A GTAP-based model for analysing Resource Efficiency and the Circular Economy: Outline of the UCL ENGAGE-materials model

Matthew Winning, Raimund Bleischwitz, Alvaro Calzadilla and Victor Nechifor-Vostinaru

1. Introduction

There has been significant interest from policymakers recently towards creating a circular economy and resource efficient future (European Commission, 2015) and there appears to be potential to improve the efficiency of how resources are utilised and it is suggested that potential economic and environmental benefits may arise (UNEP, 2016a). Also, reusing and recycling of materials is fundamental to achieve the Sustainable Development Goals. Understanding the role that specific resource flows and prices can have on the wider economy and trade patterns is essential when deciding how to implement policies to achieve such goals.

The resource nexus concept considers broad categories of energy, land, water, biomass and food, and materials. Resource efficiency can pertain to the improved use (achieving the same output with less inputs) of any of these resources in the production of goods and services in a sustainable manner. The circular economy concept often goes hand in hand with resource efficiency, and refers to an economy in which waste and pollution are reduced to zero or negligible levels through increased recycling and better management. It requires movement away from the make, use, dispose incumbent cycle of production towards a method of production which gets maximum value from resources for as long as possible. Therefore a circular economy should improve resource productivity and therefore increase economic competitiveness as well as reducing waste and pollution and tackling scarcity price volatility issues.

Resources use interlinkages and interdependencies are complex issues which require understanding across countries, sectors and resources with scarcity, volatility and politics being important issues (Chatham House, 2014). Material and mineral use in economic activity is an area which is often studied within a partial equilibrium framework or from the perspective of a specific economic sector or industry e.g. iron and steel. However, there is often knock-on and indirect effects of changes in materials through prices and policies as well as technology change, and the full extent of these effects can only be captured through multi-sectoral modelling representing the whole economic system. Therefore the development of economy-wide or integrated modelling frameworks with a focus on materials is important. Recently materials and minerals have been seen through the concepts of resource efficiency and the circular economy (CE and BioIS, 2015; Meyer et al, 2015; Ellen MacArthur Foundation and McKinsey Center for Business and Environment, 2015).

In this paper we outline the motivation for, and give details of, the development of a global computable general equilibrium (CGE) model which will enable global analysis of changes in materials throughout the supply chain and allow us to properly consider the resource efficiency and circular economy impacts of different policy, political and technology futures. In particular we describe the development of modelling capability which can focus in greater detail on the areas of resource extraction, industrial processes and material recycling, all of which are essential aspects of understanding how to improve the circular economy. The global CGE model – ENGAGE-materials - will allow us to consider the economic and sectoral effects of policies and shocks which affect materials and resources, and a global analysis is a requirement in order to identify any leakage of resource use as well as understanding trade patterns and economic interdependencies. In the first instance we focus on the development of the inclusion of iron and steel into the model. However, future work will extend the process to include other metals and potentially non-metallic minerals in a similar manner.

This paper details the novel contribution of our model development and efforts which will allow for a greater understanding of the role that global material flows from specific industries, such as steel, can have on major economies and international trade as well as their role in achieving resource efficiency and circular goals. Section 2 provides a literature and model review of macro-economic analyses focussed on resource efficiency and the circular economy as well as more specific iron and steel modelling. Section 3 details all the elements of the ENGAGE-materials model development including data sources, regional and sectoral coverage, steel sector disaggregation and main characteristics of the model production structure. Section 4 then provides results from an example circular economy policy scenario. Section 5 concludes with an overall summary and perspectives on future applications and research questions.

2. Literature and model review

In general macro-economic models do not capture the flow of physical materials through economies, and thus a prerequisite of modelling resource efficiency and the circular economy is omitted. As a result, analysis of global commodity markets is fairly difficult. Even those that do often lack the sectoral detail to consider the life-cycle of specific materials. One may compare this area in relation to materials with that of energy and climate change modelling, where more sophisticated economic tools have been developed over the last years to allow for the consideration on energy and environmental policies. Here we discuss various modelling approaches have been developed with regards to both resource efficiency and circular economy studies, and more specifically iron and steel. Here we discuss much of the recent research related to the macroeconomic impacts of issues related to resource efficiency and the circular economy.

2.1 Resource efficiency and circular economy modelling

Bohringer and Rutherford (2015) developed a multi-regional CGE model for the Ellen MacArthur foundation (Ellen MacArthur Foundation and McKinsey Center for Business and Environment, 2015) with a specific focus on the circular economy. They state the importance of a global model to ensure important spill-over and feedback effects are fully captured. Bohringer and Rutherford (2015) define three key principles relating to the circular economy concept as being: (i) preservation of natural capital, (ii) maintenance of the highest utility of products, components and materials, and (iii) the avoidance of leakage. They state that resource allocation can be altered either by policy interference, such as resource taxes or technology mandates, or can be driven by technological change. The analysis specifically concentrates on efficiency improvements and technology shift in private transport, housing, and food sectors.

In the model the world is split into 5 regions (EU, North America, Other OECD, China and ROW) which each have 16 economic sectors.[1] The model focuses in detail on transport, energy, households and food, and therefore it it omits some areas in more detail (e.g. electricity generation technologies) and specifically there is almost no representation of other minerals and materials except with the construction sector and motor vehicles. Private transportation is split out from other household consumption into a separate final demand. The analysis shows the benefits that circular economy can have on the economy and jobs as results show GDP could be 11% higher in 2030 and 20% higher in 2050 than the baseline development scenario. However, the authors are keen to stress that the technology improvement assumptions are exogenous and as such the model does not account for the costs required to achieve the technological change. While CO2 emissions are linked to fossil fuel use using fuel specific coefficients, there does not appear to be any physical materials modelled beyond gas, coal and oil.

The EXIOMOD model was developed by TNO in the Netherlands using the EXIOBASE dataset (developed under the EXIOPOL and CREEA projects) to create a global environmentally-orientated computable general equilibrium model which could consider resource efficiency questions for

[1] These sectors are coal, crude oil, natural gas, refined oil, electricity, air transport, water transport, other transport, manufacturing and services, motor vehicles, trade, construction, dwellings and other business services, beverages and tobacco, food, and all other goods.

Europe and beyond. EXIOBASE2 is currently calibrated to 2007 although a new dataset is to be released soon with 2011 as a base year. While similar to standard global CGE models through representative agent's utility maximisation or cost minimisation, there is the additional inclusion of adaptive expectations and semi-endogenous technological change. EXIOMOD is large with 43 regions and 129 economic sectors, although the model is often run with higher aggregations, and 5 households differentiated by income quantiles. The incorporation of environmental quality into the households utility function is an extremely novel and beneficial addition. In terms of resource efficiency and the circular economy, the EXIOMOD's detail is significant with 28 types of emissions, waste, land use, and material resources. There are eleven extraction sectors in the model, given in Table 1, which cover a number of important resources which can then be traced throughout the production process to end use and final demand.

Table 1: EXIOBASE mining sectors

NACE Rev 1.1 Code	EXIOBASE sector
i11.a	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
i11.b	Extraction of natural gas and services related to natural gas extraction, excluding surveying
i11.c	Extraction, liquefaction, and regasification of other petroleum and gaseous materials
i12	Mining of uranium and thorium ores (12)
i13.1	Mining of iron ores
i13.20.11	Mining of copper ores and concentrates
i13.20.12	Mining of nickel ores and concentrates
i13.20.13	Mining of aluminium ores and concentrates
i13.20.14	Mining of precious metal ores and concentrates
i13.20.15	Mining of lead, zinc and tin ores and concentrates
i13.20.16	Mining of other non-ferrous metal ores and concentrates
i14.1	Quarrying of stone
i14.2	Quarrying of sand and clay
i14.3	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.

Source: EXIOBASE (2012)

The incorporation of both physical and monetary data in the model is essential for the environmentally extended analysis. Physical materials data on both domestic extraction used and unused in Kt/M EUR are included for primary crops, crop residues, fodder crops, timber, grazing, animals, metal ores, non-metallic minerals, and fossil fuels. The model also contains two specific material recycling sectors - recycling of metal waste and scrap, and recycling of non-metal waste and scrap. Waste is also considered more in-depth with separate sectors for: Collection and treatment of sewage, Collection of waste, Incineration of waste, Landfill of waste, and Sanitation, remediation and similar activities.

The European Commission (2014) report by TNO on modelling resource efficiency related to buildings and infrastructure out to 2030 uses EXIOMOD to consider resource efficiency improvements in both the construction and use phases of the whole life-cycle of buildings and infrastructure in Europe. In the construction phase the analysis considers new buildings, refurbishment, and demolition including recycling, while the use phase considers both maintenance and exploitation. However, the paper does mention there are limitations of the approach including the lack of a building stock, the lack of a saturation effect on the consumption of households and general issues with how emissions and production technologies are modelled at an aggregate level within a CGE framework. To overcome some of these issues the model is coupled with both Life-Cycle Analysis and Material-Flow Analysis. The LCA analysis is undertaken and then aggregated to the level of EXIOMOD and technical coefficients in EXIOMOD are updated for different scenarios. After EXIOMOD is run the outputs are translated into physical units and then applied to an MFA analysis. Five policy scenarios are compared to a baseline run with no resource efficiency improvements and the modelling shows it is possible to reduce resource consumption and still increase GDP in the EU27, with individual countries seeing a GDP increase between 0.04% and 0.23% in 2030 under ‘best practice’. They state that many of the resource improvements are win-wins where the societal benefits outweigh the costs.

The Global Interindustry Forecasting System (GINFORS) model at GWS is a dynamic input-output simulation model which has been used in a number of studies to examine questions of resource efficiency as well as climate change. Unlike traditional CGE model GINFORS does not rely on long-run equilibrium of markets and is often classified as an econometric model. However, similar to other models mentioned, it is based on an environmentally extended multi-regional supply and use database of national accounts created by the World Input Output Database (WIOD) project. GINFORS level of detail is 39 world regions, 35 industries and 59 products and also includes emissions from 28 energy carriers and a resource module which considers water and land. The 12 material types are 5 different biomass, 4 fossil fuels as well as minerals construction, minerals industrial and minerals metal.[2] The materials aspect is calculated by defining a specific materials intensity in local currency and constant prices attributed to a certain economic driver which is historically observed. When forecasting the driver is multiplied by its trend intensity gives the physical extraction amounts. GINFORS has been applied for a number of resource efficiency applications including Meyer et al (2015) which linked GINFORS with a biophysical model LPJml. The results from three transition scenarios implemented showed that resource efficiency policies to reduce raw material consumption (RMC) to 5 tonnes per capita, combined with other environmental

[2] For an overview see Meyer et al (2013)

targets, could be achieved with increased growth and employment. Estimates for RMC for abiotic resources in 2013 were at around 14 tonnes per capita this a reduction of around 60% is required by the year 2050

E3ME model developed by Cambridge Econometrics is a macro-econometric model of the European member state economies as well as 11 other large economies and the rest of the world. The model is based upon an input-output framework which has separate modules for energy, emissions, and material demands. Again, E3ME is not based upon general equilibrium assumptions but instead the model consists of econometrically estimated behavioural relationships which can consider short and medium term economic impacts of various actors' decisions while able to capture the disequilibrium effects of issues such as long-term unemployment in the labour market. The model is based upon an EE-MRIO with 69 economic sectors for European countries and 43 sectors for the rest of the world. The calibration period is 1970-2012 with 2005 as the base year IO table. The model then solves from 1995 to 2050. The energy module is of a top-down nature but with a bottom-up electricity representation. There are 12 different emissions modelled of which CO2 is the most detailed as it is related to energy carriers. The materials model is described in Pollitt (2007, 2008) and specifically considers RMC, DMI and TMR. Materials are not matched at a sectoral level but instead material intensity is able to change due to the dynamic nature of the model. The material demand equations are measured much in the same way as the economic equations with DMI per unit of output being a function of economic activity, material prices and measures of technology. Long-run price elasticities for material intensity are estimated at the EU level while short-run ones are at sectoral/country level. Feeding back into the economic module the assumption is that material consumption is all consumed as intermediate inputs (not bought by households) and a small number of sectors produce the materials. The feedback is through changes in the IO coefficients.

The E3ME model was used in the CE and BioIS (2014) analysis for the European Commission which shows that resource productivity increases can be achieved in the EU with positive macroeconomic impacts. Resource productivity is defined as GDP per unit of raw material consumption (RMC). Demand for construction materials constitutes around 50% of all RMC. The model assumes a baseline out to 2030 for how RMC will evolve which takes the EU's climate and energy targets into account. In total RMC is expected to increase 0.7% per year until 2030 and GDP per unit of RMC increases by 0.9% per year until 2030. Metal and mineral RMC were expected to increase by 39% and 26% respectively in the baseline in 2030. They then introduce scenarios which increase resource productivity by 1 to 3% per year. Three types of policies to improve resource productivity are market-based instruments, private funded recycling, or public funded capital investment for efficiency improvements. The E3ME results suggest that resource productivity improvements of between 2 to 2.5% can be achieved with net positive effects on GDP. However, with higher levels of ambition there are net costs productivity improvements. They suggest around 2 million extra jobs can be created with a 2% per year improvement in resource productivity.

GTEM-C developed by CSIRO in Australia is used to in the GIAM framework which operates in conjunction with several other models including. There are 18 global regions included in the model and the sectoral aggregation of GIAM.GTEM-C is a total of 19 sectors including coal, gas, oil, petroleum, electricity, other mining, iron and steel, chemicals, non-metallic minerals and many others. There is no greater detail of resources in the model beyond the energy sector compared to standard GTAP modelling approaches. While the model has a unique approach in terms of energy, as well as endogenous technological progress, it does not include water, land or minerals in any greater detail. However, in a number of studies the model is linked with a variety of other models to analyse a number of national environmental factors within a consistent modelling framework. Other models include the ESM energy sector model, the LUTO model of agriculture and rural land use, the MMRF.H20 model which is a highly sectorally disaggregated CGE model split by water basin regions, and MEFISTO which is a model of materials and energy flows and integrated stocks. These models are fed from one to another in a highly complex manner. The Australian National Outlook (2015) uses this combination of interlinked models, including GTEM, to analyse Australia's options in achieving sustainable prosperity out until 2050. Hatfield-Dodds *et al* (2015) use the same overall modelling framework as the national outlook in an article which shows that Australia can continue with economic growth while reducing environmental pressures.

Schandl *et al* (2016) use the framework to consider the ability to decouple environmental pressure and economic growth. They combine the GIAM model, MIFESTO and the Eora MRIO model to undertake the analysis for energy use, materials use and carbon emissions for 13 major regions each with 21 sectors, 4 primary factors and 6 GHGs using the GTAP8 database. The material use data comes from the CSIRO Global Material Flow Database (Schandl et al, 2016). They implement three scenarios: a reference case, a high efficiency case and a medium case. The resource efficiency path is driven by a carbon price and also assumes that best available technologies are implemented in key resource sectors but with conservative assumptions about new technologies. The GIAM model is used as an input to create material, energy and carbon footprints using Eora by calculating a time series of year by year input-output tables to 2050 for each scenario. A satellite account for domestic materails extraction was established for different material intensity assumptions across regions. The results show that global materails extraction would grow by more than double from around 80 to 183 billion tonnes of extraction in a business as usual scenario whereas with a high carbon price this could be kept at 95 billion tonnes or 130 in the medium price case. At a regional level resource efficiency and the saturation effect can influence the material footprint of the larger nations which tends not to increase much beyond 2030. In general the GIAM framework would benefit from a greater disaggregation of materials used in the economic process within their economic model. It is a consideration which Schandl et al (2016) identify as an area for improvement along with linking material, carbon and energy to capital investment and also including a better representation of resource supply limits for a variety of possible reasons i.e. physical or social.

TABLE 2 : CE/RE model comparison

Model	Type	Database	Year(s)	No. Sectors	Resources	No. Regions	Main applications
EXIOMOD	CGE/IO	EXIOBASE	2004	127	11 extraction, 2 recycling, 3 waste, 48 raw materials	44	All environental applications
Ellen MacArthur	CGE	GTAP	2007	16	coal, crude oil, natural gas, refined oil, electricity	5	Transport, Housing, energy and food
GINFORS	Macro-econometric	WIOD	1995-2011	35 industries, 59 products	5 biomass, 4 fossil fuels, minerals construction, minerals industrial, minerals metal	38	Resource efficiency
E3ME	Macro-econometric	EE-MRIO from Eurostat and AMECO plus others	1970-2012	69 for EU; 43 for RoW	Materials module calculates RMC, DMI and TMR	All EU individually plus 11 others a RoW	Energy and resource efficiency. Hard linked materials module
GIAM	CGE	GTAP and Eora	2007	21	Soft-linked to separate MEFISTO material flow model	13	Energy and resource efficiency

We do not consider in detail much of the input-output modelling that has been undertaken in this area using Materials Flow Analysis (MFA). However, it is worth stating that there are a considerable number of studies using global and national input-output models and many of these are important in understanding how material flows can be used to calculate indicators of resource use. For instance, Wiedmann et al (2013) on the material footprint developed countries shows the claim of such countries to have decoupled resource use from economic growth does not necessarily hold. In fact many regions have increased resource use when viewed from a consumption basis as much is imported. Giljum et al (2015) uses an IO model from the GTAP database to calculate material footprint between the years 1997-2007 by examining worldwide materials extraction and materials embodied in consumption and trade and they state the importance of using RMC as an indicator due to leakage effects. The UNEP (2016b) report uses these Material Footprint approaches in its latest report to the International Resource Panel.

2.2 Iron and steel modelling

Schumacher and Sands (2007) developed a detailed dynamic-recursive CGE model of the German economy from 1995 to 2050 which contains a more detailed technological representation of the iron and steel sector as an example of how to improve realism in energy-intensive industries. In particular they use a logit nesting approach to distinguish between the technologies of basic oxygen furnace (BOF), electric arc furnace (EAF) and a direction reduction process which are all utilised to create crude steel production with a low elasticity between these. Both the BOF and EAF processes, which are considered primary and secondary production routes respectively, have both standard and advanced possibilities too, which are substitutable at a higher elasticity. They then introduce a set of CO2 price scenarios for this new technology based approach and then compare the results against an aggregate standard CES scenario. A conclusion is drawn that there is significant importance of technology-specific effects in terms of climate policies relating to differences between changes in process and in fuel input structures that would not be captured by a more general top-down CGE approach.

Yamazaki (2011) uses a single-region CGE model for Japan in 2005 which disaggregates the steel sector into a variety of technologies to allow for analysis of the effects of CO2 trading on scrap steel production in Japan. There are 38 production sectors, 53 products, 3 final demand sectors and international trade. The model distinguishes between Blast Furnace-Basic Oxygen Furnace (BF-BOF) and Electric Arc Furnace (EAF), a number of different steel products e.g. cast and forged steel products, and also between three types of scrap steel: home scrap from the steel manufacturing industry, industrial scrap from drilled or cut metal from manufacturing, and obsolete scrap which is collected. Japanese national economic and physical data on iron and steel is fairly detailed and so allows for such an analysis including which sectors to allocate tonnes of scrap steel supply and demand in the base year. The introduction of emissions trading leads to increased demand for EAF products but to an overall decline in the amountof scrap steel used due to the shrinking economy when undertaking emissions trading.

The single example of a global iron and steel economic model appears to be a conference paper from Zhou et al (2014) which created a Multi-Regional Input-Output (MRIO) model based upon GTAP 7. Here the iron and steel production sector (GTAP i_s) is disaggregated into three types: pig iron, blast furnace, and electric arc furnace. They also provide more detail the iron ore extraction sector by separating it from the 'other mining' sector (GTAP omn). And finally recycling is considered by disaggregating the Manufactures nec. Sector (GTAP omf) into three types: Steel scraps recycling, other recycling, and other manufacturing. The authors state that four countries (Japan, China, Australia, USA) they used national accounts to disaggregate intermediate inputs, final demands and outputs. They use the data World Steel Statistical Yearbook and Global Trade Atlas Database for other regions. Results are provided for primary resource us and carbon emissions, resource efficiency and carbon intensity, and for international trade. However, the MRIO model does not consider prices thereefore it is unable to incorporate a number of policies.

Moving beyond purely macroeconomic models there are industrial ecology studies such as that of Pauliuk et al (2013a, b) on the 'scrap steel age' and in-use stocks of iron that can be extremely useful in helping to frame the sorts of scenarios which we intend on implementing using the ENGAGE model focused on differentiating between primary and secondary steel and possible saturation effects.

3. Methodology

Here we outline the development of the UCL Environmental Global Applied General Equilibrium (ENGAGE) model further with respect to the inclusion of materials and minerals which will allow a detailed analysis of resource efficiency and circular economy scenarios. While many other modelling approaches have focussed on energy, land and water, we believe that materials are an under-developed area in the macroeconomic modelling framework at both national and global levels. We believe there are three main areas which could be developed further within the typical global CGE framework: extraction, industry and recycling.

The majority of Social Accounting Matrixes (SAMs) tend to have highly aggregated materials extraction sectors i.e. there are only 4 GTAP extraction sectors, and therefore the accompanying CGE models lack the relavant detail for such policy analysis. Also, the production sectors of many important metals and minerals are combined together into a single industry, and often recycling is not explicitly represented meaning any analysis on policies related to these sectors is almost impossible. Therefore we propose as a first step a greater disaggregation in the model of these three key areas (extraction, industry and recycling) in order to allow a sufficient level of detail to properly capture changes and innovation.

In section 3.1 we present a brief overview of our newly developed standard global CGE model ENGAGE. We then give details of the planned model disaggregation with regards to the extraction in section 3.2 and primary/secondary production sectors as well as discussing the data required to implement such and discuss how production structures of specific materials sectors are developed to more realistically represent firm technology choices in section 3.3.

3.1 General model structure and data

The UCL ENGAGE-materials model is a multi-sectoral, multi-region computable general equilibrium model which is based upon standard general equilibrium assumptions such a market clearance, zero profits, and utility maximisation/cost minimisation of representative agents. All industries are modelled through a representative firm, which maximizes its profits in perfectly a competitive market. The production functions of each economic sector to create a level of sectoral output are specified using a series of nested constant elasticity of substitution (CES) functions. Domestic and foreign inputs are not perfect substitutes and therefore are modelled using the ''Armington assumption'', which accounts for product heterogeneity between different world regions. A representative consumer in each region receives household income, defined as the service value of national primary factors. The national income is allocated between aggregate household consumption, public consumption and savings.

The UCL ENGAGE-materials model is based upon the GTAP9 database with a base year of 2007. The model is written in GAMS and based upon the GTAP9inGAMS model in MPSGE developed by Rutherford (2016) and the model runs in a recursive-dynamic setting from 2007-2030. Production in each sector is derived using a series of nested CES function where at the top level intermediate inputs combine with a capital-labour-energy (KLE) aggregate using a Leontief assumption.

The ENGAGE model can be used to implement counterfactual analysis of changes in relative prices of intermediate inputs and/or factors of production e.g. through changes in tax rates, and captures the direct and indirect effects of such price changes on other sectors and other regions. The GTAP database, and CGE models in general, are useful tools for short to medium term economic analysis where the underlying structure of the economy does not deviate far from the base year e.g. an election cycle or a couple of decades. However, undertaking medium and long-term economic analysis will require updates of parameters throughout the model's time horizon and as such models generally find it necessary to incorporate technological change and new products.

The main data source utilised to undertake our model improvements with respect to materials is the EXIOBASE2 dataset (Tucker et al, 2014) for 2007.[3] The EXIOBASE input-output database is used to

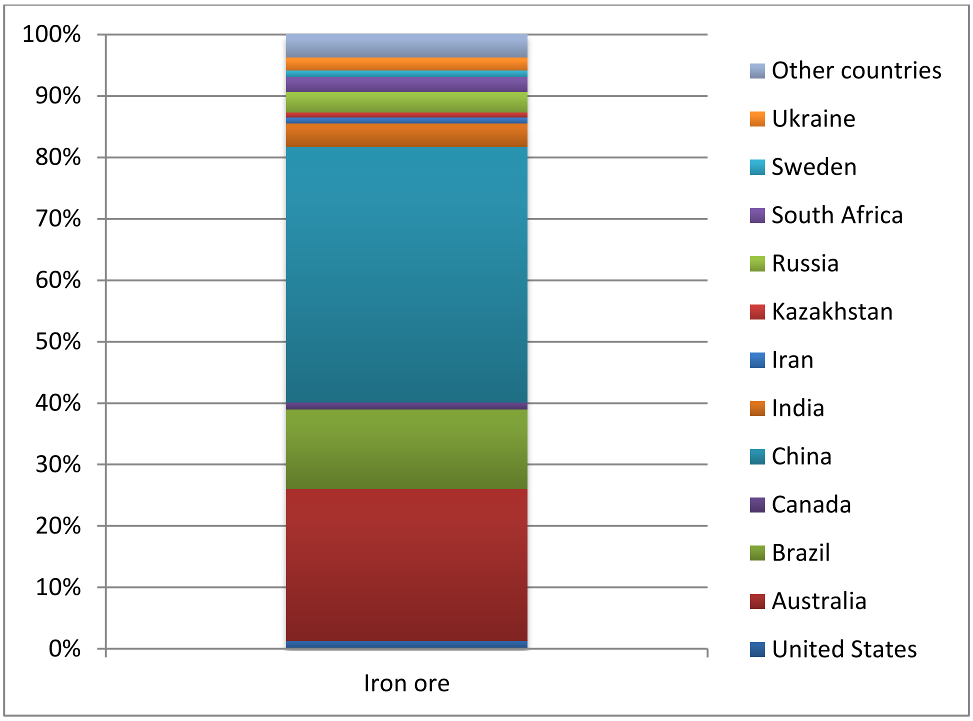
[3] www.exiobase.eu

split out the shares of the various extraction, industrial and recycling sectors which will require greater disaggregation within the GTAP model. In general we use EXIOBASE as the underlying inputs throughout the following analysis due to the level of sectoral detail (see Table 1). We therefore mapped the 129 EXIOBASE sectors to the 57 GTAP sectors. However, there are instances where the underlying EXIOBASE data does not appear to match . We give further detail on specific EXIOBASE and other data inputs below.

In addition to EXIOBASE we will combine the necessary physical and price commodity data from a number of key materials and resource datasets such as UN COMTRADE, FAOSTAT, United States Geological Survey (USGS) Minerals Yearbook, World Steel Association as well as a variety of national accounts datasets.

In the first instance we plan to make developments to the extraction, industrial and recycling sectors of the ENGAGE model in relation to iron and steel. The material we focus on specifically in this analysis is iron ore given it's relative importance as intermediate input in the global supply chain and relevance to the EU and China. The largest producer of iron ore is China which accounts for just over 40% of global production. China is then followed by Australia (25%) and Brazil (12.5%) and then by India (4%) and Russia (3%) respectively and these countries combined produces over 80% of iron ore (USGS, 2015). However, it is our intention to extend the analysis to other materails where data sources are more readily available.

FIGURE 1: Iron ore production by region (2007)



Source: USGS

Therefore key regions which produce, consume, export and import these commodities are included as separate regions in ENGAGE to the best of our abilities given data constrains. The proposed regional disaggregation of the ENGAGE model reflects these considerations and includes the following 17 regions below.

TABLE 3: List of model regions

Regions (17)	
China	CHN
Japan	JPN
India	IND
USA	USA
Russia	RUS
South Korea	KOR
Brazil	BRA
Mexico	MEX
Canada	CAN
Australia	ANZ
Indonesia	IDN
Germany	DEU
Western Europe	WEU
Eastern Europe	EEU
Asia and Oceania	ASO
Latin America	LAM
Africa	AFR

3.2 Extraction

Firstly, we disaggregate the single GTAP 'other mining' sector (No. 18 – OMN) in order to capture the flows of different key materials throughout the world economy. While mining and extraction of coal, gas and oil are all individual sectors in GTAP and therefore such models have been utilised for energy and climate analysis using GTAP models. However, this is not the case for the extraction of other materials and minerals which are important for resource efficiency and circular economy – perhaps explaining the lack of modelling of such issues using CGE models. The 'Other mining' sector includes mining of metal ores, uranium, gems, other mining and quarrying. Therefore current analysis in GTAP CGE models is unable to distinguish between different metals and minerals and only able to apply counterfactual analyses to the extraction of all metals together while clearly there are distinct production processes and government policies for specific materials. Clearly if we wish to trace the flow of such materials throughout the economy, and through global trade, then further disaggregation is required. This disaggregation will then allow analysis of price changes, policy interventions and technology innovations of these specific material extraction sectors for each individual region within our CGE framework.

Therefore we disaggregate the material extraction sector 'Other mining' (OMN - GTAP sector) in each region in order to capture the flows of different key materials throughout the world economy. This is necessary for industry-focussed analysis on resource efficiency and a circular economy using a life-cycle approach of materials. Using shares and cost structures from the EXIOBASE dataset (Tucker et al, 2014) as well as a variety of national accounts databases, and employing the SPLITCOM programme for GTAP, we split the single 'Other mining' sector into three sperate sectors: (1) mining of iron ore, (2) non-ferrous mining and (3) other mining. [4]Totals were kept consistent with the aggregate OMN sector.

In terms of physical data, there appears to be consistency between EXIOBASE and estimates taken from USGS, which is most likely due to the data coming from the same initial source. However, the monetary data from EXIOBASE appears somewhat inconsistent for some large mining producers compared to independent estimates taken from other sourecs such as national accounts. Therefore we were required to undertake an independent re-estimation of the OMN split initially undertaken using EXIOBASE.

Where complete national accounts data on specific mining sectors is available then we utliise these to split these regions and detail the relevant size of the iron mining sector, the iron ore mining sector's cost structure, and to what other economic sectors iron ore is sold. For Australia, Brazil and

[4] More disaggregated splits are currently faced with data restrictions though may become possible over time.

China we used their national 2007 input output data which sperately . We were only able to obtain data for India from 2004 and so we use these shares to split Indian iron ore mining in our database. The USA national data has iron ore mining aggregated together with other metals such as gold and silver. Canadian data sources provided us with the overall size of the iron ore mining in relation to other mining but a specific input output table was unavailable and therefore the cost structure and output structure were assumed.

For Russia we were unable to obtain national accounting data and therefore we calculate the Russian shares from a bottom-up method using average world price derived from other regions.All other model regions are considered small iron ore producers and as such we use the original EXIOBASE data source for these splits of the OMN sector.

Table 4 – EXIOBASE vs ENGAGE shares of iron ore mining

Source	**Country**	**Iron ore**		**Other mining**		**GTAP OMN TVOM $m 2007**
		EXIOBASE	ENGAGE	EXIOBASE	ENGAGE	
National Accounts 2007	Australia	4%	39%	96%	61%	53,609
National Accounts 2005	Brazil	45%	66%	55%	34%	32,390
National Accounts 2007	Canada	2%	9%	99%	91%	19,065
National Accounts 2007	China	7%	36%	93%	64%	121,248
National Accounts 2005	India	26%	25%	74%	75%	16,365
USGS and price estimates	Russia	2%	44%	98%	56%	15,576
National Accounts 2007	USA	0.3%	5%	99.7%	95%	48,041

The EXIOBASE database is clearly an important addition to the production of global environmentally extended input-output datasets which can be utilised for research and policy analysis. However, we urge caution when utilising the database to undertake and suggest diving deeper into the numbers of specific resources and sectors. For instance the overall sectoral size of iron ore mining in China shown in Table 4.

3.3 Primary and secondary production

The recycling and reuse of scrap metals is an integral element of any circular economy package. However, most macro-economic models have little or no detail with regards to recycling of specific materials and there are no single secondary production or recycling sectors within the GTAP database. Therefore, we further develop the ability of GTAP to consider such secondary production and recycling within the economy. Our aim is to model the supply of secondary materials which could come from sources such as reuse, recycling and recovery from anthropogenic stocks. The production of secondary materials may well have an input structure different to that of the primary sector due to process innovations and efficiency improvements. Again we employ a methodology here for the production of scrap steel. Other secondary productions ectors may be possible to implement in

In order to further develop the capability to consider recycling and scrap sectors several steps are taken. In our model development the industrial production sector 'Iron and Steel' (I_M - GTAP sector 25) is further disaggregated to distinguish between primary and secondary production technologies. To the best of our knowledge this has not yet been undertaken before in global CGE modelling and is necessary for the scope of our study and further follow-up research on resource efficiency and a circular economy policies. For secondary production we distinguish between the treatment of secondary steel (which utilises recycling services) and reprocessing of secondary steel into new steel which produces the final output. While primary steel production is based on the Oxygen Blast Furnace technology, secondary steel production uses the Electric Arc Furnace technology. Both technologies are explicitly modelled in our framework. The World Steel Association data was used for the calibration of primary and secondary production levels.

Recycling is currently included within GTAP sector 42 - 'Other Manufacturing' and therefore all recycling in the economy is aggregated together. However, it is unclear from the underlying national input –output tables whether scrap steel is included in the as the share of the 'other manufacturing' as an input to the primary 'Iron and steel' sector varies considerably. It may then be possible to replicate this for other secondary materials sectors like copper where the primary/secondary maetrail input is known for each country.

A list of the final proposed 30 sectors in our CGE model on resource efficiency and the circular economy are given in Table 5 and further details of the split procedure are provided below.

Table 5 – ENAGE-materials sectors

Mining related sectors (15)		**Energy related (13)**	
Iron mining	i_m	Coal	coa
Non-ferrous mining	n_m	Crude oil	oil
Other minerals mining	o_m	Gas	gas
Iron and steel primary production	isp	Petroleum & Coke	p_c
Re-processing of secondary steel into new steel	rss	Transmission and distribution	tnd
Secondary steel for treatment	sst	Nuclear power	nup
Non-ferrous primary	nfp	Coal-fired power	cfp
Non-metallic minerals	nmm	Gas-fired power	gfp
Metal products	mtp	Wind power	wip
Motor vehicles and transport equipment	mvt	Hydro power	hyp
Electronic equipment	ele	Solar power	sop
Machinery and other equipment	mae	Oil-fired power	ofp
Recycling	rcy	Other power	otp
Construction	cns		
Transport	tra		
Other sectors (6)			
Agriculture and food	agr		
Wood products	wop		
Paper products	ppp		
Chemical products	crp		
Other manufacture	oma		
Services	ser		

Initially, using EXIOBASE, we split the aggregate iron and steel production sector (I_S in GTAP) into two – Iron and Steel Primary (ISP) and Iron and Steel Secondary (ISS) as this matches the level of sectoral detail provided in the EXIOBASE IO tables. However, in the EXIOBASE documentation on physical Supply and Use tables (CREEA, 2012) it states that there are two processes within a waste treatment service entitled 'Secondary steel for treatment, Re-processing of secondary steel into new steel'. There are two clearly distinct processes captured here under one heading: one which treates the steel (and importantly uses recycling sector as an intermediate input) and another which converts the treated steel into an end product which is the output of the manufacturing sector.

Therefore to capture these distinct processes we disaggregate the newly created secondary steel production sector ISS further, using some technological and economic assumptions.

Table 6: ISP cost structure for AUS, CHN and USA

	AUS	*CHN*	*USA*
i_m	1.4%	10.5%	0.5%
n_m	6.6%	9.4%	2.7%
o_m	13.4%	2.0%	0.9%
p_c	4.1%	7.2%	3.6%
nmm	0.5%	2.5%	2.3%
isp	14.6%	24.5%	9.6%
rss	3.3%	3.1%	6.0%
ome	0.6%	4.3%	6.0%
ely	2.2%	2.5%	3.1%
trd	3.6%	2.2%	8.3%
otp	7.7%	1.4%	4.0%
obs	4.7%	0.7%	4.4%
Labor	15%	8%	27%
Capital	11%	9%	8%
Total	88.5%	88.3%	86.7%

Table 7 – RSS cost structure for AUS, CHN and USA

	AUS	*CHN*	*USA*
n_m	6.1%	9.8%	0.9%
o_m	12.2%	1.6%	0.2%
p_c	3.2%	1.9%	0.9%
nmm	0.4%	2.7%	0.6%
isp	13.4%	27.9%	16.6%
sst	3.0%	3.5%	9.0%
ome	0.3%	4.7%	10.2%
ely	9.3%	14.2%	3.9%
trd	6.1%	3.0%	8.3%
otp	10.3%	1.9%	5.7%
obs	4.5%	0.8%	4.5%
Labor	15%	10%	27%
Capital	5%	7%	0%
Total	88.9%	88.7%	87.4%

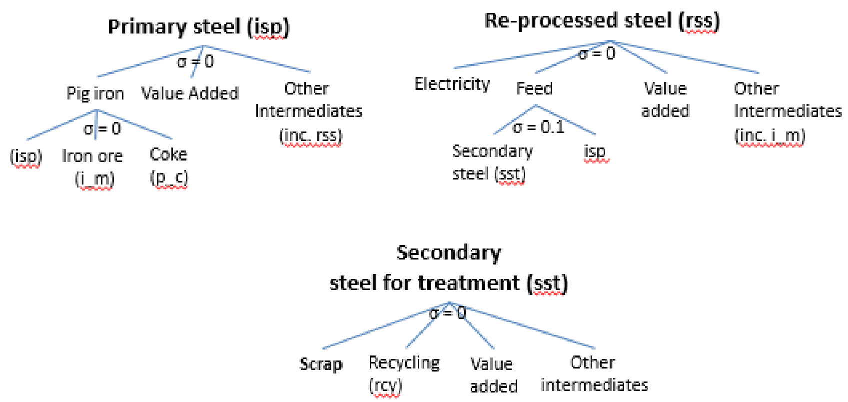
Table 8 – SST cost structure for AUS, CHN and USA

	AUS	*CHN*	*USA*
Rcy	1.6%	24%	0.01%
Capital	98.6%	76.0%	99.98%
Total	100%	100%	100%

We create two new sectors: (1) Secondary steel for treatment (SST) – that's inputs are only recycling and the value of scrap as inputs, with small amounts of value added and other intermediate inputs to balance the sector, and (2) reprocessing of secondary steel (RSS) – which is where we model the production of secondary steel through the EAF method to create new steel which is purchased by other sectors. All own-demand in the aggregate *ISS* sector is considered the output of the *SST* activity All recycling costs of *ISS* are attributed to *SST*. We also make a simplifying assumption that the value of scrap is assumed to be the value of capital in the *SST* sector i.e. the capital investment in steel treatment reflect the shadow value of steel scrap. The total output of the SST sector is then sold on directly to the RSS sector. The RSS cost structure is defined by EXIOBASE and will be similar to that of the ISS aggregate.

We also altered the production structure of these newly constructed primary and secondary production structures in order to capture a more realistic production process in these sectors. Below we show the nested production structures for these three sectors which capture greater technological detail than previouly where only one single iron and steel production sector existsed.

Figure 2 – Production structure of ISP, RSS and SST sectors



In the primary steel *(ISP*) sector the pig iron composite is created from a Leontief input of *ISP* (i.e. purchases fromitself), iron ore, and coke. The Re-processed steel (*RSS*) sector has electricity as a distinct input at the top level of the production function in order to replicate the production process used in Electric Arc Furnace. The Secondary steel for treatment (*SST*) sector combines with *ISP* in the second nest of the *RSS* sector with a very low eleasctičty of substitution between them. The *SST* sector only has one nesting level which has scrap, recycling, value added and other intermediates. Substitution of steel coming from *isp* and *rss* can be made industry specific. The changes made in our methodlogy now allow for opportunities to model policies and secnarios for scrap availability e.g. boost in overall or sector-specific recycling rates/quotas, through EXIOBASE supply and use data.

4. Results

In Section 3 we outlined a variety of ways in which we developed the modelling of iron and steel within the context of resource efficiency and the circular economy. The disaggregation of these new resource sectors on extraction, industry and recycling, combined with the regional aggregation to include resource producers and consumers, allows for a model to consider the global direct and indirect effects of policies, shocks and futures which fall on resource-intensive sectors.

For the purposes of this paper we have implemented an initial baseline and a scenario using the newly constructed database and model structure. Here we provide a sample of the initial results. The model baseline is given in Figures 3a and 3b. Figure 3a shows the increase in global steel production and how this is split between primary and secondary production. In the baseline align the regional GDP in ENGAGE to the SSP2 estimates by changing total factor productivity in each region. As a result resource extraction is linked to the economic growth. Overall steel production in ENGAGE increases by about 23% over the time period to 2030. This is somewhat short of the 30% from the World Steel Association (2015) global steel outlook.

Figure 3a: Global steel production to 2030

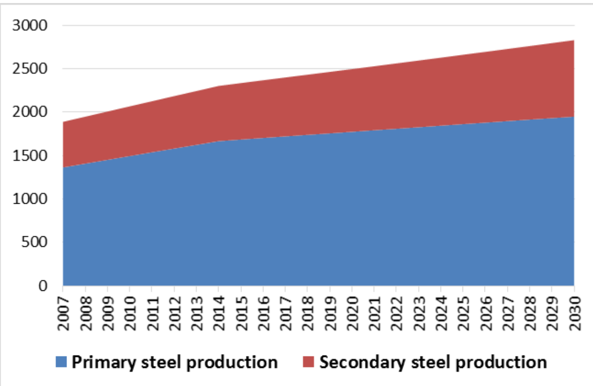
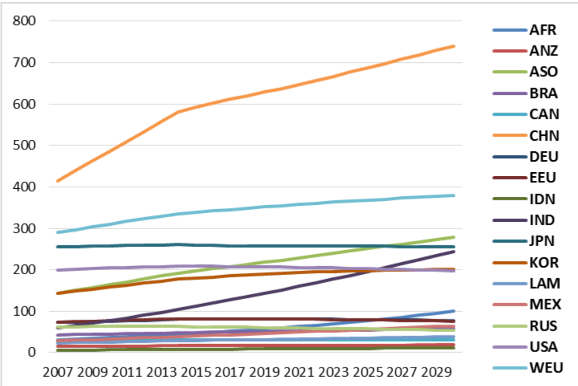


Figure 3b: Regional steel production to 2030



In Figure 3b our regional iron and steel production baseline increases also appear to roughly match the WSA (2015) estimations with India and Asia & Oceania increasing their production at a faster than most. However, originally our model had Chinese production accelerating an extremely fast pace. We therefore amended the baseline to incorporate a saturation effect for steel (Bleischwitz and Nechifor, 2017) – an analysis of which does not yet seem to be part of e.g. UNEPs International Resource Panel trends analysis (UNEP 2017; Hatfield-Dodds et al. 2017: 408). We exogenously introduced a reduction in Chinese steel efficiency in order to attain a growth pattern which reached a similar level as the World Steel Associtaion estimate for 2030. We also seek to incorporate further findings on the saturation effect, i.e. countries becoming less material-intensive as they move through stages of development, along with a general decoupling of resource use and GDP in our modelling attempts.

Figure 4 – Production share in Baseline

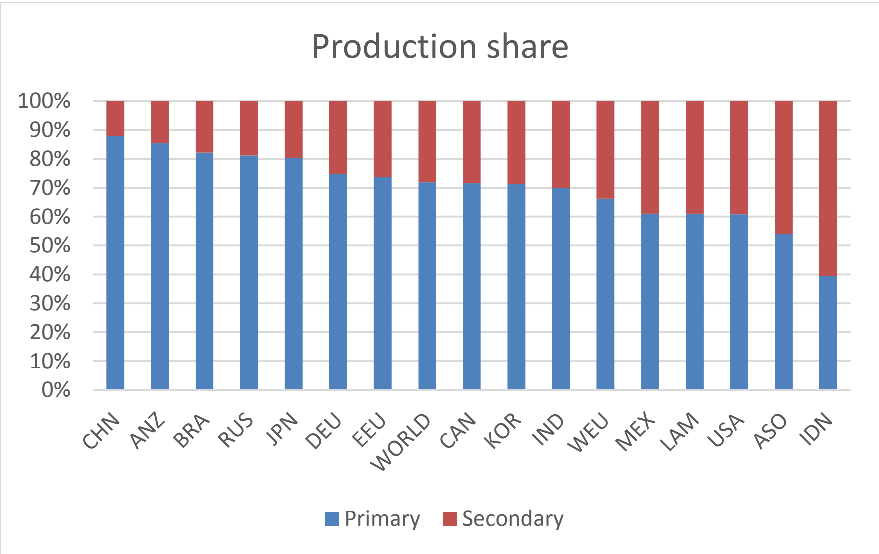


Figure 4 shows the initial regional shares in the baseline of primary vs. secondary production in 2014, as this is the last year we have data to compare with. Almost 90% of Chinese production comes from primary steel production showing that there is considerable potential to implement and gain improvements from circular economy policies aimed at increasing scrap rates. Mexico, Latin America and the USA all produce around 40% of their steel through secondary production and the two regions with the highest secondary production are Indonesia and Asia and Oceania which produce around 45% and 60% of their steel from secondary production, respectively.

For the purposes of this paper we also have implemented a policy scenario which increases of the output of the *SST* sector from 2018 to 2030 for each region. This can be interpreted as a doubling of the scrap availability in all model regions over this time period. Indeed such policies will be refined throughout in future specific analysis.

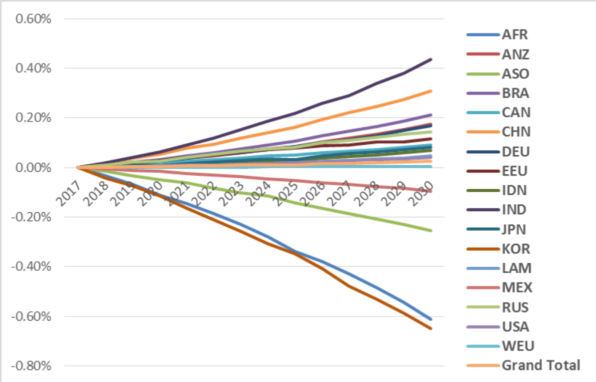
The results in Table 9 show that doubling of scrap availability leads to secondary steel production increasing by around 7% in 2030 compared to the baseline. Global primary steel production reduces somewhat as there is a shift towards secondary production, however, there is an overall increase in total production of just under 2%. It appears that the rigidities in the production processes modelled here are casuing the fact that substantial increases in scrap availability may only lead to relatively small improvements in overall economic terms; this is up for further analysis over the coming months through sensitivity analysis of both the elasticity parameters and model structure.

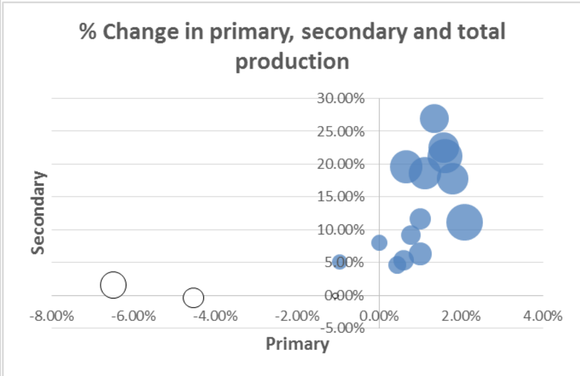
Table 9 – Global iron and steel production by type 2017-2030 against BAU

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Scrap	0.00%	4.98%	10.30%	15.99%	22.08%	28.59%	35.56%	43.02%	50.98%	59.49%	68.60%	78.35%	88.79%	100.00%
Secondary production	0.00%	0.35%	0.73%	1.11%	1.56%	2.03%	2.52%	3.05%	3.60%	4.25%	4.85%	5.52%	6.27%	7.08%
Primary production	0.00%	-0.01%	-0.01%	-0.02%	-0.04%	-0.04%	-0.06%	-0.07%	-0.08%	-0.09%	-0.11%	-0.12%	-0.13%	-0.15%
Total production	0.00%	0.09%	0.20%	0.31%	0.43%	0.56%	0.71%	0.86%	1.03%	1.22%	1.40%	1.61%	1.85%	2.10%

Global GDP by region is given below in Figure 5a and shows the majority of regions benefit from the exogenous increase to scrap availability. Those regions which are most negatively affected are South Korea and Africa which see reduction in GDP of 0.7% and 0.6% respectively in 2030 against the baseline. There is also a small reduction of GDP in Asia and Oceania region as well as Mexico. It appears that these four regions (AFR, ASO, MEX, KOR) lose out from a reduction in their primary production which outweighs the benefits of any increases in secondary production. The only region to see a fall in both primary and secondary is ASO. All other regions incur increases in both primary and secondary steel production.

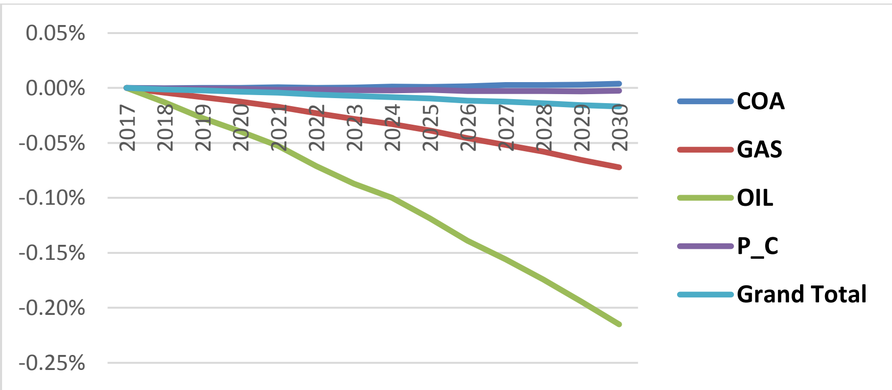
Figure 5a Regional GDP % change **Figure 5b Primary, Secondary and total production %**





The environmental effect of doubling of the scrap sector is given in Figure 6 and shows an overall reduction in the CO2 emissions from fossil producing sectors. In particular oil production decreases most given its input into primary steel production- further analysis is required here. Other decreases in coal and gas are partially offset by increased use of electricity in secondary production and associated rise in fossil fuel electricity production. The model does distinguish between electricity generating technologies but meets the increase in all electricity generating technologies equally in this scenario.

Figure 6 – Emissions of fossil fuel sectors % change



5. Conclusions

The majority of global environmental macroeconomic models have focussed on energy, water, food and land efficiency to the detriment of other materials and there has been a derth of studies concerened with resource efficiency and the cicruclar economy. The recent modelling work detailed in Section 2 has been key to recent analysis of resource efficiency and circular economy agendas, howver, there are wide ranging approaches and levels of detail when it comes to the modelling tools employed to tackle such questions. Many current models lack detail on specific resource extraction sectors and downstream resource-intensive sectors. In particular there is a lack of materials specific sectors in many of the GTAP models which consider RE and CE. Extraction, secondary production and recycling are areas that are underdeveloped in almost all the global modelling approaches except EXIOBASE which does include two recycling sectors (metals and non-metals) and several waste sectors. However, there is little published work on these areas using the EXIOMOD model. We therefore see a significant opportunity to consider materials further within macroeconomic modelling.

In Section 3 we described the development of a comprehensive database and modelling tool which can address both upstream and downstream impacts of resource efficiency and circular economy policy implications. Utilising ta global database allows for focus on the global trade aspect of changes to material flows and, in particular, how these changes affect the trade between major steel producing and consuming regions. The model development in the areas of extraction, industry and recycling combined with unique resource sector-specific production structures create a CGE modelling tool which can specifically consider questions on resource efficiency and circular economy policies at the appropriate level of detail.

Initial results show that there will be positive economic and environmental effects of policies which increase the amount of scrap availaibility globally. We estimate that doubling scrap in each region between 2017 and 2030 will lead to an increase in secondary production of 7% globally and an overall increase in global steel output of around 2%. These results will, however, differ by region depending upon initial inputs and cost structure as well as the technological production structures. Further work on sensivity analysis is required to test model responsiveness as we have begun with a very ridged production structure for secondary steel.

Future research will utilise this newly developed tool to assess scenarios, policies and narratives which are of importance to improving RE and CE understanding at a macroeconomic and sectoral level for the major producer and consumer regions. Future analysis would focus on the global steel industry and concern the impact of achieving country-specific scrap steel targets would have on EU-China trade patterns e.g. doubling scrap in China by 2050. Current work from Bleischwitz et al (2017) on the saturation effect will be used to derive demand scenarios for iron and steel in each model region.

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