assumed that climate policies are inconsistent and sufficient across jurisdictions, leading to substantial global warming. In turn, this leads to severe physical risks and irreversible consequences such as sea-level rise. This is shown in the lower right quadrant of Figure S3. Too little, too late scenarios diverge from hot house scenarios in that significant policy responses are enacted against climate change, but nevertheless are ineffective in combating global warming due to the delayed and uncoordinated response (Bertram, Hilaire et al. 2020). This is shown in the upper right quadrant of Figure S3.

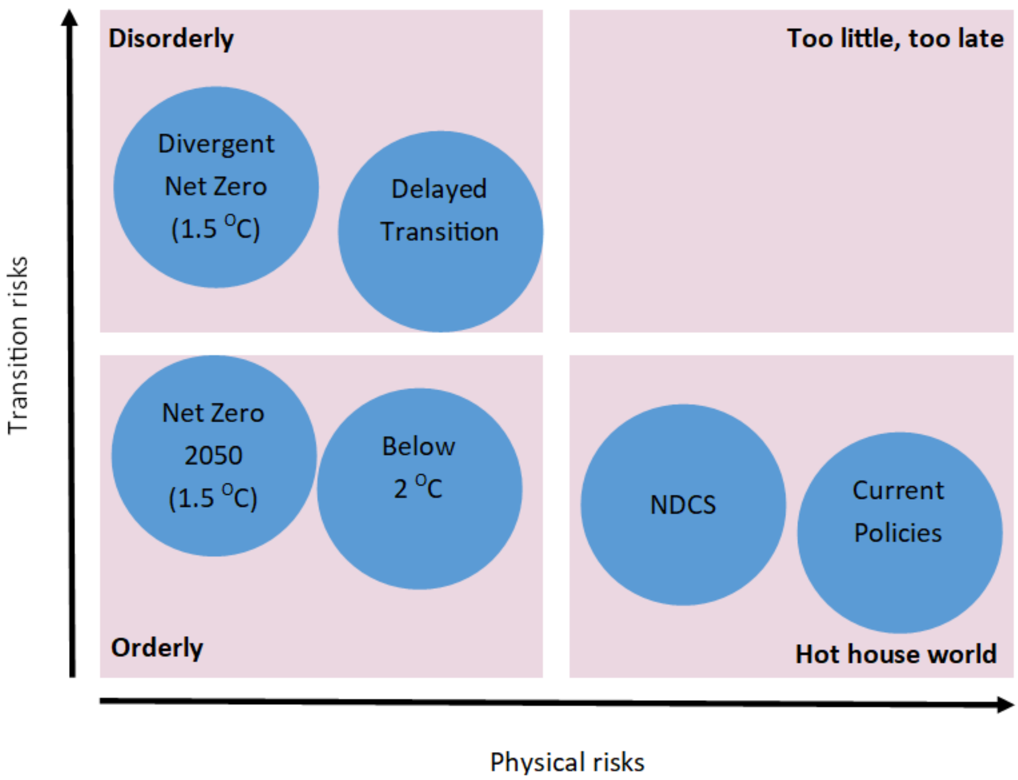

Figure S3: Diagram showing the broad catergories of NGFS scenarios alongside scales of transition risk and physical risk, which was adapted from Bertram, Hilaire et al. (2020).

The implications of these scenarios on the level of stranded capital assets they indirectly cause partly depend on the type of scenario subcategory, which is shown in the grey boxes in the diagram. These are further elaborated in the below table. Firstly, Nationally Determined Contributions and Current Policies currently pose a low risk of causing stranded capital assets. This is due to national plans of phasing out carbon-intensive industries are generally either with an extended time horizon or limited in degree of divestment.

Net Zero 2050 policies and Below 2 C policies have a varying level of stranded capital assets, depending on the assumptions and modelling method used. As the transition away from the carbon-intensive industries occurs immediately, carbon-intensive sectors with high amounts of carbon lock-in may have their capital assets stranded. Alternatively, the early transition away means that with no additional investment into carbon-intensive sectors, some current capital assets could slowly be phased out. This is more likely with the 2-degree scenario, which is less severe in a transition than the 1.5-degree scenario.

Transition risks manifest particularly in the 'delayed transition' and 'divergent Net Zero' scenarios, which in turn will cause a significant proportion of capital assets within carbon-intensive sectors to be stranded. The Divergent scenario's aim of reaching 1.5 degrees with little coordination between domestic authorities is projected to lead severe policy responses such as high carbon prices, bans or fines imposed rapidly. These responses are similar with the delayed transition, but instead are delayed until at least 2030. While this will lead to a 2050 lower temperature goal for the policy responses, the policy responses are anticipated to be equally severe due to the delay. Specific scenarios within the "Too little too late" are not developed by the NGFS but are stated to be broadly consistent with delayed transitions with the delay being longer. In turn this leads to similar instances of stranded capital assets, with potentially added risks to capital assets from physical risks such as cyclones or bushfires.

The pace of technology transitions and regional policy variations will also have an impact on the prevalence of stranded capital assets. Slow technology change would reduce the pace that existing capital with outdated technology is replaced, while fast technology change could cause widespread asset stranding. Regional policy variation would cause heterogeneous levels of stranded capital assets between countries, meaning that domestic responses to anticipated Sunk CO_2 would also vary. For example, countries which transition to Net Zero slower will likely have comparatively less asset stranding in the short term. In turn, the level of Sunk CO_2 at risk of stranding in the short term would also be comparatively lower. However, this scenario still does assume that the 2050 1.5^{o}C temperature increase limit is achieved, meaning that the asset stranding would still occur, just marginally later for some countries.

Table S1: Summarising the subtypes of NGFS scenarios				
Category	**Type**	**Description**	**Technology change**	**Regional policy variation**
Orderly	Net Zero 2050	Limits global warming to 1.5 °C through stringent climate policies and innovation, reaching Net Zero CO_2 emissions around 2050.	Fast change	Medium variation
	Below 2 °C	Gradual increase of the stringency of climate policies, giving a 67 % chance of limiting global warming to below 2 °C.	Moderate change	Low variation
Disorderly	Divergent Net Zero	Reach net-zero by 2050 but with higher costs due to divergent policies introduced across sectors and a quicker phase out of fossil fuels.	Fast change	Medium variation
	Delayed Transition	Assumes global annual emissions do not decrease until 2030. Strong policies are then needed to limit warming to below 2 °C.	Slow/Fast change	High variation
Hot house world	Nationally Determined Contributions	Includes all pledged policies even if not yet implemented.	Slow change	Medium variation
	Current Policies	Current Policies assumes that only currently implemented policies are preserved, leading to high physical risks.	Slow change	Low variation

S.3. CII without carbon intensity criteria

This Supplementary Information section expands on Section 6.1 by estimating the CII without applying the minimum carbon intensity criteria $S_i > \gamma$. Comparing Figure S4 to Figure 2, several CII have changed. 'Construction work', 'Hotel and Restaurant Services', and 'Other Business Services' all had carbon intensities below €1m/kt, and therefore were excluded in Figure S4. This is due to the total emissions embodied in the services instead being primarily indirect, which is discussed in Section S4. The inclusion of these service-based sectors within the CII estimation is instead due to the underlying size of the sectors. The Australian economy is primarily services based, leading to 'Construction work', 'Hotel and Restaurant Services', and 'Other Business Services' being the first, eighth and second largest industries by output respectively.

The low carbon intensity of 'Other Bituminous Coal' extraction compared against other mineral extractions relates to the method used to determine CII. CII estimations only consider CO_2 emissions, rather than other GHG emissions. The primary GHG emissions of coal mines are anthropogenic methane emissions, through the release of methane trapped in the coal and surrounding formations (Zhang, Da et al. 2021). Therefore, using a carbon equivalent GHG intensity criterion would likely result in 'Other Bituminous Coal' being included as a CII. Re-estimating the findings using CO_2e is a suggested extension of this research. The remaining CO_2 for 'Other Bituminous Coal' instead comes from transportation, which accounts for 29% of the total carbon emissions from underground coal mining (Ivanova, Vesnina et al. 2022).

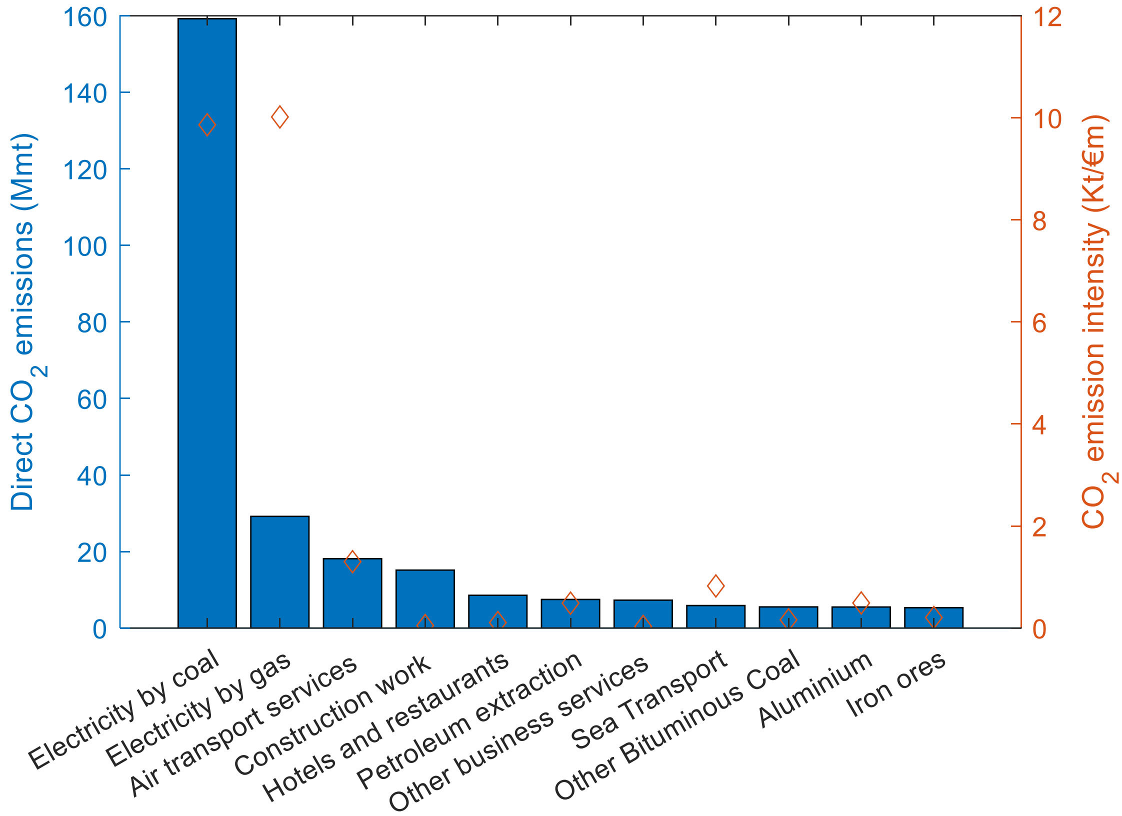

Figure S4: Estimating 2019 CII through the total production-based emissions $\mathbf{F}_{2019} > 4\text{Mmt}$ and constraining to the top ten highest emitters. 6.1 shows CII estimation while applying the additional minimum carbon intensity $\mathbf{S}_{2019} > 1\ kt/€5m$. The emission intensity is denoted by the orange diamonds with the right (orange) axis, whereas the direct CO_2 emissions are denoted by the blue columns with the left (blue) axis.

S.4. Alternative method of determining CII – CBA

This section estimates CII by CBA instead of PBA, as shown in Section S.3. and 6.1. The total carbon intensity $S_i(1-A)^{-1}$ is used for the minimum $\ddot{\gamma}$, instead of the direct carbon intensity S_i that was used for γ, as shown in Section 4.1. Further, the total footprint E_i is used for the minimum $\ddot{\tau}$, instead of the direct footprint , F_i that was used for the minimum τ in Section 4.1.

Figure S5 shows that electricity production by coal is the largest carbon emitter by a significant margin. This suggests that the electricity production by coal industry is most likely to strand its consuming assets through a disorderly production adjustment in Australia to reduce net carbon emissions through consumption-based accounting. This is primarily driven by the direct emissions from the sector, contributing to how the CBA estimation of total footprint being lower than the PBA direct footprint. This is due to a significant portion of the total output of the sector being used as intermediary inputs into other sectors, leading to the emissions being embodied in other final demand footprints. This is also consistent with the electricity by gas sector and natural gas, which has a lower total footprint compared to the PBA estimate. The transportation sectors also have a slightly lower CBA total footprint than PBA direct footprint, primarily due to their intermediary inputs into service-based sectors.

In contrast, the construction work sector has a significantly higher CBA footprint estimation, when compared against the PBA footprint estimation in Figure 2, due to the indirect emissions being the majority of the sector's total footprint. This increase in estimated carbon footprint size is consistent with the Australian construction carbon footprint estimations in Yu, Wiedmann et al. (2017). This is due to a significant proportion of emissions from CII output being ultimately attributable to construction, as shown in 5.4. This also contributes to the inclusion of 'hotel and restaurants', 'motor gasoline', and 'motor vehicles, trailers and semi-trailers' into CII estimates, unlike in the PBA method.

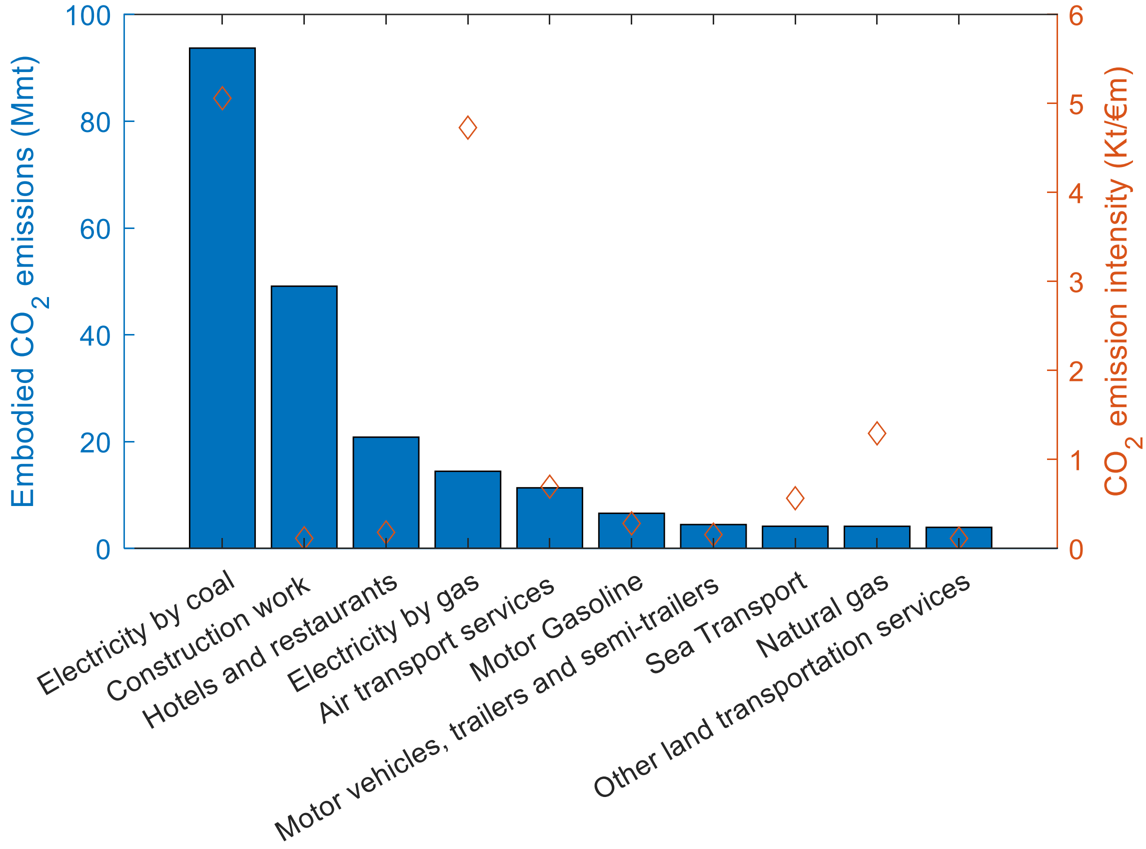

Figure S5: Estimating Australian CII in 2019 by highest embodied emissions. CII are determined through the total embodied emissions , $E_i > 5\text{Mmt}$ and emission intensity $S_i(1-A)^{-1} > 1\ kt/€10m$. The minimum emission intensity was chosen to be 1kt/€10m, instead of the 1kt/€5m used in Figure 2, as CBA leads to less carbon intensity on average for industries. Maintaining a 1kt/€5m leads to the remaining industries having a relatively negligible total carbon footprint, and therefore is too high a CII carbon intensity minimum $\ddot{y}$. Figure S6 shows CII estimation without applying the minimum carbon intensity $S_i(1-A)^{-1} > 1\ kt/€10m$. The emission intensity is denoted by the orange diamonds with the right (orange) axis, whereas the direct CO_2 emissions are denoted by the blue columns with the left (blue) axis.

Figure S6 shows that CBA estimation leads to a disproportionately large proportion of services being estimated as CII. This is shown by eight out of the ten industries being service based, with the exceptions being the two emission-intensive electricity generation industries. The high proportion of services relates to how embodied carbon accumulate along with the flow of products in industrial chains of production. Therefore, industries located downstream, such as the service sector, tend to demonstrate more embodied carbon emissions (Hu, Wood et al. 2019). This is shown by how all service-based sectors have a higher CBA total carbon footprint than PBA direct carbon footprint, as shown in Figure 2. However, the relatively low carbon intensity also reflects that the low direct emissions from the service sectors offset the carbon-intensive indirect emissions embodied within the sectors.

The applicability of the high embodied carbon footprint of service sectors towards Sunk CO_2 depends on how the responsibility for the emissions are allocated. Some literature has suggested that the backward linkage of the service sector may indirectly impose significant environmental pressure on upstream non-service sectors, known as the "pull effect" (Alcántara and Padilla 2009; Hou, Wang et al. 2021). Given that the indirect carbon emissions of the services sector are much higher than the direct emissions, this attribution method would lead to significantly more emission mitigation responsibility on the service sectors. Given that many service sectors are capital intensive, this would also lead to a significant degree of Sunk CO_2 at risk of stranding.

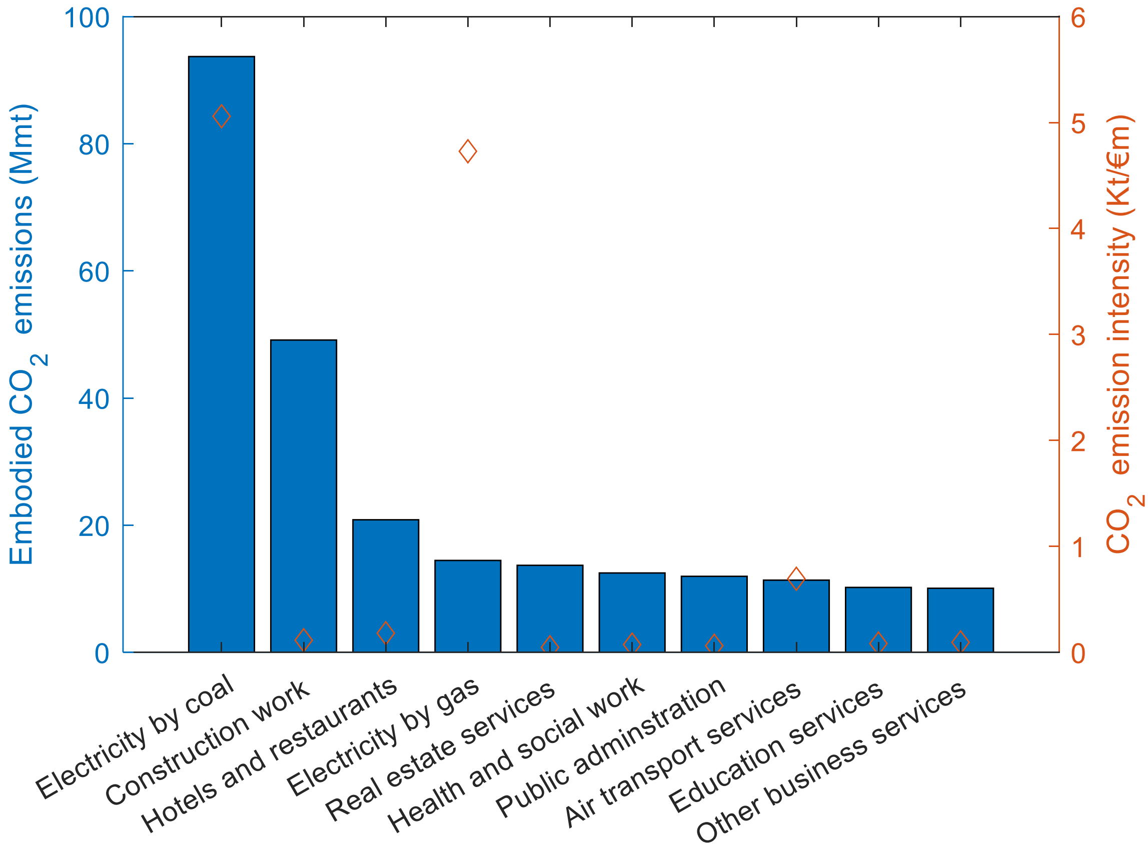

Figure S6: Estimating Australian CII in 2019 by highest embodied emissions. CII are determined through the total embodied emissions , $E_i > 5\text{Mmt}$ and constrained to the ten highest emitting industries. Figure S5 shows CII estimation while applying the additional criteria of a minimum carbon intensity $S_i(1-A)^{-1} > 1\ kt/€10m$. The emission intensity is denoted by the orange diamonds with the right (orange) axis, whereas the direct CO_2 emissions are denoted by the blue columns with the left (blue) axis.

Figure S7 shows that the emissions from electricity by coal and gas are driven by household consumption, as well as hotel services, real estate, and air transport. This suggests that disorderly shifts in household behaviour could be particularly significant to carbon-intensive energy production and services. This high level of emissions attributed to households is consistent with global estimates, which indicates 72% of global GHG emissions is attributable to them (Dubois, Sovacool et al. 2019). In contrast, construction work is primarily driven instead by GCFC demand. This would likely consist of capital such as residential or non-residential structure investment, which is expanded further in Section S5. Health services, education and public administration are primarily driven by government final demand, which could suggest that a government driven transition away from CII could disproportionately affect these industries.

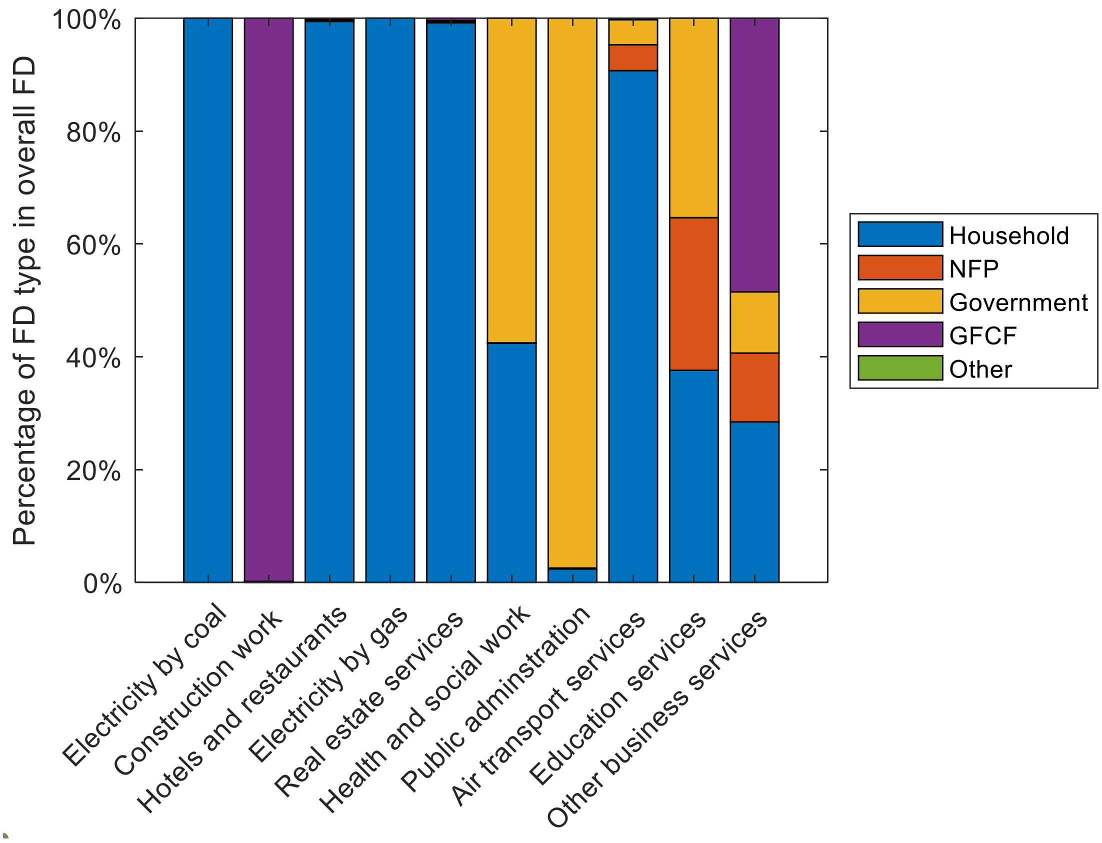

Figure S7: Disaggregating the final demand of the CII sectors estimated in Figure S6 by type of final demand. This was estimated by aggregating final demand across countries and finding the percentage of each type of final demand within each overall CII final demand.

S.5. Capital asset types

This section will further discuss the findings of 6.2 using the disaggregated capital types, with the disaggregation of the primary capital types shown in Table S2. Capital types in Wang, Hertwich et al. (2023) are based on the EU KLEMs model, which in turn extends out the OECD National Accounts. It has 6 asset subdivision categories - Residential structures, Non-residential structures, Transport equipment, Machinery and other equipment, Products of agriculture and forestry and other products. The EU KLEMs model further disaggregates the OCED subdivision 'ICT assets' into Computing equipment, Communication equipment and Software, as well as disaggregating 'Total Non-Residential Investment' into non-residential structures and infrastructure. Therefore, the most detailed level the EU KLEMS classification of assets consists of 10 investment categories, of which three are in structures, four in machinery and equipment, two in intangible assets and an additional category representing products of agriculture and forestry. In turn, Wang, Hertwich et al. (2023) makes a series of changes to determine LEF trends. The paper maintains the aggregate subdivision category total non-residential investment from the OECD accounts, while keeping the disaggregate ICT asset divisions. The paper's division 'Other Assets' encompasses products of agriculture and forestry as well as total intangibles (excluding software).

Table S2: Disaggregation of capital asset types

Total non-residential structures	Other machinery and equipment	Transport equipment
Office buildings	Medical equipment and instruments	Electricity trans, distribution, industrial apparatus
Religious buildings	Nonmedical instruments	Light trucks
Educational and vocational buildings	Photocopy and related equipment	Other trucks buses, and truck trailers
Medical Buildings	Fabricated metal products	Autos
Multi-merchandise Shopping	Engines and turbines	Aircraft
Food and beverage establishments	Metalworking machinery	Ships and boats
Commercial warehouses	Special industry machinery n.e.c.	Railroad equipment
Other commercial buildings	General industrial equipment	
Manufacturing	Furniture and fixtures	
Electric	Agricultural machinery	
Other power structures	Construction machinery	
Petroleum and natural gas	Mining and oilfield machinery	
Communications	Service industry machinery	
Mining structures	Electrical equipment n.e.c	
Hospital and institutional buildings	Other non-residential equipment	
Special care		
Lodging		
Amusement and recreational buildings		
Transit buildings; air		
Transit buildings; land		
Farm buildings		
Other structures		

S.6. Australian Sunk CO_2 trends

This section summarises the trends of Sunk CO_2 for all sectors in Australia. The first subsection describes the ten largest sectors by Sunk CO_2, linking the underlying trends to existing literature and comparing to the CII Sunk CO_2. The second section separates the Sunk CO_2 instead by historical capital asset type over time, as well as projecting the retirement rate over time of the current Sunk CO_2 by asset type. The third section expands on this by separating the current Sunk CO_2 by formation age cohort and projecting it out over time. The final section uses both the historical data and future projection method for country of origin, comparing the findings against similar literature.

S.6.1. Sectoral

Figure S8 indicates that services are disproportionately represented in Sunk CO_2, with eight out of the ten of the highest Sunk CO_2 industries. This is largely unrelated to the average lifespan of these industries, with the overall asset life in Australian being 18.4 years, close to the CII mean (19.8) shown in Figure 2. This is consistent with Sodersten, Wood et al. (2018), which found that CBA emissions of services increased substantially when the capital used in production processes was included. Consistent with S4, Sodersten, Wood et al. (2018) determined that this was due to the underlying size of the service sectors. This is augmented by the comparatively large size of the Australian service industry. Failing to include this component of the service sectors in CBA therefore strongly underestimates their mitigation responsibility (Ye, Krol et al. 2023).

Primary CII electricity by coal industry is still included as one of the industries with the highest Sunk CO_2. Similar to the service industries, this high Sunk CO_2 is primarily due to the underlying size of the 'electricity by coal' industry rather than the capital asset CO_2 intensity. However, unlike the service sectors, the Sunk CO_2 within the 'electricity by coal' smaller than the direct emissions, due to the carbon intensity of coal combustion. This is broadly consistent with Södersten and Lenzen (2020), which found that capital endogenization did not lead to a significant increase to the carbon footprint of the 'electricity by coal' sector in Australia.

The high Sunk CO_2 industries are primarily comprised of total non-residential structures investment, due to inclusion of asset subtypes such as office, medical and other commercial buildings. The large size attributed to the services sector is consistent with Sodersten, Wood et al. (2018), which found that two-thirds of non-residential structure investment was allocated to service industries, principally services related to public administration, transport and storage, real estate, and education. In addition, the transportation asset type is significant for two transport-based industries, as well as the 'travel agency' and 'Health and social work' subcategory. The significance within 'travel agency' is broadly consistent with Södersten and Lenzen (2020), which determines transport to be a leading contributor to the carbon footprint of tourism. In turn, the Sunk CO_2 within this high usage of transportation capital assets would also likely be significant. The significant Sunk CO_2 in transportation capital assets for the health and social sector is also broadly consistent with Yamada and Imanaka (2015), which found high levels of interlinkages between the transportation and health sectors. Further discussion of the disaggregation of total non-residential structure investment and transport is covered in Section S5.

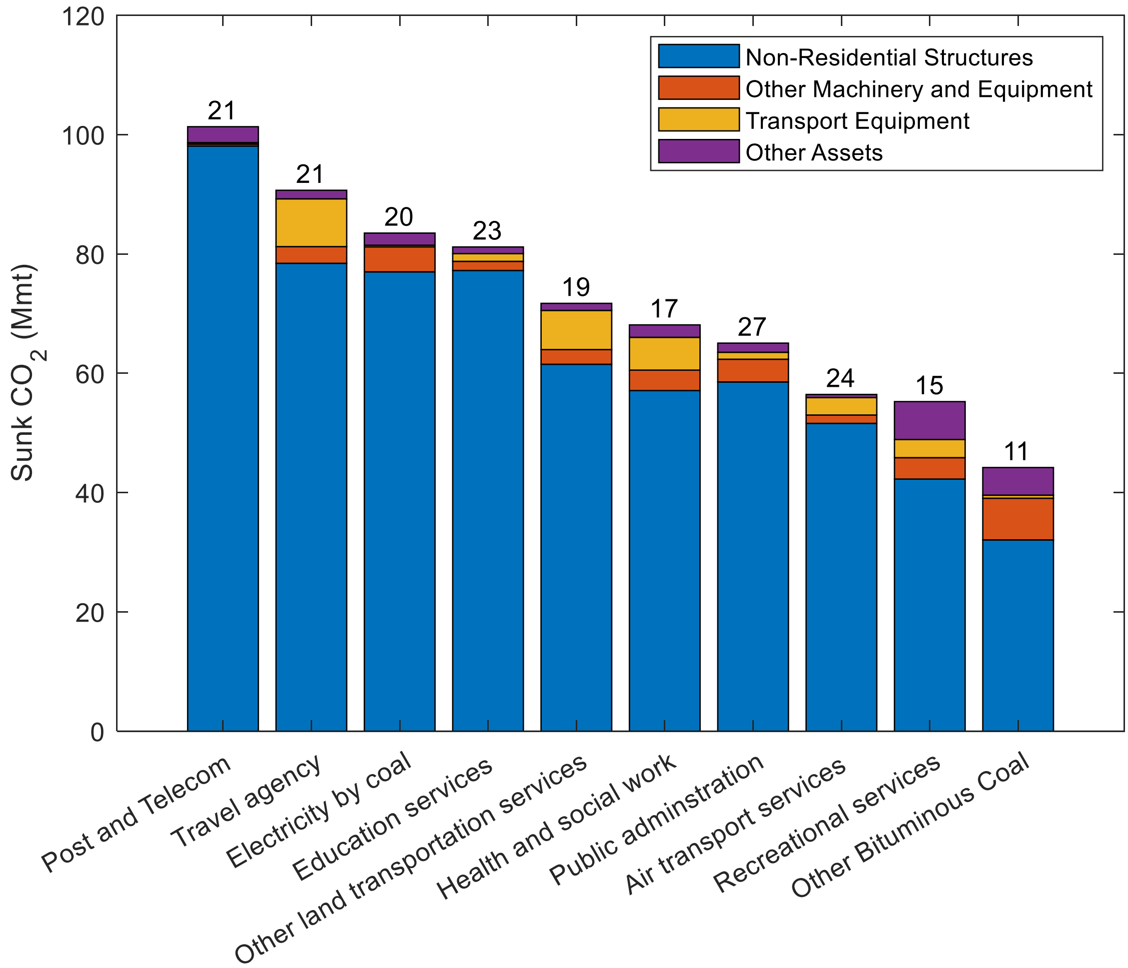

Figure S8: Provides a detailed breakdown of the highest Australian industry Sunk CO_2, disaggregated by type of asset. Average age of capital assets is shown in the labels above the bars. It excludes real estate which was formed primarily of residential investment. This exclusion is due to residential investment being 400Mmt, which means that Real estate's LEF is the approximately equivalent to the total size of the other nine next highest industries. This is consistent with Australian (Södersten and Lenzen 2020) and global (Sodersten, Wood et al. 2018) estimates of embodied emissions within capital, which both found that real estate services were the largest sector. Despite the Sunk CO_2 size, residential real estate assets are an unrealistic area for asset stranding, due to them not being used downstream commercially.

S.6.2. Capital asset type

Figure S9a shows that investments in "Non-Residential Structures" and "Residential Structures" cumulatively account for 85% of 2019 Australian Sunk CO_2. This is consistent with Wang, Hertwich et al. (2023) which found that the same asset types accounted for more than 80% of global GHG LEF.

The capital stock for these two asset types had been primarily produced through before 2010 period, with only a slight increase for capital produced after 2010, as shown in Figure S9b. This is partly due to the long average lifespan of twenty years for both Australian capital types in 2019, causing the retirement of capital to occur at a lower rate. Investments in software and transport primarily occurred between 2010-209, which is likely due to their comparatively short asset lifespan. This is consistent with Wang, Hertwich et al. (2023), which found that between 2010 to 2019, machinery and transport equipment supporting manufacturing and services accounted for 29% of global GHG LEF.

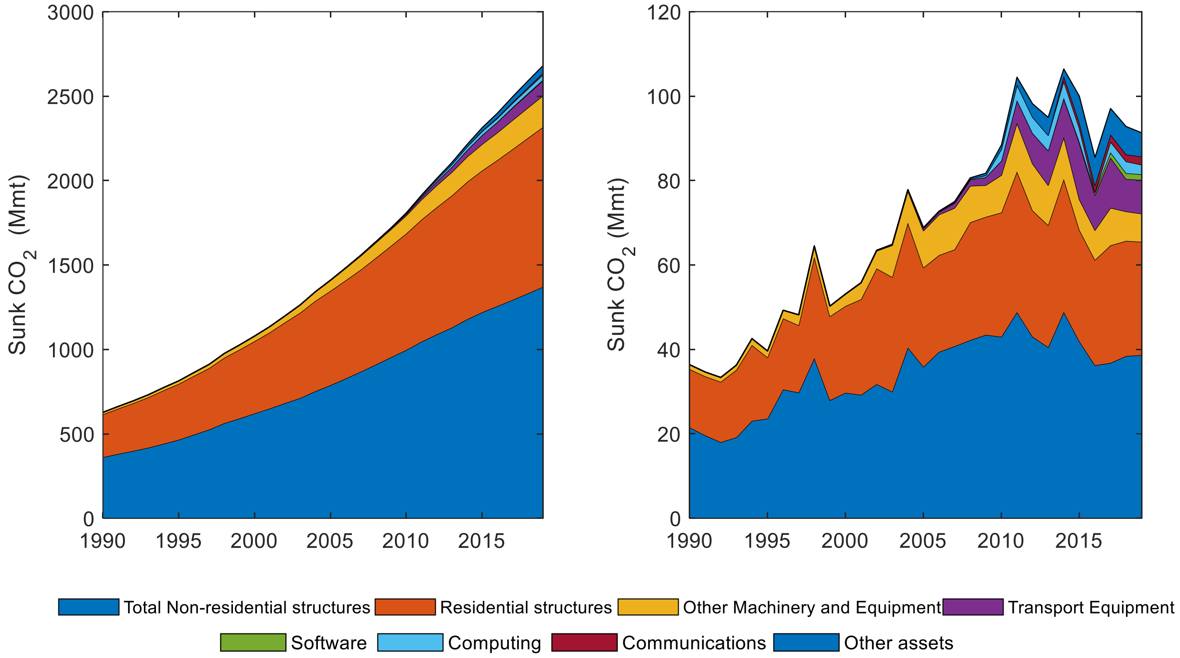

Figure S9: Shows overall Australian Sunk CO_2 by asset type, separated by year of capital investment. The left-hand side (a) shows the cumulative Sunk CO_2 for each capital asset from 1990 to 2019, whereas the right-hand side (b) shows 2019 Sunk CO_2 by year of capital investment.

Figure S10 shows the retirement function of capital from 2019 in greater depth. It shows the percentage of assets that are retired into the future, separated by type of asset. It shows that residential structures have the lowest retirement rate, with over 80% of the embodied emissions 2019 capital stock yet to be attributed by 2050. This is followed by total non-residential structures, with a 50% of the embodied emissions from 2019 capital stock yet to be attributed by 2050. The long lifespan for these two industries relates to the high lifespan of structures. Other machinery and equipment have a less pronounced lifespan, with only 10% of the embodied emissions within 2019 capital stock yet to be attributed by 2050. This would likely relate to the composition of the subcategory including 'construction machinery', 'mining and 'oilfield machinery' and 'service industry machinery', which have a lower comparative lifespan than structures. The remaining capital asset types have similar lifespans, with only 10% of the embodied emissions within the 2019 capital stock yet to be attributed by 2030. Transport equipment, such as cars, boats or aircraft have a lower lifespan then other types of machinery. In turn, the 'other assets' category primarily consists of software, computing equipment, and communications equipment, which also have a comparatively low lifespan.

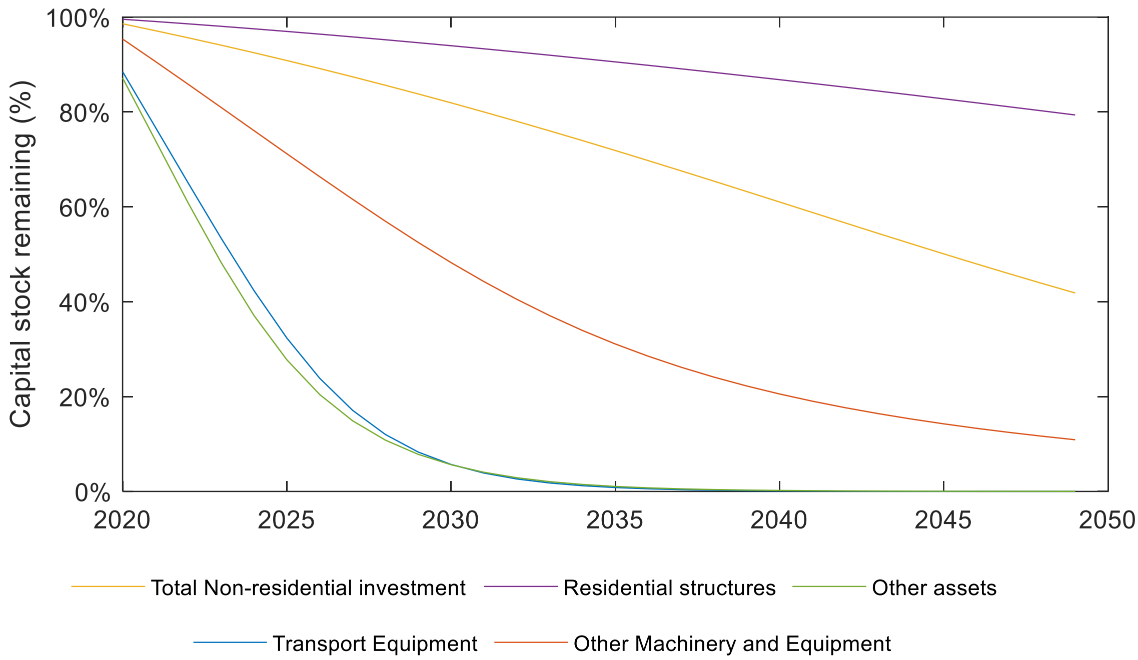

Figure S10: Shows Australian capital stock by percentage of remaining 2019 capital stock in each future year. Estimated using the retirement function discussed at length in Wang, Hertwich et al. (2023).

S6.3. Age cohort

Figure S11 shows the total embodied emissions in capital stock from the period it was initially produced. It shows that most embodied emissions from 2019 capital stock was produced in 2000 onwards. Further, it shows approximately half of the emissions from this capital stock are unattributed by 2050, and with 80% of the remaining capital emissions being initially produced from 2000 onwards. This increase in relative share is due to the higher lifespan of capital more recently produced. This trend is consistent with the convergence of capital accounting, dynamic MFA and IOA toward age-cohort–specific technological and economic attributes of capital assets (Pauliuk, Wood et al. 2015).

Therefore, capital produced from 2019 onwards will likely continue to have a longer lifespan than previous cohorts. This suggests that the proportion of the CII capital investment that at risk of stranded will continue to increase, alongside the Sunk CO_2. This is due to investments into assets with low lifespans being less likely to be stranded, as the stranding time period is more likely to occur when the asset has already exceeded its productive capacity. In turn, the policy decisions around the future investment into CII need to also incorporate the increasing lifespan of the capital structures to minimise the Sunk CO_2.

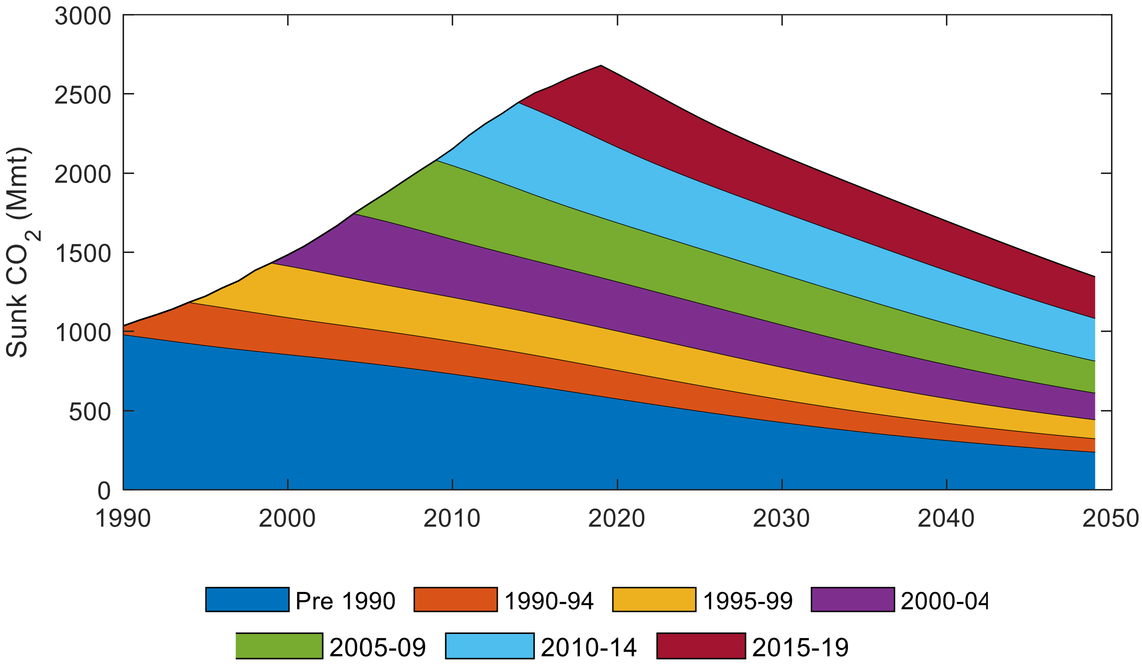

Figure S11: Shows accumulative Australian capital stock separated by age cohort of asset formation. Capital formation is not estimated past 2019, and instead only the retirement of existing capital is shown. Retirement function was estimated using the methodology discussed in Wang, Hertwich et al. (2023).

S.6.4. Country of origin

Figure S12a shows that in 2019, nearly two thirds of cumulative Sunk CO_2 is produced in Australia, with China forming ten percent. This ten percent, alongside the growth in other non-domestic regions, is predominantly due to the growth in Sunk CO_2 from capital formation after the year 2000, as shown in Figure S12b. This aligning with Ye, Hertwich et al. (2021), which documents a rapid upswing in capital formation in China from 2000 onwards. It is also consistent with Australian trade patterns, which show that Asia has rapidly grew as a source for Australia's imports, while Europe and the Americas declined (DFAT 2022).

Figure S12c shows that these shares remain consistent as the capital stock is retired. The estimated Sunk CO_2 is reduced by 35%, but nevertheless 1.5gt from 2019 capital stock remains. This reinforces the importance of evaluating how the emissions from capital are allocated, as the ramifications will continue for decades. As 6.2 explores in further depth, the underlying size of this Sunk CO_2 means that small proportions of 2019 capital stock or subsequent capital formation was stranded still leads to a substantial level of embodied emissions from international trade of which responsibility and attribution is ambiguous.

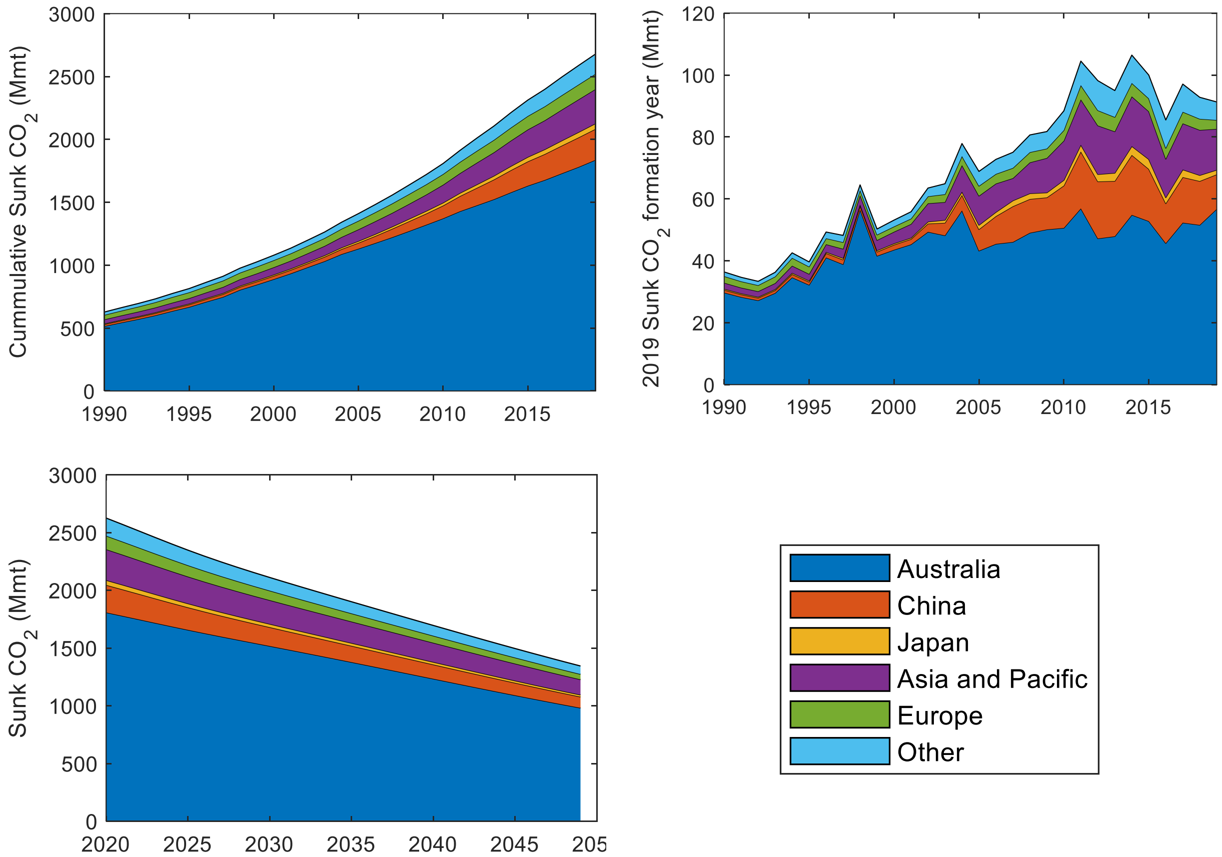

Figure S12: Shows overall Australian Sunk CO_2 by country of origin, separated by year of capital investment. Top left side (a) shows the cumulative Sunk CO_2 for each country of origin from 1990 to 2019, whereas top right side (b) shows 2019 Sunk CO_2 by year of capital investment, separated by country of origin. Bottom left (c) shows the projected capital stock after 2019. Capital formation is not estimated past 2019, and instead only the retirement of existing capital is shown. Retirement function was estimated using the methodology discussed in Wang, Hertwich et al. (2023).

S.7. CII Ghosh analysis

Instead of Equation 8 being used to determine upstream impacts, the Ghosh Model can instead be used to establish how the emissions could be attributed downstream. The Ghosh Model is different from the Leontief model in how it determines industry interlinkages (Cahen-Fourot, Campiglio et al. 2021). The Leontief inverse $\boldsymbol{L}$ relates industry gross outputs to the amount of final product (final demand) – that is, to a unit of product leaving the interindustry system at the end of the process. The alternative interpretation that the Ghosh Model suggests relates industry gross production to the primary inputs – that is, to a unit of value entering the interindustry system at the beginning of the process. Previous literature has explored the implications of a reduction of fossil inputs on stranding interlinkages (Cahen-Fourot, Campiglio et al. 2021). However, this literature has not explored the embodied emissions within the assets.

Firstly, the method for the Ghosh model will be briefly reviewed. Let $\overline{\mathbf{V}_{\varepsilon}^{\mathrm{C}}}$ equal the total inputs required from the transition sensitive industries, enabling in turn an estimation of $\overline{\mathbf{GEF}_{\varepsilon}^{\mathrm{K}}}$**,** which is the flow-on environmental effects. First, let $\mathbf{B}$ denote the direct-output coefficients matrix, estimated by: $\mathbf{B}_{\varepsilon} = \widehat{\boldsymbol{x}}^{-\mathbf{1}}\boldsymbol{T}$. This enables an alternative version of $\overline{\mathbf{LEF}_{\varepsilon}^{C}}$ to be estimated, using the same emissions intensity $\mathbf{S}_{\varepsilon}^{\mathrm{K}}$**,** $\overline{\mathbf{GEF}_{\varepsilon}^{\mathrm{K}}}$ which instead looks at the downstream attributions of the emissions embodied within CII.

$$\overline{\mathbf{LEF}_{\varepsilon}^{\mathrm{K}}} = \mathbf{S}_{\varepsilon}^{\mathrm{K}} \left(\mathbf{I} - \mathbf{B}_{\varepsilon}\right)^{-1}\overline{\mathbf{V}_{\varepsilon}^{\mathrm{C}}} \qquad \text{(Eq. S4)}$$

To show the applications of $\overline{\mathbf{LEF}_{\varepsilon}^{C}}$, a production layer decomposition will be used, consistent with Cahen-Fourot, Campiglio et al. (2021). This utilises that $(\mathbf{I} - \mathbf{B}_{\varepsilon})^{-1}$ can be approximated by the power series $(\mathbf{I} + \mathbf{B}_{\varepsilon} + {\mathbf{B}_{\varepsilon}}^{2} + {\mathbf{B}_{\varepsilon}}^{3} \ldots + {\mathbf{B}_{\varepsilon}}^{n})$**,** as $n \rightarrow \infty$**.** Successive elements of the series indicate the successive steps through which the Sunk CO_2 continues to be attributed through the productive system via sectoral interdependencies. Cahen-Fourot, Campiglio et al. (2021) refers to these layers as stranding allocation steps, which are shown in Figure S13.

Figure S13 shows that carbon-intensive electricity production and air transport have comparatively low forward linkages compared to the other sectors, particularly petroleum extraction. This is due to the sectors being significantly further downstream. The four industries are all major sources of final demand, which has no further downstream effects. Conversely, petroleum extraction and the ACII grouped within the 'other' category encompass industries that are upstream. These primary and secondary industries are mostly used in interindustry inputs, as shown in Section 5.4. Interpreting the Sunk CO_2 through the Ghosh method shows how the Sunk CO_2 are successively attributed to consecutive sectors, flowing through the economy. The relevance for policy makers is for to these estimations to be used in combination with direct economic implications to better understand how responsibility for mitigation should be attributed.

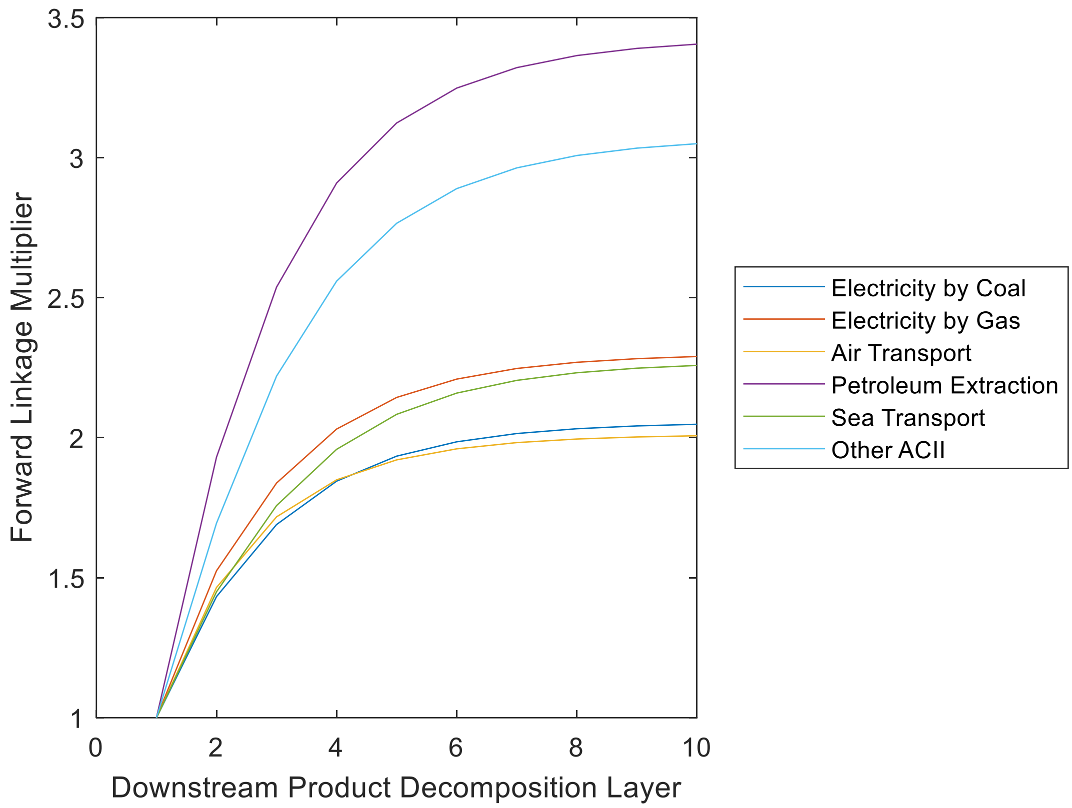

Figure S13: Shows the product decomposition layers of the transition sensitive industries, with forward linkages for each CII for each successive layer. Forward linkages identify those key industries who distribute their outputs as inputs to other industries further down the value-added chain of national production. This was estimated using Equation S4.

S.8. CII Sunk CO_2 downstream impacts

Figure S14 shows that Sunk CO_2 resulting from stranded capital assets would mostly be attributed to household consumption, which is consistent with global estimates that indicates 72% of global GHG emissions is attributable to them (Dubois, Sovacool et al. 2019). This high proportion of household consumption attribution is particularly pronounced for the carbon-intensive electricity producers and the transportation sectors. This is consistent with the Ghosh analysis and CBA final demand analysis, both of which demonstrate that these sectors are prominently downstream. Conversely, petroleum extraction also is primarily consumed by households, but this is not due to demand for the direct product, as shown by the destination analysis in 5.4. Instead, this is due to high consumer demand for downstream products such as ‘motor gasoline’.

All CII have a significant portion of potentially stranded capital assets being attributed towards GFCF. As Section 6.4 shows, this is due to most CII have a significant proportion of their outputs being attributed towards construction, which in turn produces the structures discussed in S5. With capital endogenization, this would ultimately be further attributed to the asset-consuming industries further downstream. This is particularly significant for Iron ore, which has 30% of its attribution towards GFCF. Therefore, the asset stranded, and subsequent reallocation of emissions would have cascading effects on further capital consumption. The natural gas industry also has 40% percent of its downstream attributions towards ‘change in inventory’. This is likely due to the sectoral overlaps with natural gas liquids.

The sector with the highest final attribution towards government is chemical n.e.c. This is primarily due to the two primary downstream industries being chemicals n.e.c and healthcare, as shown in Section 5.4. Chemical n.e.c. includes the pharmaceutical industry, which is a major component into healthcare. Section SI D shows that the healthcare sector's primary attribution sector is the government, due to the Australian government's high expenditure on healthcare, representing approximately 17% of total expenditure, according to the 2022-23 Australian Budget Outlook.

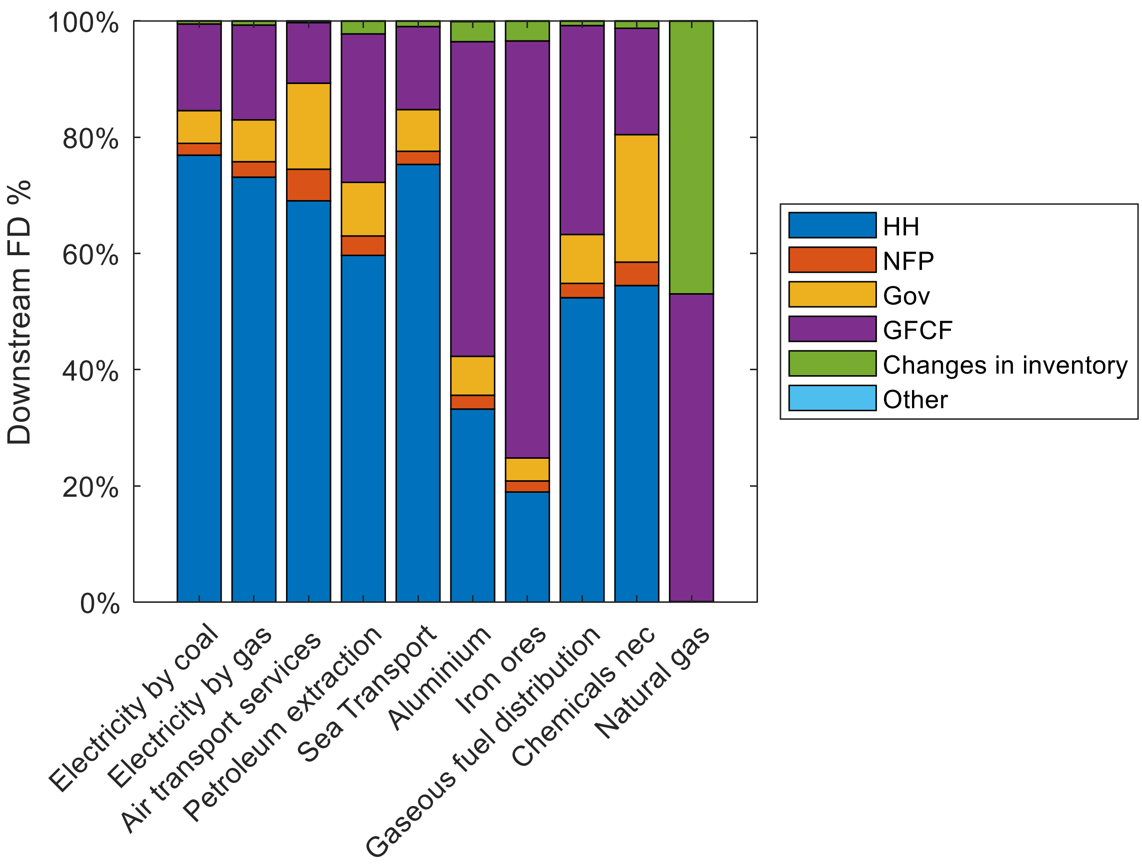

Figure S14: Shows how the Sunk CO_2 for Australian CII would be attributed downstream, disaggregated by type of final demand.

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Appendix

A. Products

Paddy rice

Wheat

Cereal grains nec

Vegetables, fruit, nuts

Oil seeds

Sugar cane, sugar beet

Plant-based fibers

Crops nec

Cattle

Pigs

Poultry

Meat animals nec

Animal products nec

Raw milk

Wool, silk-worm cocoons

Manure (conventional treatment)

Manure (biogas treatment)

Products of forestry, logging and related services

Fish and other fishing products; services incidental of fishing

Anthracite

Coking Coal

Other Bituminous Coal

Sub-Bituminous Coal

Patent Fuel

Lignite/Brown Coal

BKB/Peat Briquettes

Peat

Crude petroleum and services related to crude oil extraction, excluding surveying

Natural gas and services related to natural gas extraction, excluding surveying

Natural Gas Liquids

Other Hydrocarbons

Uranium and thorium ores

Iron ores

Copper ores and concentrates

Nickel ores and concentrates

Aluminium ores and concentrates

Precious metal ores and concentrates

Lead, zinc and tin ores and concentrates

Other non-ferrous metal ores and concentrates

Stone

Sand and clay

Chemical and fertilizer minerals, salt and other

Mining and quarrying products n.e.c.

Products of meat cattle

Products of meat pigs

Products of meat poultry

Meat products nec

Products of Vegetable oils and fats

Dairy products

Processed rice

Sugar

Food products nec

Beverages

Fish products

Tobacco products

Textiles

Wearing apparel; furs

Leather and leather products

Wood and products of wood and cork (except furniture); articles of straw and plaiting materials

Wood material for treatment, Re-processing of secondary wood material into new wood material

Pulp

Secondary paper for treatment, Re-processing of secondary paper into new pulp

Paper and paper products

Printed matter and recorded media

Coke Oven Coke

Gas Coke

Coal Tar

Motor Gasoline

Aviation Gasoline

Gasoline Type Jet Fuel

Kerosene Type Jet Fuel

Kerosene

Gas/Diesel Oil

Heavy Fuel Oil

Refinery Gas

Liquefied Petroleum Gases (LPG)

Refinery Feedstocks

Ethane

Naphtha

White Spirit & SBP

Lubricants

Bitumen

Paraffin Waxes

Petroleum Coke

Non-specified Petroleum Products

Nuclear fuel

Plastics, basic

Secondary plastic for treatment, Re-processing of secondary plastic into new plastic

N-fertiliser

P- and other fertiliser

Chemicals nec

Charcoal

Additives/Blending Components

Biogasoline

Biodiesels

Other Liquid Biofuels

Rubber and plastic products

Glass and glass products

Secondary glass for treatment, Re-processing of secondary glass into new glass

Ceramic goods

Bricks, tiles and construction products, in baked clay

Cement, lime and plaster

Ash for treatment, Re-processing of ash into clinker

Other non-metallic mineral products

Basic iron and steel and of ferro-alloys and first products thereof

Secondary steel for treatment, Re-processing of secondary steel into new steel

Precious metals

Secondary precious metals for treatment, Re-processing of secondary precious metals into new precious metals

Aluminium and aluminium products

Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium

Lead, zinc and tin and products thereof

Secondary lead for treatment, Re-processing of secondary lead into new lead

Copper products

Secondary copper for treatment, Re-processing of secondary copper into new copper

Other non-ferrous metal products

Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals

Foundry work services

Fabricated metal products, except machinery and equipment

Machinery and equipment n.e.c.

Office machinery and computers

Electrical machinery and apparatus n.e.c.

Radio, television and communication equipment and apparatus

Medical, precision and optical instruments, watches and clocks

Motor vehicles, trailers and semi-trailers

Other transport equipment

Furniture; other manufactured goods n.e.c.

Secondary raw materials

Bottles for treatment, Recycling of bottles by direct reuse

Electricity by coal

Electricity by gas

Electricity by nuclear

Electricity by hydro

Electricity by wind

Electricity by petroleum and other oil derivatives

Electricity by biomass and waste

Electricity by solar photovoltaic

Electricity by solar thermal

Electricity by tide, wave, ocean

Electricity by Geothermal

Electricity nec

Transmission services of electricity

Distribution and trade services of electricity

Coke oven gas

Blast Furnace Gas

Oxygen Steel Furnace Gas

Gas Works Gas

Biogas

Distribution services of gaseous fuels through mains

Steam and hot water supply services

Collected and purified water, distribution services of water

Construction work

Secondary construction material for treatment, Re-processing of secondary construction material into aggregates

Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries

Retail trade services of motor fuel

Wholesale trade and commission trade services, except of motor vehicles and motorcycles

Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods

Hotel and restaurant services

Railway transportation services

Other land transportation services

Transportation services via pipelines

Sea and coastal water transportation services

Inland water transportation services

Air transport services

Supporting and auxiliary transport services; travel agency services

Post and telecommunication services

Financial intermediation services, except insurance and pension funding services

Insurance and pension funding services, except compulsory social security services

Services auxiliary to financial intermediation

Real estate services

Renting services of machinery and equipment without operator and of personal and household goods

Computer and related services

Research and development services

Other business services

Public administration and defence services; compulsory social security services

Education services

Health and social work services

Food waste for treatment: incineration

Paper waste for treatment: incineration

Plastic waste for treatment: incineration

Intert/metal waste for treatment: incineration

Textiles waste for treatment: incineration

Wood waste for treatment: incineration

Oil/hazardous waste for treatment: incineration

Food waste for treatment: biogasification and land application

Paper waste for treatment: biogasification and land application

Sewage sludge for treatment: biogasification and land application

Food waste for treatment: composting and land application

Paper and wood waste for treatment: composting and land application

Food waste for treatment: waste water treatment

Other waste for treatment: waste water treatment

Food waste for treatment: landfill

Paper for treatment: landfill

Plastic waste for treatment: landfill

Inert/metal/hazardous waste for treatment: landfill

Textiles waste for treatment: landfill

Wood waste for treatment: landfill

Membership organisation services n.e.c.

Recreational, cultural and sporting services

Other services

Private households with employed persons

Extra-territorial organizations and bodies

B. Countries

Austria
Belgium
Bulgaria
Cyprus
Czech Republic
Germany
Denmark
Estonia
Spain
Finland
France
Greece
Croatia
Hungary
Ireland
Italy
Lithuania
Luxembourg
Latvia
Malta
Netherlands
Poland
Portugal
Romania
Sweden
Slovenia
Slovakia
United Kingdom
United States

Japan
China
Canada
South Korea
Brazil
India
Mexico
Russia
Australia
Switzerland
Turkey
Taiwan
Norway
Indonesia
South Africa
RoW Asia and Pacific
RoW America
RoW Europe
RoW Africa
RoW Middle East