Site-level resource efficiency analysis

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Abstract

To achieve agreed targets for reducing global carbon emissions, industry must become more resource-efficient. To this end, two viable strategies exist: energy efficiency and material efficiency. Despite their inherent interdependence, industry continues to treat these two strategies as isolated pursuits, providing in the process only a partial insight into the potential of resource efficiency. To resolve this disconnect, this thesis attempts to develop and apply tools that help integrate industrial energy and material efficiency analyses. Three areas of research are explored.

The first is concerned with a fundamental component of industrial performance: efficiency benchmarks. No agreed-upon metric exists to measure the efficiency with which the sector transforms both energy and materials – that is, how *resource-efficient* they are. This thesis applies exergy – a well-established method to consolidate energy and materials into a single metric – to a case study of the global steel industry in 2010. Results show that this exergy-based metric provides a suitable proxy to capture the interactions between energy and materials. By comparing energy and material efficiency options on an equal footing, this metric encourages the recovery of material by-products – an intervention excluded from traditional energy efficiency metrics.

To realise resource efficiency opportunities, individual industry firms must be able to identify them at actionable time-frames and scopes. Doing this hinges on understanding resources flows through entire systems, the most detailed knowledge of which resides in control data. No academic study was found to exploit control data to construct an integrated picture of resources that is representative of real operations. In the second research area, control data is extracted to track the resource flows and efficiency of a basic oxygen steel-making plant from TataSteel. This second case study highlights the plant's material efficiency options during operations. It does so by building close-to-real-time Sankey diagrams of resource flows (measured in units of exergy) for the entire plant and its constituent processes.

Without the support of effective policies the new exergy approach is unlikely to be widely adopted in industry. By collating evidence from interviews and policy documents, the third area explores why the European Union's industrial energy and emissions policies do not incentivise material efficiency. Results suggest several contributing factors, including: the inadequacy of monitored indicators; an imposed policy lock-in; and the lack of a designated industry lobby and high-level political buy-in. Policy interventions are then proposed to help integrate material efficiency into energy and climate agendas. The European Union's limited agency stresses the need for Member States and industry to drive the move to a low-carbon industry in the short-term.

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For my parents and abuelos

For Tom and Julia

Declaration: This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. The dissertation does not exceed the word limit set by the Degree Committee.

Publications

Material included in this thesis has been published in journals and presented at conferences.

Journal papers published

1. **Gonzalez Hernandez, A.**, Paoli, L. and Cullen, J. M. (2018) 'How resource-efficient is the global steel industry?', *Resources, Conservation and Recycling*, 133, pp. 132–145. doi: 10.1016/j.resconrec.2018.02.008. – The analysis in this journal article belongs to Chapter 3.

2. **Gonzalez Hernandez, A.**, Lupton, R., Williams, C. and Cullen, J. M. (2018) 'Control data, Sankey diagrams, and exergy: assessing the resource efficiency of industrial plants, *Applied Energy*, 218, pp- 232–245. doi.org/10.1016/j.apenergy.2018.02.181 – The analysis in this journal article belongs to Chapter 4.

3. **Gonzalez Hernandez, A.**, Cooper-Searle, S., Skelton, A.C.H. and Cullen, J. M. (2018), 'Leveraging material efficiency as an energy and climate instrument for heavy industries in the EU', Energy Policy, 120, pp. 533-549, doi.org/10.1016/j.enpol.2018.05.055 – The analysis in this journal article belongs to Chapter 5.

Conference papers published

1. **Gonzalez Hernandez, A.**, Paoli, L. and Cullen, J. M. (2017) 'Resource efficiency in steelmaking: energy and materials combined', Energy Procedia, 142, pp. 2429–2434. doi: https://doi.org/10.1016/j.egypro.2017.12.178.

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Conference presentations

1. Resource efficiency in steelmaking: energy and materials combined, In the *International Conference on Applied Energy*, Cardiff, United Kingdom, August, 2017. A. Gonzalez Hernandez, L. Paoli and J. M. Cullen.

2. From control data to real-time resource maps in a steel-making plant, In the *International Conference on Applied Energy*, Cardiff, United Kingdom, August, 2017. A. Gonzalez Hernandez, R. Lupton, C. Williams and J. M. Cullen.

3. Informing decisions in industry: how to communicate resource efficiency opportunities, In the *9th biennial conference of the International Society for Industrial Ecology (ISIE) and the 25th annual conference of the International Symposium on Sustainable Systems and Technology (ISSST)*, Chicago, US, July, 2017. A. Gonzalez Hernandez and J. M. Cullen.

4. Unlocking system-wide resource efficiency measures in steelmaking: a unified exergy measure, In the *3rd Wholesem Annual Conference: Energy Modelling Insights for Iterative Decision Making*, Cambridge, United Kingdom, July, 2016. A. Gonzalez Hernandez and J. M. Cullen.

5. Unlocking Plant-level Resource Efficiency Options: A Unified Exergy Measure, In *Life-cycle Engineering*, Berlin, Germany, May 2016. A. Gonzalez Hernandez and J. M. Cullen.

Other presentations and meetings

1. Presented my work to Miguel Arias Cañete, *Commissioner of Energy and Climate Change, European Commission.* Brussels, March 2016.

2. Presented my work to Jan Filip Stanilko, *Director of the Department of Innovation at Ministry of Entrepreneurship and Technology.* Warsaw, Poland, 11th of June 2018.

3. Presented my work to Silvia Bartolini, *Member of Cabinet and responsible for Energy Efficiency for Commissioner Miguel Arias Cañete, European Commission.* Brussels, 20th of March.

4. Presented my work to Hugo-Maria Schally, *Head of Unit for Sustainable Production, Products & Consumption, DG Environment.* Brussels, 21st of March.

5. Presented my work to Peter Handley, *Head of Unit for Resource Efficiency, Secretariat General, European Commission.* Brussels, 23rd of March.

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Glossary

List of Equations

Equation	Symbol	Unit	Description
2.1	η_{total}	-	Total exergy efficiency
2.1	B_{out}	GJ	Total exergy output
2.1	B_{in}	GJ	Total exergy input
2.1	B_{products}	GJ	Total exergy in products
2.1	$B_{\text{by-products}}$	GJ	Total exergy in by-products
2.1	B_{wastes}	GJ	Total exergy in wastes
2.2	η_{useful}	-	Useful exergy efficiency
2.2	B^{useful}	GJ	Total exergy in useful outputs
2.3	η_{transit}	-	Transit exergy efficiency
2.3	$B_{\text{in}}^{\text{transit}}$	GJ	Transit exergy in input flows
2.3	$B_{\text{out}}^{\text{transit}}$	GJ	Transit exergy in output flows
2.4	B_{ch}^{in}	GJ	Chemical exergy input carried in matter
2.4	B_{ph}^{in}	GJ	Physical exergy input carried in matter
2.4	B_{ch}^{out}	GJ	Chemical exergy output carried in matter
2.4	B_{ph}^{out}	GJ	Physical exergy output carried in matter
2.4	ΔB_w	GJ	Exergy input/output as work
2.4	ΔB_e	GJ	Exergy carried in heat flows
2.4	B_{losses}	GJ	Exergy carried in losses
2.5	$(B_{ch} + B_{ph})_{\text{wastes}}$	GJ	Sum of chemical and physical exergy carried in wasted streams
2.5	B_{irrev}	GJ	Sum of process irrversibilities
3.1	B_{ph}^{approx}	kJ/kg	approximated physical exergy of resource stream
3.1	T	K	temperature of resource stream
3.1	$T_{\circ}$	K	temperature of resource stream at atmospheric conditions
3.1	P	kPa	pressure of resource stream
3.1	$P_{\circ}$	kPa	pressure of resource stream at atmospheric conditions
3.1	C_p	kJ/kgK	specific heat capacity assuming constant pressure
3.1	R	kJ/kgK	specific gas constant
3.2	B_{ch}	kJ	chemical exergy
3.2	$\sum B_{\text{P}}^{\text{out}}$	kJ	sum of physical and chemical exergy in main product output
3.2	$\sum B_{\text{MB}}^{\text{recov}}$	kJ	sum of physical and chemical exergy in material by-products recovered

Equation	Symbol	Unit	Description
3.2	$\sum B_{\mathrm{EB}}^{\mathrm{recov}}$	kJ	sum of physical and chemical exergy in energy by-products recovered
3.2	$\sum B_{\mathrm{RM}^{\mathrm{in}}}$	kJ	chemical exergy of raw material inputs
3.2	$\sum B_{\mathrm{E}^{\mathrm{in}}}$	kJ	chemical exergy of energy inputs
3.3	$\sum b_P$	kJ/kg	sum of specific chemical and physical exergy of main product output
3.3	M_o	kg	mass of the main product output
3.3	$\sum b_{MB}$	kJ/kg	sum of specific chemical and physical exergy of material by-products
3.3	$\sum M_B$	kg	sum of the mass of material by-products
3.3	$\sum b_{EB}$	kJ/kg	sum of specific chemical and physical exergy of energy by-products
3.3	$\sum E_B$	kg	sum of the energy by-product
3.3	γ_F	kJ/kJ	energy-to-exergy conversion factors
3.3	$\sum E_{in}$	kJ	sum of the energy inputs
3.3	$\sum M_{in}$	kg	sum of the raw material inputs
3.3	$\sum b_{in}$	kJ/kg	sum of the chemical exergy of the raw material inputs
3.4	α	kg/kg	material yield
3.4	EI	kJ/kg	energy intensity (not including energy by-products)
3.5	$EI_{\text{by-prod}}$	kJ/kg	energy intensity accounting for energy by-products
3.5	$\sum E_{\text{by-prod}}^{\text{recov}}$	kJ	sum of energy by-products output
3.5	$\sum E^{\text{in}}$	kJ	sum of energy inputs
3.5	M_{prod}	kg	mass of main product output
3.6	B_{in}^{current}	kJ	current input chemical exergy
3.6	B_{in}^{target}	kJ	target input chemical exergy
3.6	φ	kJ	resource savings
3.7	B_{out}^{current}	kJ	current output chemical exergy
3.7	B_{out}^{target}	kJ	target output chemical exergy
3.7	RE^{current}	kJ	current resource efficiency
3.7	RE^{target}	kJ	target resource efficiency
4.1	k_I	-	k^{th} material/energy input
4.1	x_{input}	kg	materials/energy input
4.1	k_O	-	k^{th} material/energy output
4.1	x_{output}	kg	materials/energy output
4.2	m_{MG}	kg	mass of magnesium
4.2	m_{lime}	kg	mass of lime
4.2	m_{HM}	kg	mass of hot metal
4.2	m_{DSLAG}	kg	mass of desulphurisation slag
4.2	m_{DHM}	kg	mass of desulphurised hot metal
4.2	m_{NIT}	kg	mass of nitrogen
4.3	m_{ADDS}	kg	mass of additions
4.3	m_{TST}	kg	mass of tapped steel
4.3	m_{AR}	kg	mass of argon
4.3	m_{TSLAG}	kg	mass of tapped slag
4.3	m_{SSLAG}	kg	mass of secondary slag
4.3	m_{steam}	kg	mass of steam
4.3	m_{RST}	kg	mass of refined steel
4.4	m_{fluxes}	kg	mass of fluxes
4.4	m_{scrap}	kg	mass of scrap
4.4	m_{air}	kg	mass of air

Equation	Symbol	Unit	Description
4.4	m_{OXY}	kg	mass of oxygen
4.4	m_{CST}	kg	mass of converter steel
4.4	m_{CSLAG}	kg	mass of converter slag
4.4	m_{slurry}	kg	mass of slurry
4.4	m_{BOSG}	kg	mass of BOS gas
4.6	$b^{o}_{ch,el}$	kJ/kg	standard chemical exergy of element
4.6	$\Delta_r G^o$	kJ/kg	standard free energy of the reference reaction
4.6	$b^{o}_{ch,k}$	kJ/kg	standard chemical exergies of the effluent reference species
4.6	$b^{o}_{ch,j}$	kJ/kg	standard chemical exergies of the influent reference species
4.7	$b^{o}_{ch,comp}$	kJ/kg	standard chemical exergy of compound
4.7	$\Delta_f G^o$	kJ/kg	Gibbs standard free energy of formation of the compound
4.7	n_{el}	mol	number of moles in element
4.7	$b^{o}_{ch,el}$	kJ/kg	standard chemical exergy of element
4.8	$b_{ch,mix}$	kJ/kg	specific chemical exergy of solution/alloy
4.8	$\sum_i n_i b_{ch,i}$	kJ/kg	product of number of moles and specific chemical exergy of element
4.8	n_i	kg/kmol	molar mass of element
4.8	a_i	-	activity coefficient
4.9	B_{ph}	kJ	physical exergy of resource stream using enthalpies and entropies
4.9	H	kJ	enthalpy of resource stream at its given temperature and pressure
4.9	H_o	kJ	enthalpy of resource stream at atmospheric conditions
4.9	S	kJ/K	entropy of resource stream at its given temperature and pressure
4.9	S_o	kJ/K	entropy of resource stream at atmospheric conditions
4.9	T_o	K	atmospheric temperature
4.10	RE	%	resource efficiency
4.10	$\sum (B_{ch} + B_{ph})_{\text{useful}}$	GJ	sum of useful chemical and physical exergy in outputs
4.10	$\sum (B_{ch} + B_{ph})_{\text{total}}$	GJ	sum of chemical and physical exergy in inputs
4.11	EI_{norm}	%	normalised energy intensity
4.11	E_{inputs}	GJ	energy inputs
4.11	$E_{\text{by-prod}}$	GJ	energy by-products
4.11	M_{prod}	t	mass of product output
4.11	EI^{-1}_{max}	GJ/t	absolute maximum energy intensity
4.12	E_{gas}	GJ	total gas input
4.12	E_{elec}	GJ	electricity input
4.12	E_{steam}	GJ	steam output
4.12	E_{BOSG}	GJ	recovered BOSG output
4.12	M_{steel}	t	mass of steel output
4.13	B^{steel}_{ch+ph}	GJ	physical and chemical exergy of steel output
4.13	$B^{\text{BOSG (B)}}$	GJ	chemical exergy of BOSG recovered, in case B
4.13	$B^{\text{steam (B)}}_{ph}$	GJ	physical exergy of steam recovered, in case B
4.13	$B^{\text{slag (C)}}_{ch}$	GJ	chemical exergy of slag recovered, in case C
4.13	$B^{\text{slurry (C)}}_{ch}$	GJ	chemical exergy of slurry recovered, in case C
4.13	B^{gas}_{ch}	GJ	chemical exergy of gas input
4.13	B^{elec}_{ch}	GJ	chemical exergy of electricity input
4.13	B^{HM}_{ch+ph}	GJ	chemical and physical exerg of hot metal input
4.13	B^{fluxes}_{ch}	GJ	chemical exergy of fluxes input
4.13	B^{scrap}_{ch}	GJ	chemical exergy of scrap input

List of Abbreviations

ADDS	Additions	HI	Historical Institutionalism
AR	Argon	HM	Hot Metal
BAT	Best Available Technique	HSM	Hot Strip Mill
BF	Blast Furnace	IE	Industrial Ecology
BFG	Blast Furnace Gas	IEA	International Energy Agency
BMUB	Federal Ministry of the Environment, Nature Conservation and Nuclear Safety	IED	Industrial Emissions Directive
BMWi	Federal Ministry for Economic Affairs and Energy	IISI	International Iron and Steel Institute
BOS	Basic Oxygen Steelmaking	IOA	Input-Output Analysis
BOSG	Basic Oxygen Steelmaking Gas	IPCC	Intergovernmental Panel on Climate Change
BREF	Best Practice Reference documents	IPPC	Integrated Pollution Prevention and Control
CCS	Carbon Capture and Storage	ISO	International Standardisation Organisation
CDP	Cumulative Degree of Perfection	LCA	Life-Cycle Analysis
CDQ	Coke Dry Quenching		
CE	Circular Economy	LPM	Long Product Mill
CExC	Cumulative Exergy Consumption	LHV	Low Heating Value
CO	Coke Oven	ME	Material Efficiency
COG	Coke Oven Gas	MEFA	Material and Energy Flow Analysis
CS	Crude Steel	MFA	Material Flow Analysis
CSAP	Canadian Steel Producers Association	MG	Magnesium
CSLAG	Converter Slag	MIOT	Monetary Input-Output Tables
CST	Converter Steel	MORE	Monitoring and Optimisation of Resource Efficiency
DECC	Department for Energy and Climate Change	MRIOA	Multi-Regional Input-Output Analysis
DG	Directorate General	MSF	Multiple Stream Framework
DMI	Domestic Material Input	NIT	Nitrogen
DRI	Direct Reduction Ironmaking	NG	Natural Gas
DS	Desulphurised	OECD	Organisation for Economic Co-operation and Development
DSHM	Desulphurised Hot Metal	OXY	Oxygen
DSLAG	Desulphurisation Slag	PA	Process Analysis
EAF	Electric Arc Furnace	PFD	Process Flow Diagram
EAP	Environmental Action Programme	PIOT	Physical Input-Output Tables
EC	European Commission	RCI	Rational Choice Institutionalism
EE	Energy Efficiency	RE	Resource Efficiency

EEA	European Environment Agency	RS	Rolled Steel
EEI	Energy Efficiency Index	RST	Refined Steel
EED	Energy Efficiency Directive	SD	Sankey Diagram
EI	Energy Intensity	SET	Strategic Technology Plan
EIO	Enterprise Input-Output	SM	Secondary Metallurgy
EMAS	Eco-Management and Audit Scheme	SI	Sinter
ESTEP	European Steel Technology Platform	SSLAG	Secondary Slag
ETS	Emissions Trading Scheme	STD	Standard Deviation
EU	European Union	TSLAG	Tapping Slag
ExFA	Exergy Flow Analysis	TST	Tapped Steel
GDP	Gross Domestic Product	UNIDO	UN Industrial Development Organisation
GHG	Greenhouse Gas	UK	United Kingdom
GJ	Gigajoules	WSA	World Steel Association

List of terms used in this thesis

Term	Abbreviation	Description
Energy efficiency	EE	The efficiency with which energy carriers are transformed.
Energy-intensive industries	-	These include sectors such as the steel, aluminium, paper, cement, chemicals and petro-chemicals industries, where energy use is a significant fraction of production costs.
Heavy industries	-	Synonym of *energy-intensive* industries, described above
Material efficiency	ME	The efficiency with which non-energy carriers (i.e. raw materials) are transformed.
Plant-level	-	Covering a single facility.
Production route	-	Covering a given collection of processes across a material's supply chain, e.g. the blast-furnace-basic-oxygen-furnace route encompasses: a coke oven, a sinter plant, a blast furnace, and a basic-oxygen-furnace.
Site-level	-	Covering multiple facilities within a given geographical location.
Resource efficiency	RE	The efficiency with which both energy and non-energy carriers are transformed.

1
Introduction: efficient industrial resource use

The International Energy Agency (IEA, 2017) estimates that industry accounts for about 38% of current global final energy use, 70% of which is concentrated in only five energy-intensive sectors: iron and steel, aluminium, chemicals and petrochemicals, cement, and pulp and paper[1]. In 2014, as shown in Figure 1.1, this equated to 8.3 Gt (gigatonnes) of direct energy-related CO_2 emissions – 24% of global emissions and over 40% if indirect emissions from upstream transformations are considered (IEA, 2017). Today, past trends of increased energy use and emissions continue to undermine industry's efforts to achieve agreed climate targets. Since 2000, the sector's absolute energy use has continued to rise at an annual rate of 2.9% (IEA, 2015*b*), despite the 12% decrease in aggregated industrial energy intensity per unit of value-added.

1.1 Material efficiency: the new 'hidden fuel' in climate strategies

In its 2-degree scenario, the IEA (2017) predicts that, by 2050, global direct absolute emissions must be at least 44% less than in the 'business-as-usual' scenario (5.6 versus 10 Gt CO_2 in 2050). The agency posits that this ambitious emissions mitigation target will need to be driven primarily by energy-intensive industries, which must contribute about 80% of the sector's cumulative direct CO_2 emission reductions. If these forecasts prove accurate, and industry's current production

[1] These are sectors where energy use is a significant fraction of production costs, also denoted as 'heavy industries'.

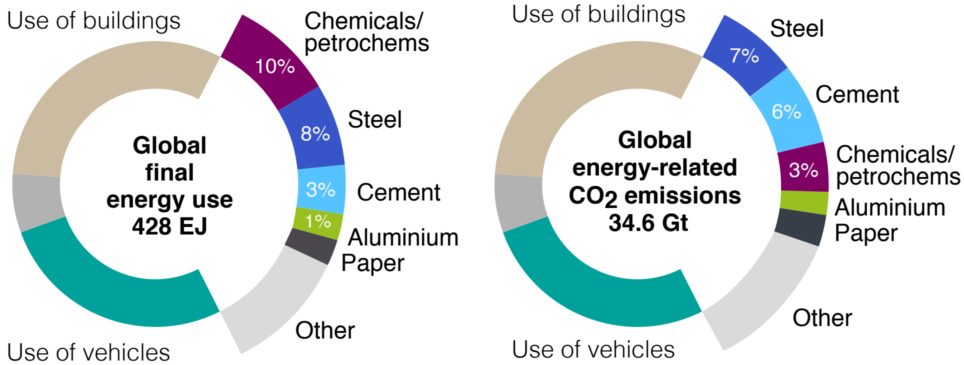

Figure 1.1: Energy use and CO_2 emissions for 2014 disaggregated into sectors, data from (IEA, 2017).

trend remains unchanged, more strenuous efforts to decarbonise the sector will be needed.

In the short-to-medium term, while more disruptive decarbonisation technologies – such as carbon capture and storage – are still under development, meeting these targets will require a resource efficient industry; one that can reduce its emissions by using less energy and materials to produce goods and services.

The remarkable reductions in process energy intensity (joules input per tonne output) achieved in the past fifty years, means that potential gains from energy efficiency (EE) in industry are now limited in comparison to the scale of CO_2 emission reductions required (Allwood et al., 2010, IEA, 2015*c*). Recently, however, a growing body of academic literature has begun to show renewed interest in material efficiency (ME): an alternative option that, for the same level of service, reduces energy use through reductions in material use and waste. In fact, Allwood et al. (2011) confirmed that, under current growth estimates and without the pursuit of ME, it would not be possible to achieve the emissions reductions predicted by the (IPCC, 2007).

Based on case studies of the steel and aluminium industries, Allwood et al. (2011) propose nine strategies to improve ME across the five energy-intensive materials: (1) light-weighting, (2) reusing, (3) re-manufacturing, (4) recycling, (5) diverting scrap, (6) extending product lives, (7) using products more intensely, (8) improving process yields, and (9) substituting materials. Figure 1.2 summarises these nine strategies along other common ME and EE measures. These are classified according to two criteria: the actors responsible for their implementation; and whether they are input- or output-oriented. Input-oriented actions can be achieved through changes in production practices, whereas output-oriented actions often require changes in consumption.

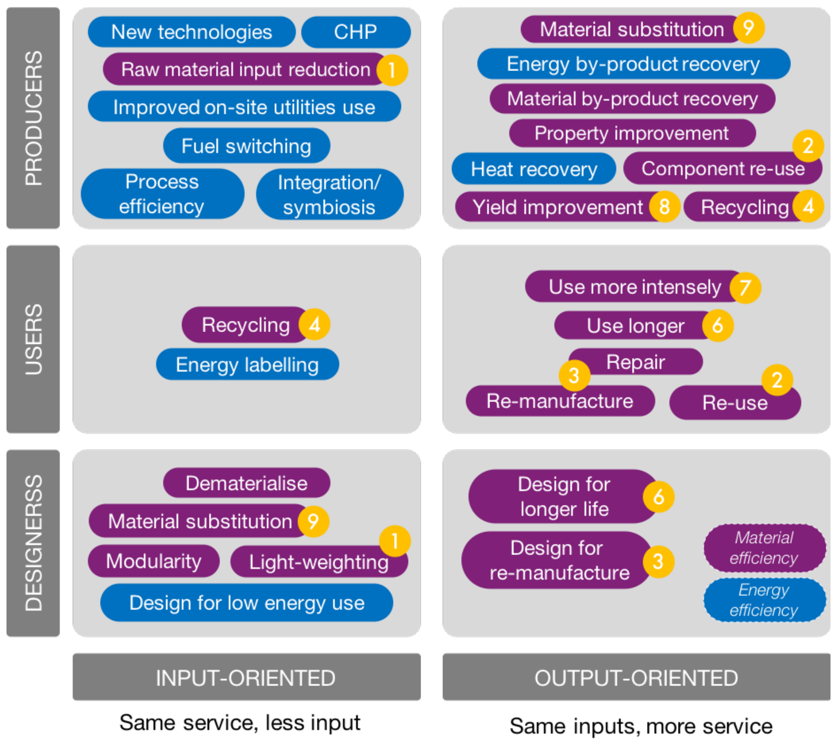

Figure 1.2: Energy and material efficiency actions available to reduce energy use, classified according to the actors involved in implementing these; modified from Allwood et al. (2011). The numbers in the yellow bubbles correspond to the numbers in the list above.

Several studies have confirmed the technical potential available to improve ME in heavy industries, including work by Milford et al. (2011) and Cullen et al. (2012) for the steel industry, among many others. Given the absence of rebound effects – which can dampen efficiency improvements and stimulate an absolute increase in material use – these improvement potentials can lead to real CO_2 emissions savings. Beyond academia, ME has also been commended by the IEA (2015*c*), the IPCC (Fischedick et al., 2014), the G7 Alliance on Resource Efficiency (OECD, 2016), and the UN's Environmental Programme (Etkins and Hughes, 2016) as an important policy option.

Until recently, ME was excluded from respected forecasting exercises. In 2015, however, the IEA

(2015c) for the first time developed a *Material Efficiency Scenario*. Their projections for 2040 indicate that CO_2 emissions and energy use are 20% and 17% lower relative to the *New Policies Scenario* (the agency's main scenario)[2]. These results show that "material efficiency could deliver larger energy savings in energy-intensive industries than energy efficiency" (IEA, 2015c).

Altogether, this evidence suggests that there is scope for improving ME in industry, and that, alongside EE, this is an indispensable complementary strategy to achieve imposed energy use and CO_2 emissions reductions. Beyond identifying this potential at the global and industry-sector level, producers must develop the tools to realise these improvements in practice. The adoption of ME and EE interventions in the production of bulk materials, however, is not without difficulty. The operation of production facilities is extremely complex and involves many trade-offs: operations need to be safe, reliable, efficient and do so whilst being profitable. Therefore, the overarching research question motivating this work and weaving the narrative of this thesis is:

Q0 – How can we help industry firms become more resource-efficient?

Here resource efficiency denotes the combination of both energy and material efficiency. The remainder of this chapter describes some of the key elements that play a role in industry's understanding of its resource efficiency. This initial descriptive process helps guide my research questions, which I define at the end of Chapter 2 after reviewing the available literature.

1.2 Measuring resource efficiency: energy and material use

Industrial efficiency benchmarks can provide a meaningful basis on which to base decisions about improvements in energy and material efficiency. Governments use sector-level benchmarks to negotiate voluntary agreements, or even to distribute the emission allowances in the EU's emissions trading scheme (EC, 2012c). Industry firms employ these to show how each individual facility is performing with respect to a reference; contextualising their performance helps incentivise and prioritise the implementation of improvements. For benchmarks to effectively promote the uptake of EE and ME measures, these need to appropriately quantify change when improvements are made, and in doing so, be transparent and consistent.

[2]Including: energy-related components of Intended Nationally Determined Contributions pledged by governments in preparation for COP21; and policies that have been announced but are yet to be implemented.

Many EE benchmarking methods have been developed in the academic and grey literature. Academic studies, such as those by Worrell et al. (2008) and Saygin et al. (2011), as well as industry-driven approaches by for example UNIDO (2010) or IEA (2014), provide EE indicators for processes, facilities, sectors and regions. These indicators all measure energy intensity – the net amount of energy used (in joules) relative to the amount of useful product output (in tonnes) – with a focus on energy inputs and energy by-products. At best, they capture information related to material inputs through additional explanatory metrics, such as scrap input or product mix; at worst, they ignore both materials input and material by-products. For material-transforming processes (e.g. blast furnaces or steam crackers) narrowing the scope of efficiency indicators to include only energy use fails to capture the key driver for the process – the upgrade in material quality – and places undue focus on the dissipation of high-value fuels into wasted heat.

ME benchmarks are less common. In the steel sector, for example, the closest to a ME benchmark is the comparison of iron yields (worldsteel, 2009), where the iron contained in the outputs is compared to the iron carried in the inputs – in tonnes/tonnes (%). Other academic studies go as far as measuring individual aspects related to specific ME measures. For example, for recycling and re-use interventions, industry practitioners and policymakers employ percentages such as recycling rates, recycled content (Graedel et al., 2011), scrap usage (BIR, 2016); and re-use rates (Densley Tingley et al., 2017). Yet these metrics provide no indication of the amount of energy burned or of environmental impact caused.

To capture this, some studies use indicators, such as embodied energy (GJ/t) and embodied emissions (tCO_2/t), e.g. Milford et al. (2011). These, however are designed for measuring impacts and assigning responsibilities, and do not reflect how well a given process is at transforming both energy and materials; mainly because they allocate inefficiencies from upstream processes.

The above evidence suggests that most efficiency metrics focus on EE and treat ME as an isolated strategy, despite the inherent interactions between energy and material use. The few metrics that could be employed as proxies for ME only focus on specific ME measures, and typically do not include the energy impacts of reducing material use. Neither do these proxies provide an integrated measure of the processes' efficiency at upgrading resources.

1.3 Plant-level analyses: increasing the granularity

Measuring the scale and efficiency of resource use across systems – such as societies, a given sector or a single production process – has a long tradition (Ayres and Ayres, 1999, Ford et al., 1975, Summers, 1971). The majority of academic studies assess resource use at high temporal scales, covering countries or sectors. For example: studies by Cullen and Allwood (2010) on the global energy system, by Cullen and Allwood (2013), Milford et al. (2011), Daehn et al. (2017) on the global steel and aluminium industries, by Levi and Cullen (2018) on the global chemicals/petrochemicals sector and by Eisenmenger et al. (2017) on the resource use for Austria.

At plant- and sector-level, other examples of studies investigating annual resource use and efficiency include work by Wu, Wang, Pu and Qi (2016) and Costa et al. (2001). Yet, to materialise potential improvements in resource efficiency, individual industrial firms must identify and prioritise interventions at actionable time-frames and scopes. That is, within boundaries directly controlled by a given industrial firm. For this to happen, a detailed awareness of resource flows is needed.

At the detailed level of plant operations, a smaller number of studies exist that analyse resource use. Examples include work by Lambrecht et al. (2017) and Alvandi et al. (2015). Rather than exploiting the potential of using metered resource data – enabled through advancements in sensor technology and data analytics – these studies mainly use production simulation software, such as Umberto (IFU Hamburg GmbH, 2014) or Anylogic® to conduct material flow analyses (MFAs). Occasionally, a sample of control data is used, but only to validate the results.

Most other studies within the field of *operations research* that do use control data, mainly focus on operational aspects such as the diagnosis of faults (Russell et al., 2000), and the optimisation of product quality (Farooq et al., 2017) or cost (Brunke and Blesl, 2014, Yang and Lee, 2010). This suggests that, at the plant-level, where real resource-use data over time is available, a holistic picture of energy and materials is still missing.

1.4 Visualising resource flows: effective communication

Enhanced computer resources and control systems along with the more advanced algorithms and modelling techniques now available, have collectively fostered the use of data as an inherent part of the culture of many companies. As the volume of gathered data grows, it becomes increasingly arduous to unravel the valuable information it contains, compromising the main purpose of gathering such large volumes of data in the first place. A way around this has been the use of visualisation tools, which have proved to shed unparalleled clarity.

Among the above studies, Sankey Diagrams (SDs) are the most widely used visualisation to depict the structure and scale of energy and material flows. This is because the same balancing principles that apply in material and energy flow analyses (MEFAs), apply in the architecture of SDs: the inputs to and outputs from a given slice (vertical cross-section) are balanced. Originally employed by Riall Sankey (1896) to depict energy flows through a steam engine, these diagrams have proliferated since; and even more extensively in the past thirty years (Schmidt, 2008).

The initial singular applications of Sankey diagrams involved the mapping of energy and heat flows, a practice that became standardised in the early 1930s. Before the end of that decade, they also begun to be used in the management of materials, for example, in a study by Reichardt (1937) on the iron flows in Germany. Four decades later, SDs were being used in studies investigating the integrated structure of both energy and materials. Among many, some examples of this are the analyses by Szargut et al. (1988) and Masini and Ayres (1996), where energy and material flows in the chemical and metallurgical industries are mapped. More recently, Soundararajan et al. (2014) reviewed nine examples of SDs on energy systems, all published in the last eight years – including the studies by Cullen et al. (2012), Cullen and Allwood (2013). But the appeal of SDs has transcended academia. Even international expert organisations, such as Eurostat (2016) and IEA (2016) now publish SDs online to raise public awareness.

In all the studies discussed in this section, SDs are adopted for their ability to depict, in a single visual, system structures, connections and relative flow scales. And yet, to date, the potential of these diagrams to depict the resource use during real-time plant operations has not been exploited. Combining the visual clarity of resource flows in a Sankey diagram, with the detailed flow information obtained from process control systems, seems to be a fruitful research area to explore.

1.5 Incentivising resource efficiency: EU-level policies

Previous studies evaluating the economic potential of ME show that current financial incentives to adopt this in heavy industries are inadequate (Cooper, 2017, Skelton and Allwood, 2017). For example, Allwood et al. (2011) conclude that high labour taxes are acting as a major barrier in heavy industries, as this means that any "opportunity to substitute excess material use for reduced labour is likely to be attractive". Conventional business models often used by companies are another barrier: these "are oriented towards growing sales volumes'' and are therefore designed to "increase product replacement rates" (Allwood et al., 2011). The lacking financial stimulus combined with the increasing urgency to prevent climate change, makes it more pressing for policymakers and regulators to take action.

In the EU, specific aspects of ME are covered by the European Commission's (EC) environmental Directorate (EC, 2005, 2011*b*, 2015*a*). These policies are driven by rationales of scarcity, criticality, economic growth and price increases, and therefore lead to ME strategies that fail to leverage the energy-saving potential of ME (Valero et al., 2015). An example of this is the EMAS tool, a promising voluntary data collection and reporting scheme developed by DG Environment. The EMAS *encourages* companies to provide information about their energy, material, and water use, as well as waste generation, land use and the emissions of polluting gases (EC, 2013*a*). Based on standardised methods such as the ISO 50001 and the EN 16001 standards (IEA, 2012*a*, ISO, 2011*b*), the EMAS tool overlooks the energy-saving potential of ME, and still treats energy and material use as different strategies having different objectives. In fact, this approach besets the EU's energy and climate strategies, where ME is currently overlooked as a tool to achieve the region's binding energy and emissions targets (EC, 2009, 2013*b*, 2014*b*).

In an attempt to understand why this is the case, Cooper-Searle et al. (2017) use a public policy lens to look at the processes underpinning climate policy formation in the UK climate agenda. The authors collect valuable evidence from interviews with stakeholders, through which they are able to portray their perception of the problem, as well as their attitude towards potential solutions. However, the study's remit is limited to the UK's automotive sector, and therefore only provides limited insight into the EU's agenda-setting process for energy and climate matters in the heavy industries sector.

Other studies exploring the ineffectiveness of EU climate policies at promoting ME, such as work by Aidt et al. (2017), Neuhoff et al. (2016) and Skelton and Allwood (2017), are largely guided by economic theory and therefore do not explore the political and behavioural aspects that affect policy decisions and agendas. They focus on the ETS – the cornerstone of climate policies for heavy industries – but in doing so, overlook other relevant EU-level policies such as the circular economy package and the Energy Efficiency Directive (EED), and the interactions between these. A comprehensive, qualitative explanation of why ME measures are not part of the EU's energy and climate strategies for heavy industries, is yet to be offered.

1.6 The research process

So, how can we help industries become more resource-efficient? Section 1.2 identifies the need for more holistic RE metrics that can capture resource interactions; Section 1.3 and 1.4 reveal the need for practical analytical tools to analyse and communicate resource efficiency at real-time, operational scales; Section 1.5 highlights the need for a more comprehensive explanation of why ME is not part of the EU's energy and climate policy agendas for heavy industries. A more thorough investigation into these three needs promises to provide a valuable contribution to the improvement of resource efficiency in industry.

To gain a better understanding of the nature of these research needs, the next logical step is to assess the available literature. The literature review explores what options already exist to help industries become more resource-efficient. Armed with this knowledge, it is then possible to define more detailed research questions and to design appropriate solutions.

The process of translating these ideas into a formal research problem, and eventually a full thesis, is shown in Figure 1.3. This process is iterative (rather than linear) with several opportunities to revisit and refine the research problem, questions and results. Research questions and hypotheses are revisited and refined as knowledge is gained on the subject and as initial analyses are conducted. This also applies to the choice of research methods, the selection of which is reviewed as progress is made with the data collection and analysis stages.

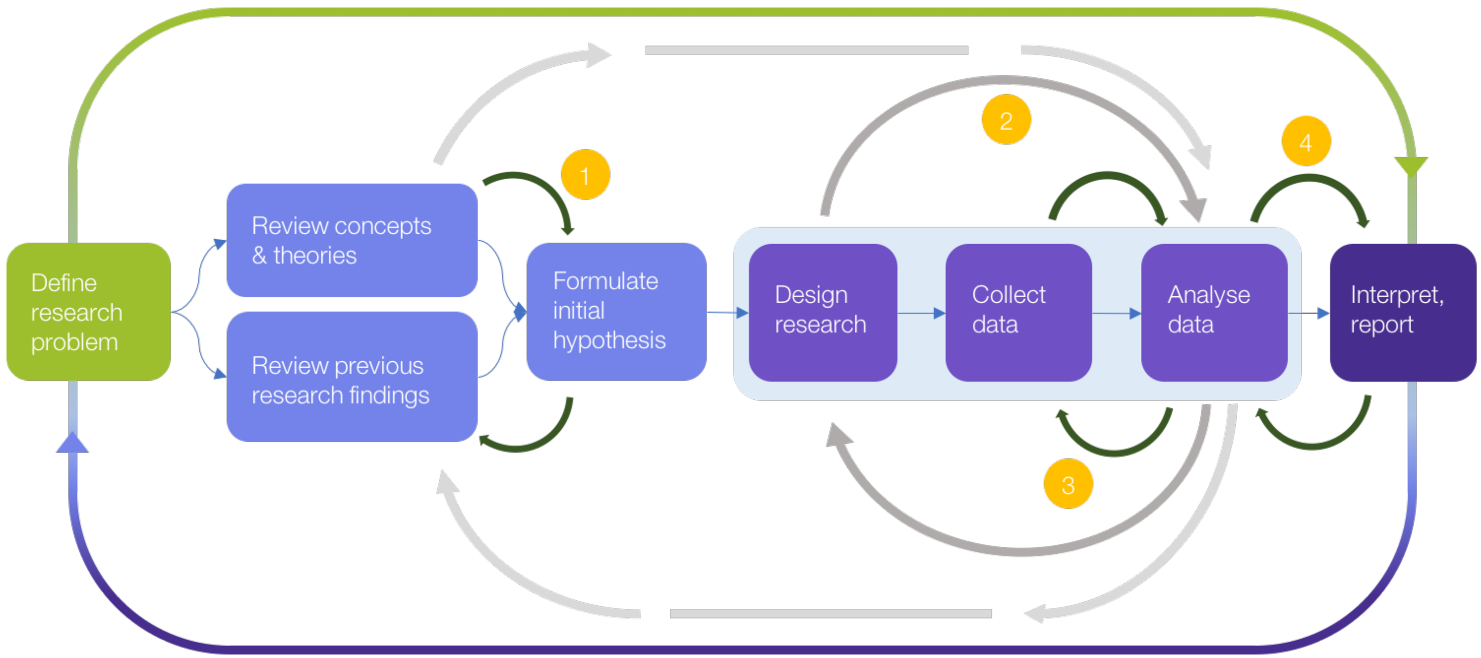

Figure 1.3: Summary of nature of research process, from the definition of the research problem to the interpretation of results. As shown here, these activities overlap and are inherently iterative. Four iterations loops have been identified. The literature review takes place over a long period of time. Advances in the specific research field can cause one's research questions to change (loop 1). Similarly, we redefine our questions and assess our method choices as we progress with the data collection and analyses processes (loop 2). Once the results are obtained, both our methods (loop 3) and the conclusions (loop 4) derived from these should be verified and validated.

2

Review: fostering resource efficiency in heavy industries

A clear rationale exists for improving RE (resource efficiency) in industry. Good resource management enables: the avoidance of waste; a wise use of scarce resources; the reduction of costs; improved responsiveness to future regulation; and perhaps most importantly, the abatement of industrial energy-related CO_2 emissions. Consequently, much has been written about improving the efficiency of heavy industry – the potential economic and environmental gains are immense.

The introduction section above provides a compelling sense of direction for the thesis and has clarified the motivations driving the research endeavour. The following chapter presents a review of the literature on efficiency metrics, methods, applications and policies. It distils information on the different approaches to improving efficiency, across energy and materials, and concludes by describing the knowledge gaps which will be addressed. The chapter is divided into five sections, as summarised in Figure 2.1.

Section 2.1 reviews the portfolio of metrics available to quantify EE and ME in industry; Sections 2.2 and 2.3 then survey methods and tools previously developed to analyse the energy and/or material efficiency of production plants; Section 2.4 finally explores the current policy landscape for EE and ME in Europe and previous studies that have endeavoured to explain existing barriers and potential solutions for their adoption in energy-intensive industries. The three identified knowledge gaps are described in Section 2.5, from which the research plan for Chapters 3-5 is devised. This plan is based on the research proposals made in Sections 2.1.4, 2.3.4 and 2.4.4, where the above research questions have been refined.

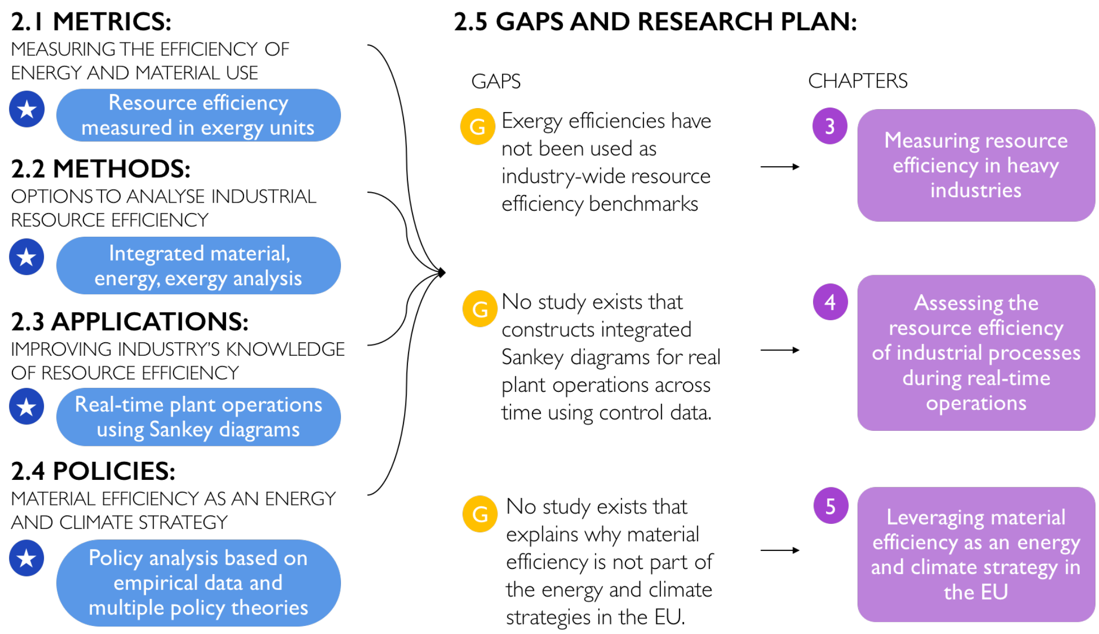

Figure 2.1: Chapter structure, including an outline of the knowledge gaps and of the refined research plan.

2.1 Metrics: measuring the efficiency of energy and material use

In the context of resource use, indicators are employed in every sector – from international development, policy and governance to industry firms – and for multiple purposes. Unsurprisingly, there is a plethora of metrics available to quantify RE, many of which are expressed as ratios of two measured quantities, rather than absolute values. One resource value is compared to another as a simple fraction, as shown in Figure 2.2. Many different values can be placed on the numerator and denominator, and the value can be measured in different units. Differences between RE metrics result from the scope of resources considered, the targets that resource use is measured against, and the units chosen. In this section, the most popular metrics used in industry and academia, that is, those classified as either economic (2.1.1), physical (2.1.2) or impact-oriented (2.1.3) are reviewed – highlighted in purple in Figure 2.2.

There are many ways of defining a 'good' metric. Neuhoff et al. (2009) define good indicators as "representations of quantitative or qualitative data, which can be used to understand the state of a problem, and illustrate the progress made towards obtaining a solution". Expanding upon this definition, this review assesses the appropriateness of RE metrics in relation to: (1) their ability to appropriately describe the physical and chemical mechanisms taking place; (2) the degree to which they encourage users to change their behaviour in the desired direction; (3) the ease with which they can be measured, i.e. on whether their measurement is repeatable and inexpensive. With these criteria in mind, the benefits and drawbacks of each of the three types of metrics is discussed, and the most appropriate metric proposed in Section 2.1.4.

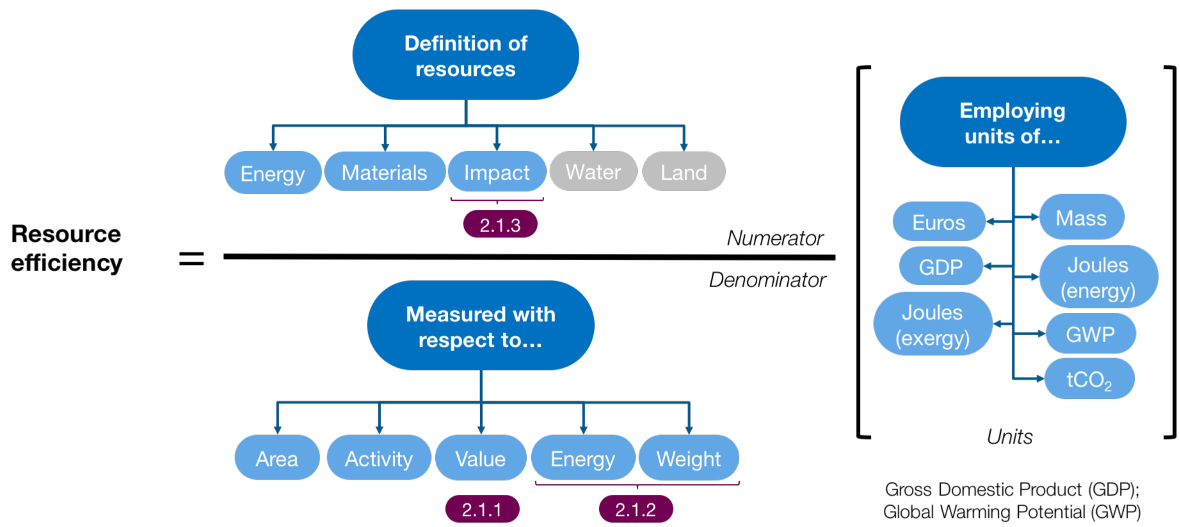

Figure 2.2: Portfolio of indicators used to measure RE. Purple bubbles show the most widely-used metrics and the numbers depict the outline of this section's structure. Resources in grey are not covered in this review.

2.1.1 Economic-based indicators

Economic-based indicators are typically employed in policies to track macro-level changes of entire societies or sectors. In energy policies, EE (energy efficiency) is often expressed in terms of *energy productivity*, i.e. the ratio of value-added per unit of energy used (IEA, 2014). Energy productivities have long been used to inform countries on their relative economic and environmental performance (which are ultimately interrelated). Atalla and Bean (2017) go as far as claiming that energy productivity is a more "direct measure of a country's economy", is more intuitive, better aligned with efficiency and of grander ambition than physical *energy-intensity* metrics. Indeed, this could explain why energy productivity has taken its place as a major climate and energy target in many countries (e.g. the US (Keyser et al., 2015) and Germany (BMWi, 2016)).

Resource productivity is the analogous metric often used to explain historical and future trends in resource use. It is in fact the most widespread measure within resource policies. Resource productivity – the lead indicator in the EU's circular economy (CE) package (EC, 2011*c*, 2015*a*) – represents RE as the economic output (gross domestic product or GDP) per unit of resource input (domestic material consumption or DMI). Many other definitions of resource productivity, however, are not without incidence. For example, as part of their 'Sound Material-Cycle Society' initiative, Japan tracks two other variations of this metric: GDP per input of natural resources (DMI) and GDP per Raw Material Equivalent (Etkins and Hughes, 2016). Di Maio et al. (2017) propose a value-based RE metric, defined as the value of resources output by a sector (in units of value added) per volume of resources used, weighted by their market price. The authors argue that resource prices "reflect both the[ir] quality and the scarcity" and defend that monetary metrics are both better at capturing local situations and easier to communicate than mass-based ones.

Beside measures of resource productivity, other economic-based indicators have been developed to quantify resource use: emissions efficiency, i.e. GDP per global emissions, or of the ecological impact of resource use e.g. €/impact. Etkins and Hughes (2016), Huysman et al. (2015), Mudgal et al. (2012), Van der Voet et al. (2005) reviewed an extensive range of policy-level RE indicators.

Cullen (2009) contends that one of the main reasons why economic measures are still widely used is the "availability of detailed data for analysis". Despite this benefit, economic-based indicators are known to have multiple drawbacks. If the monetary value of resources, waste disposal and process operations align with the amount of resources consumed, this can be a suitable proxy for RE. Yet, if these do not align, and inefficient resource use can still lead to increased profitability, then, it is "unlikely that a market operating solely according to market rules will deliver a resource-efficient outcome in physical terms" (Etkins and Hughes, 2016). Economic indicators have also been criticised for being "insensitive to changes in the environmental pressures" and scarcity (Valero et al., 2015, Van der Voet et al., 2005) – environmental impacts vary significantly across materials. As a result of these drawbacks, policymakers and corporations are forced to rely on baskets of complementary indicators, each of which is designed to measure a specific aspect of RE.

To guarantee the transition to a resource-efficient industry, as pointed out by Huysman et al. (2015) and IEA (2014), it is necessary to complement these economic-based indicators with physical, market-independent ones. In fact, to conduct a sound economic analysis of an industrial system, there must be an underlying understanding of its physical flows.

2.1.2 Physical-based indicators

A portfolio of physical energy and material efficiency metrics can be used to track improvements in energy and material use in heavy industries. Energy-only and material-only indicators are reviewed first, and the most prominent method to combine these is later proposed.

Energy efficiency

The most common and well-understood physical measure of EE for heavy industries is *energy intensity*. This is often measured in units of *joules per tonne of material output*, but several other alternative forms have also been developed. The literature reveals that energy-intensity-type indicators can be used at any system level, from individual processes to entire sectors or regions.

Worrell et al. (2008) published perhaps the most widely cited study of global best-practice energy use for several energy-intensive industries, including: iron and steel, aluminium, cement, pulp and paper, ammonia, and ethylene. For the steel industry for example, the analysis evaluates high performance reference plants, based on data from the International Iron and Steel Institute (IISI, 1998) in the late 1990s, with energy intensities (GJ/t of physical unit of output) reported at the level of fuels, steam and electricity inputs – both in terms of primary and final energy. For this sector, similar energy-intensity studies have also been produced by international and national steel bodies, such as the European Steel Association and European Steel Technology Platform (2014) and the Canadian Steel Producers Association (CSAP, 2007).

Phylipsen et al. (1997) proposed a modified energy-intensity metric called the *Energy Efficiency Index* (EEI), which enables the comparison of EE between countries. The EEI metric accounts for structural effects by measuring the ratio of average to best practice energy intensity for each country. This method has been applied: to benchmark industry sectors in the Netherlands (Phylipsen et al., 2002); in detailed EE studies of steelmaking processes (Siitonen et al., 2010); and in global industry benchmarks (Ke et al., 2013, Saygin et al., 2011, UNIDO, 2010).

In spite of the popularity of economic EE indicators, energy-intensity metrics have also set foot in policymaking. One example is the EU's ODEX index, which the EC (European Commission) uses to track EE improvements. This transforms energy-intensity values into rates of energy savings in percentages (EC, 2012*b*). A second example is the Strategic Energy Technology (SET) plan, where energy intensities are also used to set reduction targets for individual industry sectors (EC, 2017*e*). Other examples include reports by the IEA (2008, 2010*b*). These studies all use energy-intensity-based metrics to track EE improvements.

Table 2.1 summarises a selection of studies that have developed or employed EE metrics for energy-intensive industries. Figure 2.3 portrays the benchmark results obtained from UNIDO (2010). Most industries report values in units of gigajoules per tonne (GJ/t), although in some cases *proxy* units are used as approximations for energy use, such as megawatt-hour per tonne (MWh/t) in the case of aluminium smelting.

Table 2.1: Selection of EE metrics from the literature; *EEI* – Energy Efficiency Index; SEC - Specific Energy Consumption.

Reference	Metric	Unit	Aggregation level
worldsteel (2014*a*)	Energy intensity	Joules per tonne of output	Global
Ke et al. (2013)	SEC and EEI	Joules per tonne of output; ratio of energy intensities (%)	Case study
EC (2012*b*)	ODEX Index	Ratio of energy intensities (%)	Europe
Saygin et al. (2011)	EEI	Ratio of energy intensities (%)	Global
Siitonen et al. (2010)	SEC and EEI	Joules per tonne of output; ratio of energy intensities (%)	Case study
IEA (2010*b*)	Energy intensity	Joules per tonne of output	Global/region
UNIDO (2010)	EEI	Ratio of energy intensities (%)	Global
Worrell et al. (2008)	Primary, final energy intensity	Joules per tonne of output	Global
IEA (2008)	Energy intensity	Joules per tonne of output	Global/region
CSAP (2007)	Energy intensity	Joules per tonne of output	Canada
Phylipsen et al. (2002)	EEI	Ratio of energy intensities (%)	Regional
Worrell et al. (2000)	Primary energy intensity	Joules per tonne of output	US
IISI (1998)	Energy intensity	Joules per tonne of output	Reference
de Beer (2000)	SEC	Joules per tonne of output	Reference
Phylipsen et al. (1997)	EEI	Ratio of energy intensities (%)	Regional
Van Wees et al. (1986)	Energy intensity	Joules per tonne of output	Case study

Sectors (products and processes) (year data refers to)	Meth. (B/I/L)	Units	Global average	Best Available Technology (BAT)	Intl. Benchmark/ Lowest EEI	Worst Plant (or region)	Coverage of the data (%)
Petroleum refineries (2003)[1]	*I*	EEI	1.25	1	-	-	90
Chemical and petrochemical							
High value chemicals[2] (2005)	*B & I*	GJ/t HVC	16.9	10.6	12.5	33.6	75
Ammonia[3] (2007)	*B & I*	GJ/t NH3	41	23.5	31.5	58	100
Methanol[4] (2006)	*B & I*	GJ/t MeOH	35.1	28.8	30	58	80
Non-ferrous metals							
Alumina production[5] (2007)	*B & I*	GJ/t alumina	16	7.4	7.8	18.4	100
Aluminium smelting[6] (2007)	*B & I*	MWh/t primary aluminium	15.5	13.4	14.2	20.8	>95
Copper[7]	*B*	GJ/t copper	13.8	6.3	7.4	50.9	50
Zinc[8] (2006)	*I*	GJ/t zinc	23.6	-	15.2	37.2	100
Iron and steel (2005)[9]	*I*	EEI	1.45	1	1.16	2.2	100
Non-metallic minerals							
Clinker[10] (2007)	*B & I*	GJ/t clinker	3.5	2.9	3	6.6	100
Cement[10] (2007)	*B & I*	kWh/t cement	109	56	88	144	100

Figure 2.3: Benchmark results for various energy-intensive sectors; modified from UNIDO (2010). Average SECs are based either on benchmark surveys (B) or indicators (I).

From the metrics reviewed above, energy intensity has gained the closest to a universal acceptance, in industry, academia and the policy sphere. Yet energy-intensity metrics only quantify the extent to which energy inputs, the main material product (in tonnes) and energy by-products are used and produced, ignoring the value of material by-products or material inputs. Further, by virtue of having different denominators (depending on the material produced), these metrics are inappropriate for comparing performance across sectors. To capture the effectiveness of industrial material use, many other metrics have been developed – often categorised under the rubric of *material efficiency*. These are explored in-depth in the following section.

Material efficiency

As *material efficiency* can take multiple forms (see Section 1.1) and requires action across entire value chains, a larger variety of physical metrics have been developed to track the progress of each of these. Table 2.2 summarises a subset of these, but more extensive reviews can be found in work by Allwood et al. (2011), Cleveland and Ruth (1998), Shahbazi et al. (2017).

Table 2.2: Selection of material efficiency indicators used in the literature

Reference	Metric	Unit	Scope
Material consumption			
Gao et al. (2016)	Raw material consumption intensity	tonnes of raw material / tonne of output	Cement plant
Gao et al. (2016)	Raw material consumption (absolute)	tonnes	Cement plant
EEA (2016*b*)	Domestic material consumption (DMC)	tonnes	Regional
Blaser et al. (2012)	Total Material Requirement (TMR)	tonnes	Regional
Blaser et al. (2012)	Material Input per Service unit (MIPS)	tonne in per tonne product	Regional
Circularity			
Ellen MacArthur Foundation (2015)	Material Circularity Indicator	percentage (%)	Regional
Linder et al. (2017)	Product-level Circularity	cost of recirculated parts/ cost of all parts	Conceptual
Cullen (2017)	Circularity Index	percentage (%)	Supply chain
Reycling			
BIR (2016)	Steel recycling ratios	Ratio Steel Scrap / Crude Steel	Global
Gao et al. (2016)	Waste rate	waste produced per unit of product	Cement plant
Gao et al. (2016)	Recycle rate of waste	rate of recycled waste to waste produced	Cement plant
Graedel et al. (2011)	Old scrap collection rate	EOL products collected/ EOL products	Global
	Recycling efficiency rate	recycled EOL/ EOL products collected	Global
	End-of-life (EOL) recycling rates	recycled EOL/ EOL products	Global
	Recycled content	used scrap /total material input	Global
	Scrap ratio (metals)	percentage (%)	Global
Buchert et al. (2009)	Recycling rate	percentage (%)	Global
Hashimoto (2004)	domestic processed output (DPO)	tonnes	Conceptual
Hashimoto (2004)	direct material input (DMI)	tonnes	Conceptual
Reusing			
Densley Tingley et al. (2017)	Re-use rate	percentage (%)	UK
Hashimoto (2004)	By-product recovery	By-products used/ by-products produced	Conceptual
Hashimoto (2004)	material use time	tonnes of product stocks per/ tonnes of used products recovered and disposed of	Conceptual
Improving yields			
Milford et al. (2011)	Metallic yield	tonne out per tonne in (%)	Global
worldsteel (2009)	Metallic yield	tonne out per tonne in (%)	Reference

A widely used metric is *material intensity*, a ratio which can be measured in multiple ways, including: tonnes per GDP (Cleveland and Ruth, 1998, EC, 2011*b*); tonnes per area, volume, hour or service (Allwood et al., 2010, Eisenmenger et al., 2017, Gao et al., 2016). Blaser et al. (2012) denote the last ME metric as 'Material Input per Service Unit', where the weight of the product is measured in relation to the total volume of material that is used over the entire life-cycle of the product – including direct and indirect inputs. For yield improvements, the industry often quantifies the output-to-input ratios of pure metal contents, such as Fe (iron) or Al (aluminium). The worldsteel (2009) report is an example of a yield benchmarking exercise for the steel industry. For re-use options, *re-use rates* are typically used (e.g. Densley Tingley et al. (2017)).

Recycling is, by far, the most widely studied ME intervention. To measure this, industry practitioners and policymakers often employ a diversity of metrics, most of which are in the form of percentages: recycling rates, recycled content (Allwood, 2014, Esch et al., 2010, Graedel et al., 2011), or scrap usage (BIR, 2016). Even solely within recycling-rate metrics, multiple definitions exist, each of which is designed for different "types of material cycles" and "sections of the material's life cycle"(Hashimoto, 2004). Hashimoto (2004) proposed six recycling rate indicators. These include, for example, *material use time* (the ratio of amount of product stocks to amount of used products recovered and disposed of) which is proposed as a measure of the re-use of used products; or *material use efficiency* (the amount of material used per material consumed) and *by-product recovery rates* (the fraction of by-products used to the amount generated), which are both proposed as indicators to track the recovery of by-products.

Recently, the concept of a *circular economy* has become the new environmental mantra among industry practitioners, policymakers and even academics. As a result, *material efficiency* interventions have been rebranded into *circularity* strategies. A new academic field has emerged to investigate ways of quantifying the circularity of products and processes – so far, no standardised metric has been agreed upon. In discussing the metrics available to measure ME in industry, it is however fitting to explore some of the most relevant circularity metrics proposed. Linder et al. (2017) compiled a selection of these, highlighting the benefits and shortcomings of each.

For example, Ellen MacArthur Foundation (2015) propose a mass-based metric, *Material Circularity Indicator* (MCI), for quantifying the circularity of products; its value ranges between 0 and 1, with higher values indicating higher circularity. A normalised and weighted average of this metric is proposed as the measure of circularity for businesses. The rest of the metrics reviewed are either based on life-cycle assessments (e.g. Eco-efficient Value Ratio by Scheepens et al. (2016)), focused solely on recycling (e.g. Circular Economy Index by Di Maio and Rem (2015)) or based on cost (e.g. product-level circularity by Linder et al. (2017)).

One of the main criticisms of the ME and CE indicators just described is that they quantify specific aspects of material use, but provide no indication of the energy or environmental implications of the given ME strategies. As explained by Cullen (2017), circularity indicators "which put the economic growth *cart*, before the environmental impact reduction *horse*" warrant caution. To quantify the energetic implications of looping materials, Cullen (2017) propose a *Circularity Index* for materials, which is instead defined as the product of two quantities: one which measures the energy needed for material recovery relative to that needed in primary production, and another that measures the mass of end-of-life materials relative to the total demand for that material. The author argues this provides an improvement from previous metrics because his measure accounts for losses in both quantity (in mass) and quality (in energy). Other studies use life-cycle or footprint-type indicators; these are discussed in Section 2.1.3.

In a recent study, Shahbazi et al. (2017) review ME metrics currently used by the manufacturing industry. The authors conclude that the literature does not address the practical aspects of measuring ME in manufacturing firms, more specifically "*how to manage ME performance, how other indicators interact with ME measurements, and how they are connected to overall goal and strategy of company*". One of the difficulties of doing this arises from the fact that conventional energy metrics and ME indicators are measured in different units.

Many of the complex systems in industry – and indeed in nature – involve multiple resources, impacts and transformations. Therefore, tracking a single resource individually can only provide partial insight when evaluating RE. This is especially true in industry processes where inputs of energy and materials (for instance) are intertwined and often interchangeable. Consequently, the analysis becomes increasingly challenging. To resolve this, academics from a different field developed the concept of *exergy*: a means of measuring energy and material use in a single metric.

Exergy efficiency: integrating energy and materials

Exergy can be defined as *"the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment"* (Sciubba and Wall, 2007). The term was coined by Rant (1956) and is founded on work by Gibbs (1873), Keenan (1932) and Nesselmann (1952, 1953) – among others. Masini and Ayres (1996) neatly summarise its utility: *"...exergy provides a systematic and uniform general-purpose indicator for both materials and energy resource[s] [...] for any industrial process. In fact, an exergy balance [...] provid[es] a concise means of characterizing any materials transformation process. It links resource analysis, industrial engineering and environmental analysis. Moreover, it can be used for assessing process efficiency, identifying potential opportunities for future technological advances..."*.

For engineers and thermodynamicists, exergy is a method used mainly to reveal process losses and to optimise designs and operating conditions. Yet, for industrial ecologists, exergy is often a metric, a lens for analysing specific aspects related to resource use – from scarcity (Valero et al., 2015) to environmental damage (Dincer and Rosen, 2007, Seager and Theis, 2002). In fact, in the field of Industrial Ecology (IE), the use of exergy metrics does not require the application of a full thermodynamic analysis; exergy has been applied to various analytical frameworks, including life-cycle (Finnveden and Östlund, 1997), input-output analyses (Rocco, 2016), production-factor economics (Serrenho, Warr, Sousa, Ayres and Domingos, 2016), and societal exergy accounting exercises (Sousa et al., 2017). In this section, exergy is treated as a metric through which to measure energy and material use. To follow is a discussion on its various forms, and the possibilities it affords for measuring RE[1].

Generally, exergy efficiencies are defined as ratios of resource inputs to resource outputs, and can include either energy or materials alone, or a combination of the two. Both the numerator and the denominator are measured in joules of exergy, providing a dimensionless metric that ranges between 0 and 1. Whereas energy metrics follow the first-law thermodynamic principle of energy conservation, exergy, in addition, incorporates the second law of thermodynamics, which illustrates that energy (also in the form of materials) has *quality* as well as quantity.

Across the exergy literature, efficiency definitions have been adapted to specific industrial applications so that these reflect the actual mechanisms taking place. Marmolejo-Correa and Gundersen (2012) and Brodyansky et al. (1994) suggest that different definitions are deemed to be more or less fitting depending on: the specific system level (i.e. whether a device or a sector); the nature of the exergy transformations and losses involved – whether chemical or physical and whether energy

[1]Further discussions on the benefits of exergy as a method of analysis are covered in Section 2.2.4.

or materials are being transformed; and the particular purpose of the study, i.e. whether the aim is to understand device irreversibilities or the environmental impact of resource use. Table 2.3 summarises the results from a selection of studies performed in the past 30 years (between 1986 and 2016). These cover a wide range of industries and are performed at differing system levels; some represent the efficiency of a sector in a specific region, others of specific plants.

Table 2.3: Summary of exergy efficiencies from studies found in the literature for a range of industrial sectors. Inorg: inorganic; org.: organic; chem: chemicals; Al: Aluminium; [a] Sulphuric acid; [b] Ammonia and syngas; [c] Secondary steelmaking; [d] Acetylene; [e] Methanol

Studies	Steel	Al	Lead	Copper	Inorg. chem	Org. chem	Glass	Paper	Cement
Wall (1988)								43	
Szargut et al. (1988)	29-34[c]	10	4	3	25[a]	56[b]		19	10
Masini and Ayres (1996)	36-41	32	24	22			22	48	
de Beer (2000)	29-48								
Ayres and Ayres (1999)	23	24	11	10					
Costa et al. (2001)	30-67[c]								
Ertesvåg (2001)	28-48								
Gong (2005)								42	
Wang et al. (2007)						43[d]			
Liu et al. (2010)						47[e]			
McKenna (2009)							22		
Al-Ghandoor et al. (2010)	25-38	40			33	32	34	22	38
Ayres et al. (2011)					29	35			14
Balomenos et al. (2011)	14								
Madlool et al. (2012)									28
Cullen et al. (2012)	23-37	30-46							
Kandilci and Saraç (2014)									11
Atmaca and Yumrutaş (2014)									39
Flórez-Orrego and de Oliveira Junior (2016)						66[b]			

One way of classifying exergy efficiencies is by distinguishing between total and rational definitions. The total exergy efficiency (η_{total}), as originally proposed by Nesselmann (1952) and Fratzscher and Beyer (1981), is described as the ratio of total output (B_{out}) to total input exergy flows (B_{in}). By including all of the outgoing exergy flows, this definition of efficiency (Equation 2.1) only reflects the internal exergy losses (irreversibilities) in the process and avoids the need to make judgements on the usefulness of the output products.

The original total exergy efficiency definition has later been modified to account for the external exergy losses contained in *waste*. This can be denoted as the *useful* exergy efficiency; its denominator is still the total amount of resource inputs (Equation 2.2), but the output products are instead classified into useful ($B_{\text{products}} + B_{\text{by-products}}$) and wasted streams ($B_{\text{wastes}}$). Total exergy efficiency definitions are particularly suitable for evaluating the performance of processes that *fully* transform all inputs into useful outputs – such as most of the metallurgical industry studies in Table 2.3 – but fails to appropriately characterise the efficiency of resource conversion for cases where components remain untransformed.

$$\eta_{\text{total}} = \frac{B_{\text{out}}}{B_{\text{in}}} = \frac{B_{\text{products}} + B_{\text{by-products}} + B_{\text{wastes}}}{B_{\text{in}}} \tag{2.1}$$

$$\eta_{\text{useful}} = \frac{B_{\text{out}}^{\text{useful}}}{B_{\text{in}}} = \frac{B_{\text{products}} + B_{\text{by-products}}}{B_{\text{in}}} \tag{2.2}$$

Conversely, rational (also task or utilitarian) efficiencies distinguish between energy and materials that undergo transformations – and that are therefore consumed – and those that remain unreacted (Brodyansky et al., 1994). In the case of chemical reactions, rational efficiencies are typically denoted as *transit* exergy efficiencies (η_{transit}). Brodyansky et al. (1994) explains that energy and materials, as well as individual chemical compounds in these flows, can all carry transit exergy through a process (Equation 2.3). For example, in ammonia production it is common for nitrogen to remain partly unreacted. Other industries where rational exergy efficiencies are common include: oil and gas (Cornelissen and Hirs, 1999, Nguyen et al., 2014) and manufacturing (Gutowski et al., 2009) sectors. Ignoring this in the efficiency definition leads to unrealistic descriptions of resource conversions, yielding overly optimistic values (Sorin and Paris, 1998).

$$\eta_{\text{transit}} = \frac{B_{\text{out}}^{\text{useful}} - B_{\text{out}}^{\text{transit}}}{B_{\text{in}} - B_{\text{in}}^{\text{transit}}} \tag{2.3}$$

The cumbersome nature of exergy has hindered its dissemination in the management of production plants; in the development of sector-level or global benchmarks; and in the definition of policy targets. However, work by Cornelissen (1997), Renaldi et al. (2011), Tanaka (2008) and Lior and Zhang (2007) have provided clarity in the use of different exergy efficiency definitions for different processes, attempting thereby to standardise these for both plant management and policy making. Allowing for the variations in definitions, it is thus possible to apply the resource efficiency metric – in exergy units – across all industry sectors.

Yet all metrics have their limitations. Brunner and Rechberger (2004) contend that using exergy to describe the quality of resources can be biased towards energy carriers. The exergy of fuels clearly reflects their function: providing heat (either directly or indirectly) to a process or reaction. For non-energy carrying materials, however, quantifying the work that can be extracted from these may not be the most suitable measure for truly capturing their utility. In response to this, Bakshi et al. (2011) argue that the chemical exergy of materials is meaningful because it expresses the theoretical amount that can be saved if these are input as raw materials elsewhere.

2.1.3 Impact-oriented indicators

Academics and industry practitioners have endeavoured to go beyond measuring just economic or physical implications, and have included the associated environmental impacts of resource use. The multi-dimensional nature of resource use means that a multitude of these effects can be quantified, from toxicity to eutrophication, global warming potential or ozone depletion potential, among others. Impact-oriented indicators are typically used as part of a basket of indicators, often in life-cycle-type analyses. For example, in the EU-funded project *TOP-REF*, the authors propose a selection of 16 key resource indicators to be used by production facilities in the process industry (Deloitte and CIRCE, 2014). Other research studies, such as that by Huysman et al. (2015), have focused on developing systematic frameworks through which to choose the most appropriate RE metrics. The authors argue this is vital for "decision-making models, making it possible to select relevant indicators for specific needs".

Impact indicators often measure indirect energy use and emissions, such as embodied energy (GJ/t) and emissions (tCO_2/t) – commonly allocated to specific products. For example, Milford et al. (2011) compute the embodied energy and emissions that could be saved by improving yields, whereas Cooper et al. (2014) use these to estimate the optimum life-time of appliances. Embodied energy indicators have also been proposed among *exergy* experts. Two renowned examples are the metrics devised by Szargut et al. (1988): *cumulative exergetic consumption* (CExC) and *cumulative degree of perfection* (CDP). The former (CExC) quantifies the sum of the resources consumed across the entire production process of a given material in units of exergy per tonne, whereas the latter (CDP) expresses this in relative terms – i.e. in terms of efficiency, with final useful outputs in the numerator and the cumulative exergy input in the denominator. Szargut's metrics were introduced as ways to: compare the resource use of different production processes, analyse the cumulative effect in utilising wastes and, evaluate the effects of substituting energy and materials.

In the above studies, impact-oriented indicators are useful for comparing the energy or emissions savings from various ME measures and for assigning responsibilities to different products/processes (EC et al., 2012) – an already controversial task (Allwood and Cullen, 2009, Ayres, 1995). Yet they do not reflect how well a given process is at transforming both energy and materials; mainly because they allocate upstream inefficiencies (i.e. the energy consumed and/or wasted in previous processes) which makes it challenging to diagnose the source and cause of the losses for individual processes. As they are typically measured with respect to the main output, they are also unable to capture the benefits of recovering material by-products such as the slag or slurry produced in steelmaking.

The rich volume of measured impacts makes it challenging to draw meaningful conclusions. Academics have been grappling with the idea of aggregating these into a single metric, but this remains a highly controversial issue in the academic community. Several options have been proposed to combine indicators, including their weighting (Huppes et al., 2012), normalisation (Benini et al., 2014) or monetisation (Krieg et al., 2013). In integrating multiple indicators, real trade-offs between impacts are ignored, and a high degree of subjectivity is involved.

2.1.4 Proposed metric: exergy efficiency

Section 2.1 reveals that there are numerous ways to measure RE, each with its own advantages and disadvantages. As defined at the beginning of this chapter, this thesis seeks for a metric that is able to appropriately capture the efficiency with which both energy and materials are transformed in production processes. This metric should help plant managers make decisions on how to improve EE and ME (i.e. be actionable), and in doing so must: take account of resource interactions; be comparable across different processes and sectors; reflect both resource quantity and quality; ignore market-related aspects.

Three main types of indicators were reviewed: economic, physical and impact-oriented metrics. Economic indicators provide a removed understanding of the underlying physical flows involved in production, and impact-oriented metrics are designed for assigning responsibilities to different products or processes rather than for measuring the efficiency of these – they allocate upstream inefficiencies. Physical, market-independent indicators are deemed most appropriate to measure the RE of production processes in heavy industries. In fact, sound economic and impact-based analyses must be rooted on a detailed understanding of fully balanced physical flows.

Among the physical-based indicators, energy-intensity metrics ignore the value of material by-products and material inputs, do not reflect an upgrade in material quality and are difficult to compare across industries or processes producing different products. ME and CE indicators often focus on measuring the effectiveness of specific strategies, e.g. recycling or re-using. These can result in unintended consequences, whereby one aspect is improved at the expense of another. Measuring efficiency in mass units also neglects the changes in resource quality during production.

Based on this, *exergy efficiencies* are proposed as the measure of resource efficiency for heavy industries. The benefits of using exergy as a measure of RE can be summarised as follows:

- Exergy makes it possible to characterise energy and material-transforming processes more easily and to neatly combine measures of energy and material use in a single metric. Both mass and energy balances alone fail to show the upgrade in material quality that is enabled by dissipating high-value fuels into low-value heat.
- It reflects resource *quality* and gives insight into *which* material or energy streams are worth recovering: those with high exergy content from which work can be extracted. Its foundation on the second law also provides a better engineering understanding of the irreversibilities generated during production.
- It captures the benefits associated with improving the recovery of material by-products, such as slag or slurry, which cannot be done using energy-based metrics.
- Exergy provides an integrated measure of energy and material use, which is dimensionless and can thus be used to compare efficiencies across industry sectors.
- The plethora of exergy studies conducted in the literature demonstrates that a well-established procedure exists to quantify exergy efficiencies – this ensures the trace-ability and repeat-ability of its measurement.

2.2 Methods: options to analyse industrial resource use and efficiency

In Section 2.1.4, the metric of exergy was deemed as the most promising measure of RE. This sets out the unit of measure of analysis, but does not dictate the method – historically exergy has lent itself to many environmental tools developed to analyse resource use. This section therefore concentrates on reviewing the wide array of relevant exergy-related methods in more detail.

Since the inception of the Industrial Ecology (IE) field in the 1990s, industrial ecologists have adopted multiple methods to analyse environmental aspects related to industrial activity – most of which precede the IE field itself (Ayres and Ayres, 2002, Frosch and Gallopoulos, 1989). This is certainly the case for its three most popular resource accounting methods: Material and Energy Flow Analysis (MEFA), Life-Cycle Analysis (LCA) and Input-Output Analysis (IOA). Despite not being responsible for devising these, IE has expanded, reinvented and even mainstreamed these tools across academia, policymaking and industry. The methods' malleability combined with the multi-faceted nature of 'sustainability' matters, has allowed researchers to use IE as a testing ground to develop a plethora of new, hybrid methods. In fact, the exergy metric has been used in all three methods (e.g. Cooper, Hammond and Norman (2017), Rocco et al. (2014)).

The next sections weigh the advantages and disadvantages of using these physical-based methods[2]: IOA (Section 2.2.1), LCA (Section 2.2.2) and MEFA (Section 2.2.3), and combinations of these, to analyse the resource use and efficiency of industry. Expanding on the exergy concepts introduced in Section 2.1, an entire section (2.2.4) is then dedicated to the method of exergy analysis – or Exergy Flow Analysis (ExFA); a method that combines the First and Second Laws of Thermodynamics. Since exergy has been applied to the study of industrial systems at least since the mid 1800s (Carnot and Thomson, 1897, Gibbs, 1873), there is a rich body of literature outside of IE that must also be reviewed.

2.2.1 Input-Output Analyses

Input-Output Analyses (IOAs) have been used to track monetary flows since before the 1970s (Suh and Kagawa, 2005). Originally developed by Leontief (1966), IOA reveals the relationships between different resources and commodities within an economy, and how changes in these

[2]Other methods which encompass other non-physical inputs are therefore excluded. Examples of these include, Data Envelopment Analysis (Cooper et al., 2004) or Process Analysis (Boustead and Hancock, 1979, Cullen, 2009, Rocco, 2016), where additional aspects such as labour and machinery costs are often included.

relationships can affect the overall economy or resource use.[3] More recently, multi-regional IO analyses (MRIOAs) have become popular among ecological economists. Large database initiatives have been set up to improve the availability and consistency of environmental data, from which MRIOAs can be based. One example is the GTAP database, a global database comprised of IO tables, bilateral trade data, energy data, and other relevant economic information (Peters et al., 2011). Based on this database and the MRIO tables constructed by (Peters et al., 2011), Skelton (2013) was able to identify key steel-using sectors, quantify their incentives to adopt ME, and the impact carbon prices and labour taxes can have on these incentives.

Since the 1990s, IOA has been advocated as an analytical framework to estimate and represent material flows (Clift et al., 2015) by transforming monetary flows into physical equivalents (Duchin, 2009), i.e. into physical IO tables or PIOTs (Lenzen and Lundie, 2012). Physical IOAs are valuable because they enable the attribution of extracted resources to individual countries and economic sectors. In doing so, they also help identify risks of material leakage and burden shifting, and are able to arrive at monetary damage values. By applying the concept of mass conservation, PIOTs can also improve the accuracy of their monetary counterparts (MIOTs), and account for both direct and indirect resource consumption. Many approaches are detailed in the literature for constructing and analysing PIOTs, e.g. Duchin (2009), Hawkins et al. (2007), Hubacek and Giljum (2003). One of the most popular methods is the environmentally-extended global multi-regional IO (Domenech et al., 2014), where global interconnections between the environment and the economy are analysed from a multi-region/multi-country perspective; this facilitates the quantification of impacts on economic sub-sectors and specific resource products. The multitude of approaches proposed and the discrepancies between them has prevented the standardisation of physical IOAs (Hubacek and Giljum, 2003).

At firm-level, IOAs are often denoted as enterprise input-output (EIO) models. Although a more unconventional application, EIO has also been used since the 1960s (Lenzen et al., 2010). Albino and Kühtz (2004) provide an example of a study applying IO modeling to measure the environmental impact of a company. This study, however, limits the process output to a single product, again struggling to objectively allocate resource use to multi-product processes; also the case of a study by Fraccascia et al. (2017). Lin and Polenske (1998) propose the an IO structure to perform the process analysis of a steel plant. This technique was used to: trace resource flows; calculate

[3] A full description of the IOA method and its applications can be found in (Miller and Blair, 2009).

direct and indirect energy inputs for processes; evaluate alternative technologies; and estimate energy, material and capital demand.

However, all physical IOAs suffer from six drawbacks: (1) most of the IO methods proposed, struggle to represent recycled flows or stock changes; (2) there is still a debate around the materials that should be separately balanced (Hubacek and Giljum, 2003); (3) PIOTs can hold resources measured in different units (i.e. material in tonnes and energy in joules) but then track these independently, hindering the integration of the analysis of energy and materials; (4) PIOTs tend to be based on highly aggregated data, which then limits their utility in environmental analyses (Hoekstra and van den Bergh, 2006) and are yet to be fully developed across sectors and regions; (5) tracking materials is challenging also because economic costs continue to be allocated downstream even when physical material flows stop, i.e. the allocation of the steel cost of a delivery truck to the food sector (6) converting monetary into physical units is not straightforward and strongly dependent on the chosen conversion factors (e.g. energy intensities).

2.2.2 Life-cycle analysis

Life-cycle analysis (LCA) is a bottom-up approach for measuring the environmental impacts of a product's life-cycle, drawing from data on resource requirements (Skelton, 2013). Although typically product- rather than process-centered, occasionally, LCAs are used to compute the life-cycle impact of production processes (e.g. World Aluminium (2017)). A detailed procedure for performing an LCA is outlined in Pennington et al. (2004), Rebitzer et al. (2004).

Since 1997, when the first international standard was published, interest in LCA has continued to soar (ISO, 1997). LCAs provide a meaningful way to capture the resource use ensued across the life-time of a product and as such, are now widely used as comparative product marketing tools in companies (Early et al., 2009, United Nations, 2016), and as environmental decision-support instruments in industry associations (World Aluminium, 2017, worldsteel, 2017) and policymaking (EC et al., 2012, EEA, 1997).

A controversial issue around all types of LCAs is their subjectivity. In *attributional* LCA, resource use across multi-product processes is arbitrarily allocated across multiple products, either weighted by cost, mass, volume, or embodied energy (Allwood and Cullen, 2009). Another source of subjectivity arises from the allocation of resource use to future product uses, i.e. if recycled

(Ayres, 1995). To resolve the first of these allocation issues, the concept of *system boundary expansion* or *consequential* LCA has been proposed, as described in ISO (2006). Boundary decisions, however, are still subjective, and if taken to their limit can end up including the whole world's impact for a single product. For the second, debates on how to address this are still ongoing.

Aside from this, LCAs are known to suffer from at least four other limitations. Firstly, LCA studies are often incomparable: the mismatch in system boundaries and assumptions considered makes it often impossible to compare environmental impacts across products. Secondly, they can be obscure: the data is often untraceable and the dearth a formal material accounting method challenges the detection of data errors (Ayres, 1995). Thirdly, they can be inaccurate and inconsistent: many companies rely on theoretical or average values computed in the literature, resulting in values that do not correspond to their specific case and in solutions that may not add up (Ayres, 1995). Lastly, they are product- rather than process-oriented: for manufacturers, this highly stylised analysis can provide a comparison between two similar products on environmental performance, but it rarely provides actionable insights on which processes to improve.

In practice this means, that when the same product is assessed by different LCA practitioners, the resulting impact studies can have different results. Consequently, policymakers and industry practitioners currently mistrust LCA, and foot-printing efforts are currently stalled for mainstream products. Based on interviews, Cooper-Searle et al. (2017) conclude that there are "many challenges with LCAs, which limit their appeal within government". Interviewees associated their lack of trust to the uncertainty in the results, the method's complexity, and the limited comparability.

2.2.3 Material and energy flow analysis

Material Flow Analyses (MFAs) – also known as Material and Energy Flow Analyses (MEFAs) if they include energy flows – are the backbone for a portfolio of scientific fields and applications, and one of the most widely used methods for analysing resource use in production processes. They are governed by the principle of energy and mass conservation, whereby all inputs and outputs at any given 'node' or process, must balance.

MEFAs are commmonplace in chemical engineering, where *flowsheeting* has been routine for decades. *Flowsheets* reveal the structure of a plant, including information on equipment models and resources. Their main purpose is to create detailed physical models of chemical processes in equilibrium (Denz et al., 2014) and thus balance energy and mass flows. When used as design tools, they allow the investigation of options for plant design. Alternatively, when used in simulations, they imitate real plant behaviour and ensure that embedded mathematical models are reconciled against real data (Dimian et al., 2014). Some examples of process simulation software are: Aspen HYSYS[4], Dymola, Unisim, CHEMCAD[5] and gPROMS[6] (Klemeš et al. (2011)).

The application of MEFA-type studies to address environmental concerns is more recent. Only after Leontief's development of Input-Output Analysis (IOAs) for the study of economies, did MEFA begin to gain popularity at highly aggregated levels, such as that of societies or the world (Brunner and Rechberger, 2004). At the country level, material flow accounts are now a routinely-updated part of national statistics (e.g. Japan (Ministry of the Environment, 2007), the UK (Office for National Statistics, 2017), and the EU (European Parliament and Council of EU, 2011, Eurostat, 2018)). Its prevalence can be largely ascribed to the IE community, who expanded its applicability and established it as one of the foundations of resource and waste management (Allesch and Brunner, 2015). In this context, the first *Practical Handbook on Material Flow Analysis* (Brunner and Rechberger, 2004), was a fundamental publication, later becoming the de facto introductory textbook for academic researchers.

These academic developments laid the groundwork that helped standardise methods for analysing resource use – a primary driver for popularising the adoption of specific practices within firms (Herva et al., 2011, IEA, 2012*a*). To this end, in 2007, UNIDO proposed the development of an international standard for energy management. Within four years, the ISO 50001:2011 had already been developed, and many countries worldwide began to implement programs to incentivise its adoption. Since then, ISO 50001 (and EN 16001) has been widely applied: 5267 certificates were granted within just the EU-28 in 2014 (Hirzel et al., 2016). The take-up of energy management standards is impressive, and yet these focus only on reducing energy carriers, with no mention of the energy savings available from reducing material use.

In parallel to the ISO 50001 developments, the practice of conducting MEFAs was standardised in 2011 as part of the Material Flow Cost Accounting (MFCA) ISO standard (ISO, 2011*a*). MFCA provides a necessary complementary framework: its value resides in the fact that, unlike con-

[4]http://www.aspentech.com/
[5]http://www.chemstations.com/
[6]http://www.psenterprise.com/gproms.html

ventional accounting methods, it is founded on a detailed mass balance, allowing the losses of every process involved to be quantified. MFCA facilitates the calculation of costs associated with material losses (i.e. waste streams or air emissions) alongside those associated with products. In doing so, it seeks to emphasise the economic benefits of improving ME.

As with LCA, MEFA can suffer from high data uncertainty and a lack of data availability, where values are often missing or conflicting. This complicates the reconciling of the data to ensure it adds up. Kopec et al. (2016) explain that the most common tactic to reconcile data is to qualitatively assess the relative confidence of the available sources, and "then either manipulat[e] the data quantity or choos[e] the data or data source that appears to fit best or that is most consistent". Other more sophisticated methods include: linear reconciliation methods (Brunner and Rechberger, 2004); constrained optimisations, mainly linear least-square methods (Kopec et al., 2016); Bayesian techniques (Lupton and Allwood, 2017*b*). Despite the possibility of errors, MEFA is still a valuable tool to trace the underlying physical flows of resources in industry.

2.2.4 Exergy Flow Analysis

Section 2.1.2 introduced the concept of exergy as a unit of measure to quantify RE, but little was said about how the exergy method (ExFA) is operationalised in practice. This section expands on the exergy metric and reviews how previous studies have used exergy to track resource use.

Any flow of energy or mass, with properties different from those in the environment, contains *exergy*. These property differences, or thermodynamic potentials, can be related to a resource's temperature, pressure, chemical composition, concentration, height, and velocity, among other aspects. Figure 2.4 depicts the various components of exergy, classified according to their carrier, energy level, origin and component. In metallurgical and chemical processes, the physical and chemical components of exergy carried by matter are most important. Physical exergy (B_{ph}) arises from the potential of a substance to do work due to differences *temperature* and *pressure* relative to the environment, whereas chemical exergy (B_{ch}) arises from the potential of a substance to do work due to its difference in chemical composition and concentration with respect to the environment. Besides these, some processes may transform mechanical (B_w) and electrical (B_e) exergies.

The main difference between mass- or energy-based approaches and exergy analyses is that the latter is based on the Second and First rather than solely on the First Law of Thermodynamics.

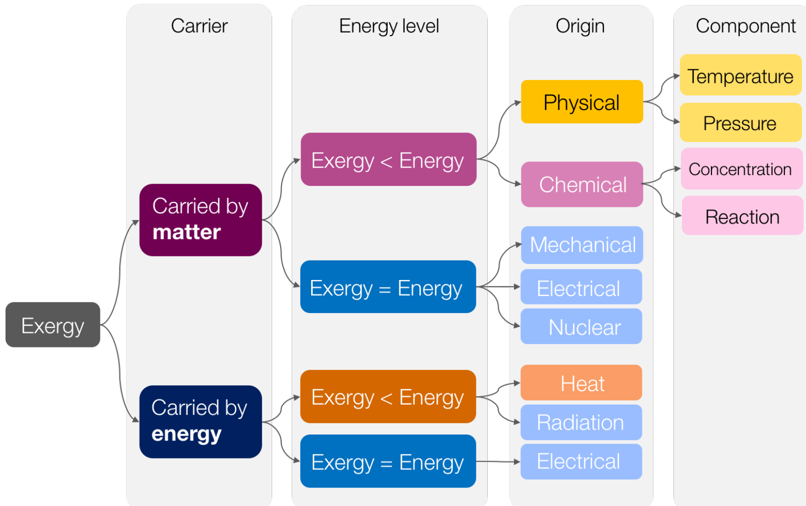

Figure 2.4: Classification of exergy flows; image modified from Marmolejo-Correa and Gundersen (2012).

The Second Law formalises the principle of entropy destruction, that is, that reactions have a direction, and as a result exergy inputs do not entirely become exergy outputs, some are lost as process irreversibilities. Hence, material and energy flows must balance, whereas exergy flows do not. Equation 2.4 illustrates the general expression for exergy flows across an industrial process.

$$B_{ch}^{\text{in}} + B_{ph}^{\text{in}} = B_{ch}^{\text{out}} + B_{ph}^{\text{out}} + \Delta B_w + \Delta B_e + B_{\text{losses}} \tag{2.4}$$

B_{losses} can be divided into two elements (as detailed in Equation 2.5): internal and external losses. *External losses* ($(B_{ch}+B_{ph})_{\text{wastes}}$)consist of the exergy associated with the waste streams or material losses that arise from production processes. For example, in the steel industry these include coal dust, blast furnace slag, flue gases or sludge. *Internal losses* (B_{irrev})reflect the entropy-generating or exergy-destroying mechanisms that result from the internal irreversibilities present in all real processes, i.e. heat transfer, friction, expansion or compression mechanisms.

$$B_{\text{losses}} = (B_{ch} + B_{ph})_{\text{wastes}} + B_{\text{irrev}}. \tag{2.5}$$

Ideally, exergy should be calculated from a reference equilibrium environment. This is straightforward for the physical component, where the temperature and pressure of the surroundings is taken as the datum, commonly 101.325 kPa and 298 K. For chemical exergies, defining a reference state is more challenging. In reality, this is not possible as the continuous transmission of solar radiation – both in terms of entropy and energy – shifts the natural environment away from thermodynamic equilibrium. To facilitate the calculation of chemical exergies in a so-called "non-equilibrium environment", Szargut (1957) defined the concept of *reference species*. Szargut's model assumes that there are three sinks, each of which is independent from the other: the atmosphere, the hydrosphere and the lithosphere (the crust). In all reactions, products *"must go to one of the three, depending on whether they are volatile (to air), soluble in water (to oceans) or neither (to earth's crust)"* (Masini and Ayres, 1996).

Several variations of the exergy approach have been developed. An example is *emergy*, a method which represents exergy in terms of one single form of energy, i.e. solar equivalents (Brown and Ulgiati, 2004, Liu, Geng, Wang, Sun, Ma, Tian and Yu, 2015). This method, however, is less relevant for material transformations. Another example is *exergoeconomics*, developed by Tsatsaronis (1993) and Lozano and Valero (1993). This evaluates the performance of energy systems by combining exergy and economic analysis. However, the more conventional, physical-based exergy analysis – presented in this section – has been the dominant theory.

As is the case with all methods, ExFAs are not without shortcomings. Hammond (2004*a*,*b*) argues that for accurately capturing the interrelated constraints imposed by the First and Second Laws of Thermodynamics, energy and exergy analyses must be performed side-by-side. Cooper, Hammond and Norman (2017) recently corroborated this argument by analysing the relationship between improvement potentials (in energy and exergy) and actual changes in efficiency. Here, the author explains that "the actual determinants of which metric (or both) are most helpful is highly sector specific and relates to the actual energy services consumed and the set of techno-economic considerations relating to them". For sectors with high-exergy-content products, however, the author concludes exergy analyses are preferred. Beyond this, the challenges discussed in Section 2.1.4 with regards to exergy as a *metric* also apply to the use of exergy as a *method*.

In this section, MEFA and ExFAs have been described as two distinct, alternative methods. This has so far been appropriate because the two methods analyse resource use from different perspectives – a result of their abiding by different thermodynamic laws. But there are foundational ways in which ExFAs rely on mass and energy flows. For industrial systems, it is sufficient to analyse the exergies contained in resource streams, that is, the chemical and physical components resulting from their composition, pressure and temperature. In these cases, only three extra steps are required to convert from an MEFA to an ExFA: (1) energy and material flows must be translated into chemical exergy flows through tabulated conversion factors; (2) the physical properties of streams – i.e. temperatures and pressures, or enthalpies and entropies – must be known to calculate their physical exergies; (3) the remaining difference between incoming and outgoing exergy flows must be computed to estimate process irreversibilities.

In assessing resource use, many researchers have found it beneficial to jointly conduct both MEFAs and ExFAs. Yang and Liu (2016) investigate the energy use in a natural gas purification system using a combined MFA-ExFA approach. The authors argue this allows them to evaluate and improve the system's performance "in both quantitative and qualitative perspectives". Wu, Wang, Pu and Qi (2016), Wu, Qi and Wang (2016) perform a combined energy, exergy and mass (based on carbon flows) analysis, which enables them to gain greater insights into the resource use and environmental performance of a Chinese steelmaking network, more so than any of the methods would provide in isolation. The approach facilitated the investigation of the link between exergy and CO_2 emissions, and the consideration of decarbonisation options where the two are unrelated, i.e. renewable energy. They conclude that a dashboard with energy, exergy and CO_2 emission indicators provides more complete support to help decision-makers optimise the production network.

The integration of ExFA and MEFA is still reasonably novel, and is yet to be applied across many sectors and at different scales. These two methods combined, and the ability to switch between mass, energy and exergy views, holds much promise for understanding the resource use in production plants.

2.2.5 Proposed method: Integrated material, energy and exergy flow analysis

This section has reviewed the main characteristics, strengths and weaknesses of four resource management methods: input-output, life-cycle, material and energy flow, and exergy analyses. These are summarised in Table 2.4 below.

The intention of this work is to trace resource flows and to analyse the associated efficiency with which production processes transform these. In this context, IOAs and LCAs are less appropriate. IOAs are better suited for highly-aggregated analyses of entire sectors or regions, whereas LCAs are designed to measure overall impact/environmental performance, providing limited insight into the underlying flows being transformed within production systems. Armed with this evidence, it

Table 2.4: Summary of advantages and limitations of reviewed methods (Allwood and Cullen, 2009, Ayres, 1995, Boustead and Hancock, 1979, Brunner and Rechberger, 2004, Bullard et al., 1978, Clift et al., 2015, Cullen, 2009, ISO, 2006, 2011*a*, Pennington et al., 2004, Rebitzer et al., 2004, Weisz and Duchin, 2006)

Tools	Advantages	Limitations
LCA	• Covers wide range of environmental impacts. • Considers direct and indirect resource use. • Standards exist (ISO 14044).	• Requires expertise and is time consuming. • Data collection is often opaque and inconsistent. • Allocation of resource use to products can be arbitrary. • LCA databases commonly contain secondary data. • Mainly product- rather than process-oriented.
IOA	• Considers direct and indirect resource use. • Attributes resources to countries and sectors.	• Difficulty in converting from monetary to physical units. • Lacking data, which is time consuming to collect. • Data is usually highly aggregated. • Data from surveys can be biased and inconsistent.
MEFA	• Ensures inputs and outputs add up. • Transparent; e.g. no need for allocations. • Standards exist (ISO 14051). • Process- rather than product-oriented. • Provides systems perspective.	• Lack of data can cause issues with data reconciliation. • Can be time-consuming. • Often considers flows only, overlooking stocks.
Exergy	• Helps identify real process inefficiencies. • Single framework for energy and materials. • Can consider direct or indirect resource use. • Process- rather than product-oriented.	• Complex methodology. • Can be time-consuming. • Less known to policymakers and production managers.

is concluded that conducting an integrated material, energy and exergy analysis is the best option to obtain a complete understanding of industrial resource use.

Although combining multiple methods can increase the workload, this extra effort is mitigated by the fact that an exergy balance can be derived from mass and energy balances using simple conversion factors, e.g. conversion factors transform energy and material flows into exergy, either in units of gigajoules of exergy per tonne (GJ/t) or gigajoules of exergy per gigajoules of energy (GJ/GJ). This shift between metrics can be facilitated by using matrices in Matlab or Python. The constructed exergy flows are then used to quantify the RE of processes, plants and sectors.

2.3 Application: improving industry's understanding of resource efficiency

Having identified integrated MEFA-ExFAs as the most promising approach to assess RE in industry, this section expands the review to include previous studies that have used any or a combination of these methods. As much has been written on assessing industrial efficiency, attempting to cover all previous studies would be in vain. This review, therefore, only covers a subset of relevant MEFA and ExFA studies – summarised in Table 2.5 (spread over two pages), and examined in Sections 2.3.1-2.3.3. In distilling these, particular focus was placed on five criteria, which are believed to be key for providing a holistic and transparent analysis of industrial resource use. Namely, whether the studies: (1) cover energy, materials, or both jointly; (2) analyse resource use at actionable time frames and (3) scopes (labelled temporal and spatial granularities); (4) are representative of plant operations (denoted as 'type of data used'); and (5) visualise resource flows using Sankey diagrams (SDs).

2.3.1 Resource coverage

Because improvements in industrial resource use have traditionally focused on increasing EE, most energy studies neglect ME measures, including over 15 of the studies listed in Table 2.5. Among this large volume of studies focusing on EE, those performed at the device level typically analyse: the optimisation of machine design (CECIMO, 2012), capacity and process parameters (Mori et al., 2011); the reduction of idle times (Schmitt et al., 2011); improvements in scheduling (Fang et al., 2011, Herrmann et al., 2011, Mouzon, 2008); improved monitoring and control (Verl et al., 2011); and the use of more efficient machine components (Thiede et al., 2012). Modern machines are generally supplied with electricity so many studies limit their analysis to electrical

Table 2.5: Summary of studies investigating the energy and/or material flows of industrial processes; (1) represents *Resource coverage*; (5) represents *Visuals*; aggreg – aggregated; E – energy; M – materials; theoretic. – theoretical.

Studies	(1)	(2) Temporal granularity			(3) Spatial granularity			(4) Type of data used				(5)
	E & M	Secs./ mins	Hours/ days	Months/ years	Device (s)	Plant/ site	Region/ sector	Model/ theoretic.	Control (sample)	Control (bulk)	Aggreg. stats.	SDs
Zhang et al. (2018)				✓			✓	✓				
Levi and Cullen (2018)				✓							✓	✓
Matino et al. (2017)				✓		✓		✓	✓			
Karali et al. (2017)				✓			✓	✓				
Gao et al. (2016)				✓		✓		✓				✓
Alvandi et al. (2015)						✓		✓				
Abele et al. (2015)		✓	✓		✓					✓		
Ghadimi et al. (2014)			✓			✓			✓			✓
Denz et al. (2014)			✓			✓		✓				✓
Viere et al. (2014)			✓			✓		✓				✓
Zschieschang et al. (2014)		✓				✓		✓				✓
Eberspächer et al. (2014)		✓	✓		✓			✓	✓			
Cullen and Allwood (2013)				✓			✓				✓	✓
Porzio et al. (2013)			✓	✓		✓		✓	✓			✓
Milford et al. (2013)				✓			✓				✓	
Cullen et al. (2012)				✓			✓				✓	✓
Kellens et al. (2012)				✓		✓					✓	
Thiede (2012)		✓	✓			✓		✓	✓			✓
CECIMO (2012)		✓	✓		✓			✓	✓			
Schmitt et al. (2011)		✓	✓		✓			✓				
Mori et al. (2011)		✓	✓		✓			✓	✓			
Fang et al. (2011)			✓		✓			✓	✓			
Milford et al. (2011)				✓			✓				✓	
Herrmann and Thiede (2009)		✓	✓		✓	✓		✓	✓			
Mouzon (2008)		✓	✓		✓			✓	✓			
Wohlgemuth et al. (2007)		✓	✓		✓	✓		✓				

Studies	(1)	(2) Temporal granularity			(3) Spatial granularity			(4) Type of data used				(5)
	E & M	Secs./ mins	Hours/ days	Months/ years	Device (s)	Plant/ site	Region/ sector	Model/ theoretic.	Control (sample)	Control (bulk)	Aggreg. stats.	SDs
Eisenmenger et al. (2017)	✓			✓			✓				✓	
Bühler et al. (2016)	✓						✓				✓	
Flórez-Orrego and de Oliveira Junior (2016)	✓		✓		✓	✓		✓				
Wu, Qi and Wang (2016)	✓			✓		✓					✓	✓
Khattak (2016)	✓			✓	✓	✓		✓	✓		✓	✓
Valero et al. (2015)	✓			✓			✓				✓	✓
Fröhling et al. (2013)	✓	✓				✓			✓			
Valero et al. (2012)	✓			✓			✓	✓				
Gutowski et al. (2009)	✓			✓	✓			✓			✓	
Ayres et al. (2011)	✓			✓			✓				✓	✓
Ostrovski and Zhang (2005)	✓		✓		✓			✓				
Kirova-Yordanova (2004)	✓		✓			✓		✓				✓
Petela et al. (2002)	✓		✓		✓			✓				
Costa et al. (2001)	✓			✓		✓					✓	
Ayres and Ayres (1999)	✓			✓			✓				✓	✓
de Beer (2000)	✓			✓		✓			✓			
Michaelis et al. (1998)	✓			✓			✓				✓	
Nakicenovic et al. (1996)	✓			✓			✓				✓	
Masini and Ayres (1996)	✓			✓			✓				✓	✓
Bisio (1993)	✓			✓	✓			✓				✓
Wall and Ran (1990)	✓			✓			✓				✓	✓
Szargut et al. (1988)	✓			✓		✓		✓			✓	✓
Akiyama and Yagi (1988)	✓			✓		✓					✓	
Wall (1988)	✓			✓		✓			✓		✓	

energy use in machining and peripherals (Radgen and Blaustein, 2000, Zein et al., 2011). Where several processes are involved, EE analyses investigate technical measures such as: installing a multi-machine heat recovery system (Allwood et al., 2012); supplying an internal heating network (Duflou et al., 2012); improving the dimensioning of supporting processes (Duflou et al., 2012).

At the level covering multiple sites, studies typically analyse industrial symbiosis, that is, the sharing of resources across sites. Three main types of exchanges are commonly seen: by-product reuse, sharing of utilities and a joint supply of services (Chertow, 2007). To analyse these, the following methods are employed: pinch analysis, originally developed by Flower and Linnhoff (1979); the optimisation of water networks (Olesen and Polley, 1996); integration of utility systems (Kim et al., 2010) and by-product exchanges (Kastner et al., 2015). Here, energy and material flows are often both covered, but are typically analysed separately. There is a limited number of examples of industrial-symbiosis studies that use exergy (e.g. Valero et al. (2012)).

Among the few studies that analyse the energy-saving potential of ME, plant- or supply-chain-level applications have frequently focused on either measuring material yields in mass, e.g. (Gao et al., 2016, worldsteel, 2009) or on quantifying cumulative savings, e.g. as embodied energy or emissions (Milford et al., 2011, 2013). Conventional energy studies and recent analyses of ME fail to quantify how efficiently industry uses both energy *and* materials (the combination of which is denoted here as *resource efficiency*). In doing so, these studies overlook the fact that in complex industrial systems, energy and material flows are interrelated and often interchangeable.

Most of the sector- and plant-level exergy studies were performed over two decades ago. Toward the end of the 1980s, armed with the species reference model developed by (Szargut et al., 1988) many researchers began to investigate complex industrial systems. At this point, exergy was mainly used as a tool to identify process losses and to quantify improvement potentials (Bisio, 1993, Brodyansky et al., 1994, Masini and Ayres, 1996, Szargut et al., 1988, Wall, 1988) or as a resource accounting mechanism (Ayres and Ayres, 1999, Costa et al., 2001, Wall and Ran, 1990). Before this time, exergy had primarily been used in the analysis of energy systems for its ability to distinguish between high-grade mechanical or electrical work and low-grade heat (Carnot and Thomson, 1897, Gibbs, 1873, Kotas, 1985).

Fewer recent studies were found that analyse integrated resource use in units of exergy. Among these, exergy analyses of energy-intensive material producers have been applied[7]:

- At the country level, for the US (Ayres et al., 2011), the EU (Serrenho et al., 2014, Valero et al., 2015), Austria (Eisenmenger et al., 2017), China (Zhang et al., 2012) and the UK (Cooper, Giesekam, Hammond, Norman, Owen, Rogers and Scott, 2017);

- For specific technologies, such as, iron blast furnaces (Liu, Chen, Qin and Sun, 2015, Petela et al., 2002), steel electric furnaces (Hajidavalloo and Dashti, 2010) or direct-reduction iron-making processes (Kadrolkar et al., 2012), smelting processes (Ostrovski and Zhang, 2005), and cement-making (Madlool et al., 2012).

- Across entire facilities, including steel-making (Wu, Wang, Pu and Qi, 2016), ammonia (Flórez-Orrego and de Oliveira Junior, 2016) and acetic acid plants (Wang et al., 2007).

2.3.2 Scope and data: temporal and spatial scales

Table 2.5 reveals that full MEFAs are typically conducted to track material or energy flows at aggregated system levels, primarily over entire regions or sectors on a yearly basis. For example, Cullen and Allwood (2013), Cullen et al. (2012), Leal-Ayala et al. (2015) analyse the mass flows through the steel, aluminium and tungsten supply chains. Van Ewijk et al. (2017) and Levi and Cullen (2018) performed similar tasks but for the paper industry, and the chemicals and petrochemicals sector respectively. Investigating the use, and more specifically the waste of materials, remains a key application of MEFAs. This was confirmed in a comprehensive exercise by Allesch and Brunner (2015), who reviewed 83 MFA studies applied to waste management since 1992.

Among the highly-aggregated exergy studies, Masini and Ayres (1996) analyse the exergy flows for five key metal sectors in the US, whereas Michaelis et al. (1998) analyse the exergy flows of the UK's steel industry. Wall (1988) and Wall and Ran (1990) investigate the exergy flows of the Swedish and Japanese societies, and Eisenmenger et al. (2017) assess those for Austria.

At plant-level, where daily operational decisions are made, MEFAs are mostly applied to simulations, theoretical data, or aggregated data collected in annual reports. For example, Ghadimi et al. (2014) devised a methodology to analyse the resource use of manufacturing plants, where the MEFA is conducted using theoretical estimations, and validated using process modelling and

[7] Reviews of exergy analysis applied to industrial processes can be found at Luis and Van der Bruggen (2014), Madlool et al. (2012).

sub-metering. Fröhling et al. (2013) introduced a framework to "improve network-wide resource efficiency", which is based on thermodynamic models and which can be used for scenario modelling.

Similarly, Zschieschang et al. (2014) and Denz et al. (2014) coupled both a *flowsheeting* simulator (CHEMCAD) and a simulation-based optimisation commercial software to the Umberto® tool. This was used to analyse and optimise the resource flows in chemical plants. By linking chemical models to MEFAs, they are able to investigate the modification of process or equipment design and to give plant managers detailed information on "the technical feasibility and chemical causality" behind resource inefficiencies. Two other examples of plant- and device-level studies that use process models are Wohlgemuth et al. (2007) and Alvandi et al. (2015). Smith and Ball (2012) and Despeisse et al. (2013) developed more general guidelines to link environmental considerations to conventional operational procedures. Here, the authors designed a framework that relies on a combination of multiple data sources, including annual financial and physical data, as well as control data samples and models.

This same trend is observed across ExFA studies. In the late 1980s and 1990s, ExFAs performed prior to the 'big data' era used either yearly-averaged consumption data or theoretical calculations, both of which involved significant effort to complete. Examples of highly-aggregated studies include work by Costa et al. (2001) and Masini and Ayres (1996), where the exergy efficiency of an indicative steel plant and the US steel industry are respectively investigated. Early studies based on modelled or theoretical data include studies by Szargut et al. (1988) (for metallurgical and chemical industries), de Beer (2000) (for a reference steel plant) and or Brodyansky et al. (1994) (on chemical plants and reactors).

More recent examples of modelled or yearly studies are work by Flórez-Orrego and de Oliveira Junior (2016) and Kirova-Yordanova (2004) (for an ammonia simulation), and by Wu, Wang, Pu and Qi (2016), Wu, Qi and Wang (2016) (for a Chinese steel network) respectively. To facilitate the detailed simulation of exergy flows in chemical plants, which is currently time-consuming and cumbersome, Ghannadzadeh et al. (2012) designed a method to integrate exergy calculations into chemical process models (e.g. CHEMCAD or ProSimPlus®). There are only a few ocassions where control data been used to validate resource simulations. For example, Khattak (2016) combines control data samples, experiments and models to analyse the resource use of a sugar factory and a manufacturing plant. Yet, none of the above ExFAs have used control data to assess plant-level resource use, and therefore these studies fail to portray a realistic picture of the resource use variations that take place during actual operations.

The absence of MEFA and ExFA studies based on control data from real operating plants could result from multiple factors. Firstly, evidence suggests that control data is not always accessible for researchers – this is often highly sensitive for companies. To compensate for this, many studies substitute real metered data with alternative methods to estimate energy use (e.g. Dietmair and Verl (2009), Kara and Li (2011), Thiede (2012)). Ghadimi et al. (2014) and Thiede et al. (2012) roughly estimate machine energy consumption using the nominal power use of machines and estimates of machine load factors. Kara and Li (2011) propose using empirical modeling, whilst Dietmair and Verl (2009) employ state-based simulations.

Secondly, the limited use of control data in the analyses of resource use results from the fact that metered data has, in the past, been used mainly to address other operational aspects. The main applications have been: the diagnosis of faults (Ge, 2017, Hoskins et al., 1991, Russell et al., 2000, S.X. Ding, 2014), and the optimisation of product quality (Farooq et al., 2017, Rangaiah and Kariwala, 2012) or cost (Brunke and Blesl, 2014, Tripathi et al., 2013, Yang and Lee, 2010). Analysing control data for these applications has delivered significant productivity gains in industrial facilities. Much could be learned from the success of these examples, and applied to the use of control data for assessing plant RE.

Today, falling prices of electronics and the proliferation of sensors make it easier to gather previously-unavailable data on real-time resource use. Recently a number of academic-industry-policy consortia have been set-up to do exactly this – to investigate the use of control data as a means of measuring the efficiency of production plants in real time. Examples include, the MORE project (MORE, 2017), which focuses on conducting real-time MEFAs for the chemical industry, and the COCOP project (under the SPIRE initiative (SPIRE, 2017)), which performs optimisations of the plant operations for the copper and steel sectors (COCOP/SPIRE, 2017). These studies continue to analyse energy and materials in isolation and to report separate indicators.

2.3.3 Visuals: improving clarity

A key component of this thesis is to understand how the use of resources and the efficiency of the processes that transform them are communicated to operators, decision-makers and experts. Data visualisations have proliferated in industry and academia as powerful tools for enabling analysis, facilitating access to a wide audience, and improving the capacity to decipher large volumes of data. More specifically, in the context of energy and material use analyses, Sankey diagrams (SDs) are one of the most prevalent visualisations. The history of SDs and their relevance to the Industrial Ecology community has been reviewed in the illustrious study by Schmidt (2008).

SDs describe a system using arrows of thickness proportional to their flow magnitude, and are often used for presenting the results of MEFAs (and ExFAs), allowing the balancing of inputs and outputs to be clearly observed. Figure 2.5 portrays the schematic of an archetypal one. SDs depict a network that is mathematically formulated by *nodes* (e.g. processes) that are linked by *edges* (e.g. material flows). Typically in the form of static representations, they provide a useful snapshot of a system's structure and scale at a given time. Horizontal slices (y-axis) are often used to classify the types of energy or material sources (British department for Business, Energy & Industrial Strategy, 2012, Cullen and Allwood, 2010, IEA, 2016) – as in Figure 2.5. Vertical slices are instead, commonly used to represent energy or material conversion stages.

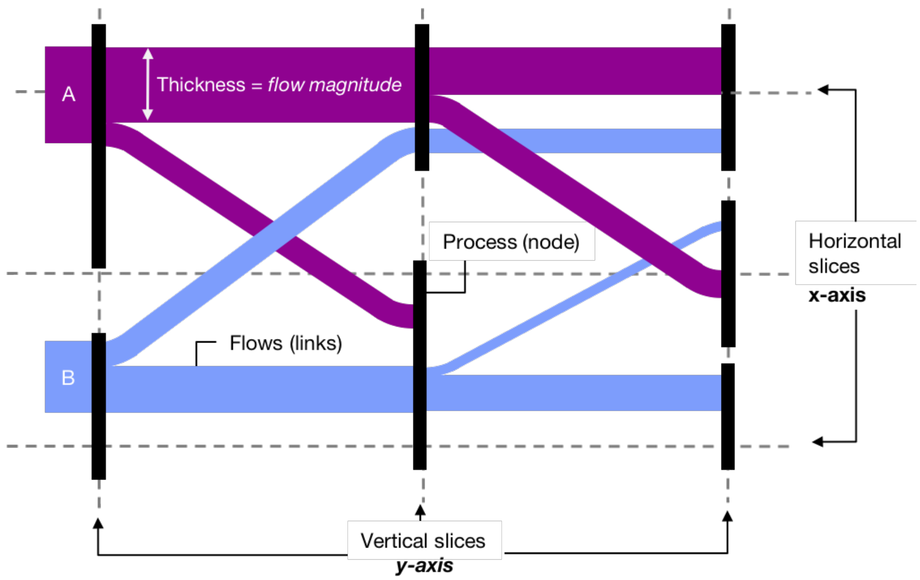

Figure 2.5: Schematic of a Sankey diagram; A and B stand for two different types of resources

A perusal of the studies in Table 2.5 reveals that among industrial resource studies, SDs are commonly used to visualise yearly flows of both individual and combined resources at regional or sectoral levels. Some academic examples include: the global energy flows from primary to final services, measured in exergy (Cullen and Allwood, 2010); the mass flows for the five most energy-intensive material producers – i.e. steel (Cullen et al., 2012), aluminium (Cullen and Allwood, 2013), plastics (Levi and Cullen, 2018), cement (Gao et al., 2016) and paper (Van Ewijk et al., 2017). Outside of academia (not included in Table 2.5), international expert institutions such as the IEA (2016), the IPCC (Fischedick et al., 2014), or Eurostat (2016) now use them to represent energy flows and CO_2 emissions across regions.

Although a less conventional application, evidence suggests that SDs are beginning to make their way into plant-level analyses. These are mostly used in combination with well-established simulation software. Three examples of hybridised tools that use SDs were found in the literature. First, the work by Denz et al. (2014), Zschieschang et al. (2014) and Viere et al. (2014) where the Umberto® tool is coupled to a chemical engineering flowsheeting model. As part of a wider project, the authors have already applied this to several industrial case studies, including a tungsten manufacturing plant and a barrium sulfate plant. Second, based on work by Thiede (2012), Li et al. (2017) recently devised a tool to combine the method of energy or environmental value stream mapping with a Sankey-building software. Third, Ghadimi et al. (2014) combine state-based simulations of processes with Umberto®, and use this to investigate the case of an aluminium flat-rolling facility. No examples were found of studies that use Sankey diagrams to visually map the integrated resource use (in exergy) of real plant operations from control data.

An advantage of SDs is their ability to portray different information for a range of applications and purposes. To this end, Soundararajan et al. (2014) review ways in which various authors have implemented these. This flexibility in the design of SDs, however, has been primarily limited by the software available to construct these. Examples include: e!Sankey (IFU, 2014), S.Draw8 [8] and SankeyMATIC [9], to name but a couple (a more extensive list of Sankey drawing software can be found at *http://www.sankey-diagrams.com/sankey-diagram-software*). Reportedly, these software are missing three key features, which undermine the use of SDs in production plants: the ability to depict data dynamics, that is, to portray time-series data; the ability to neatly show data at different aggregation levels; and of easily switching units, i.e. from mass to energy, or to CO_2 emissions.

Recently, Lupton and Allwood (2017*a*) developed an open-source, Python tool named floWeaver (Lupton, 2017) in order to overcome these limitations. The authors devised a new software that makes it easier to: input data in almost any format; define multiple flow groupings according to

[8] http://www.sdraw.com/en/index.html
[9] http://sankeymatic.com/

different criteria; and automatically produce multiple SDs for a given structure, thereby facilitating the illustration of time-series data. These new developments are likely to make SDs more appealing to map time variations, common in the analyses of plant-level production operations.

2.3.4 Proposed application: integrated plant-level analysis from control data

Having detailed information on resource use at actionable time-scales and scopes (i.e. close to real-time) is key for encouraging industry to improve RE. With the soaring capabilities of sensors, the decline in the price of electronics and the improvements in data analytic methods, there is an opportunity to extract available control data to construct these tools and methods. This could help reduce the amount of time, expertise and money needed to conduct energy and material audits – currently viewed as problematic by heavy industries (EC, 2012*a*). Yet none of the ExFAs in Table 2.5 exploit this potential, and an integrated picture of energy and materials during real-time operations is yet to be explored.

To close this gap, it is proposed to create a method that helps plant managers make on-site decisions about RE, and which capitalises on three tools: (1) the well-established exergy method to combine the analysis of energy and materials; (2) the use of control data collected in real-time by plant meters; (3) Sankey diagrams to transparently depict combined resource flows for decision-makers. Close links with industrial partners – Emerson (the PhD sponsor) and steel producers – provides a unique opportunity to access and exploit the value residing in control data.

2.4 Policies: the energy-saving potential of material efficiency

Resource efficiency – measured using exergy to integrated materials and energy – has been shown to be a compelling avenue of research worth pursuing. Yet, the apparent under-exploitation of ME in industry and the absence of political support, suggests that the newly developed RE tool is unlikely to be widely adopted without the support of effective policies. Therefore, in this next section, a review of the success of policies that shape industrial resource use is conducted.

The section is divided into three. First, an overview of EU policies in the areas of resources, energy and climate – all of which could incentivise ME – is provided (Section 2.4.1). Second, the body of literature investigating policies around the issue of ME are reviewed (Section 2.4.2). Third, a selection of policy theories that could be used to explore the formation of policy agendas in the EU is studied (Section 2.4.3).

2.4.1 EU policies regulating resource use and emissions in heavy industries

The EU has a breadth of policy instruments at hand to incentivise and enforce the reduction of energy and material use (the combination of which is denoted as 'resources') in heavy industries. The policy pyramid approach (Reinaud and Goldberg (2011)) is used to characterise the EU policy landscape shaping resource use in heavy industries. This method divides policies into three groups: top-level, effort-defining policies; supporting measures that encourage the delivery of defined efforts; implementation tools that help operationalise these. Figure 2.6 depicts a summary of the pyramid for the EU policies related to energy and material use. Currently, four policy areas can influence this, including: (1) the Energy Union; (2) Directorate General (DG) for Energy (EC (2006, 2011*b*, 2014*b*)); (3) DG Environment (EC, 2011*c*, 2014*d*); (4) DG Clima.

Starting at the top of the pyramid, there are three effort-defining policies for heavy industries, all motivated by the need to reduce energy and emissions: the 2020 climate and energy package; the 2030 climate and energy framework (EC (2008*c*, 2014*a*)); the Energy Union. These impose two targets for 2020 and 2030: one on emissions (20% and 40% reduction) and one on energy use (20% and 27% reduction). These targets are economy-wide and do not impose sectoral reductions.

The ETS is the main supporting measure for these three effort-defining policies (EC (2009)). Beyond this, the remaining regulatory mechanisms only provide limited support: (1) Eco-design directive, which targets energy-consuming devices (but only up to a specific size); (2) Energy Efficiency Directive (EED), which enforces energy auditing in large enterprises (Article 8); (3) IED, which defines best available techniques for installation permits (EC (2010)); (4) the Raw Materials Initiative, which aims to improve the market for secondary materials (EC (2008*b*)); (5) waste legislation, now covered by the CE package (EC (2015*a*)); (6) the strategy for a Digital Single Market (EC, 2016*a*); (7) the renewed industrial strategy (EC, 2017*b*). While the Digital Single Market and the industrial strategies do not provide additional objectives for reducing industrial resource use, these do facilitate the collaboration of industry firms across supply chains – mainly through information sharing platforms and financial support.

At the bottom of the pyramid, the remaining instruments mainly provide the foundations from which longer-term progress can be initiated: guidelines, monitoring frameworks (e.g. RE and Raw Material scoreboards (EC (2016*b*), Humphris-Bach et al. (2016))) and research funding (EC (2017*e*)). Figure 2.6 depicts that a number of implementation tools are available to facilitate

Figure 2.6: Pyramid for EU's climate, environment and energy policies related to energy-intensive industries; colours indicate the policy area in charge of the given policy.

stakeholder participation, including: training programmes, information platforms, impact assessments and public consultations. Table 2.6 shows more details about the policies included in the policy pyramid, within the period between 2006 and 2017. Here, additional information on the policy area, title, number, lead service (i.e. DG in charge), and type of policy action is provided. Policies are listed according to the date in which they were published.

Table 2.6: List of relevant EU policies (2006-2017). *Accom. doc.* – Accompanying document; *Assess.* – assessment; ENV. – Environment.

Number	Area	Title	Lead service	Type of action	Date	Level
COM(2005) 666 final	Waste	Thematic strategy on prevention and recycling of waste	DG ENV.	Decisions	2005	SM
COM(2006) 545	Energy	Action Plan for Energy Efficiency	DG ENERGY	Decision	2006	SM
2008/98/EC	Waste	Waste Framework Directive	DG ENV.	Directive	2008	SM
COM(2008) 30 final	Energy, climate	20 20 by 2020 Europe's climate change opportunity	Commission	Decision	23/01/08	ED
COM(2008) 397 final	Energy, resources, climate	Sustainable Consumption & Production and Sustainable Industrial Policy Action Plan	DG ENV.	Decision	16/07/08	SM
No 1099/2008	EE	Energy Statistics	DG ENERGY	Regulation	25/10/08	IT
COM(2010) 2020 final	Growth	Europe 2020; strategy for smart, sustainable, inclusive growth	Commission	Decision	03/03/10	ED
COM(2011) 109 final	EE	EE Action Plan	DG ENERGY	Decision	2011	SM
COM(2011) 13 final	Waste	Thematic strategy on prevention and recycling of waste	DG ENV.	Report	19/01/11	SM
COM(2011) 112 final	Climate	Low-carbon economy roadmap to 2050	DG CLIMA	Decision	08/03/11	SM
SEC(2011) 288 final	Climate	Low-carbon economy roadmap to 2050	DG CLIMA	Impact assess.	08/03/11	IT
COM(2011) 571	Resources	Resource efficiency roadmap	DG ENV.	Decision	20/09/11	ED
SEC(2011) 1067 final	Resources	Analysis associated with the Roadmap to a RE Europe	DG ENV.	Accom. doc.	20/09/11	SM
SEC(2011) 1565 final	Energy	Energy 2050 roadmap (scenario analysis)	DG ENERGY	Impact assess.	15/12/11	IT
2012/27/EU	EE	EED (Energy efficiency directive)	DG ENERGY	Directive	25/10/12	SM
COM(2013) 762 final	EE	Implementing the EED- Commission guidance	DG ENERGY	Accom. doc.	06/11/13	SM
1386/2013/EU	Energy, resources, climate	7th Environment Action Programme (EAP)	DG ENV.	Decision	20/11/13	SM
SWD(2014) 211	Resources	Analysis of an EU target for Resource Productivity	DG ENV.	Accom. doc.	2014	SM

Number	Area	Title	Lead service	Type of action	Date	Level
COM(2014) 15 final	Energy, resources, climate	Energy and climate policy framework from 2020 to 2030	DG CLIMA	Decision	22/01/14	ED
ISBN: 10.2779/68165	Energy, resources, climate	7th Environment Action Programme (EAP)	DG ENV.	Informative report	01/03/14	SM
SWD(2014) 209 final	Waste	Ex-post evaluation of Five Waste Stream Directive	DG ENV.	Accom. doc.	02/07/14	IT
COM(2014) 398 final/2	Resources	Circular economy action plan	DG ENV.	Decision	25/09/14	SM
SWD(2014) 206 final/2	Resources	Progress report on the Roadmap to a RE Europe	DG ENV.	Accom. doc.	25/09/14	IT
COM(2015) 80 final	Energy	Energy Union package	Energy Union	Decision	25/02/15	ED
SWD(2015) 135 final	Climate	Modifications to ETS beyond 2030	DG CLIMA	Impact assess.	15/07/15	SM
COM(2015) 572 final	Energy	Energy Union Roadmap	Energy Union	Decision	18/11/15	ED
P8 TA(2015) 0460	Energy, resources	Sustainable European industry of base metals	Parliament	Resolution	16/12/15	SM
COM(2016) 110 final	Climate	The Road from Paris	Energy Union	Decision	02/03/16	SM
SWD(2016) 110 final	Industry	Digitising European industry, Digital Single Market	Commission-wide	Accom. doc.	19/04/16	SM
P8 TA(2016) 0293	EE	Implementation report of the EED	Parliament	Resolution	23/06/16	SM
P8 TA(2016) 0383	Climate	Implementation of Paris Agreement	Parliament	Resolution	06/10/16	SM
COM(2016) 761 final	EE	Amending the EED	DG ENERGY	Decision	30/11/16	SM
COM(2016) 759 final	Energy, climate	Proposal for integrated governance system	Energy Union	Decision	30/11/16	SM
SWD(2016) 405 final	EE	Amendment to the EED	DG ENERGY	Impact assess.	30/11/16	IT
COM(2016) 860 final	Energy, resources	Clean Energy for All Europeans	Energy Union	Decision	30/11/16	ED
COM(2017) 33 final	Resources	Implementation of CE action plan	DG ENV.	Decision	26/01/17	SM

Visualising these policies in terms of the coverage of the main ME and EE measures across existing EU energy, climate and environmental policies reveals the image in Figure 2.7. Policies led by DG Environment are shown in green, whereas those led by DG Energy are shown in light blue, those driven by DG Growth are depicted in orange, and those controlled by DG Clima are portrayed in purple. Commission-wide initiatives are illustrated in dark blue. Individual ME and EE measures are identified at the top; policies are positioned across the measures they can have an impact over.

Figure 2.7 shows that only a selection of ME strategies are currently covered by DG Environment, with little support offered for measures such as light-weighting or improving yields. Energy policies target primarily heating, cooling, waste heat, and fuel switching. The ETS (the cornerstone of climate policies), which theoretically promotes the adoption of any low-carbon measure, has shown to provide limited incentives to adopt ME (Aidt et al. (2017), Neuhoff et al. (2016), Skelton and Allwood (2017)). In parallel, BREFs (Best Practice Reference Documents) target hazardous emissions, rather than CO_2, and only cover the boundaries of production facilities, limiting the extent to which they can regulate upstream environmental impacts and outgoing materials – where gaps for ME improvements lie (Environmental Protection Agency (2016)).

2.4.2 Analyses of EU-level material efficiency policies

Section 2.4.1 shows that ME cuts across multiple Directorates and policy objectives. As such, it is unsurprising that the literature on ME policies is similarly diverse. The reviewed studies, summarised in Table 2.7, are grouped into four categories, those which investigate: (1) the suitability of ME indicators; (2) the barriers to ME; (3) the analysis of policy agendas; (4) options for and impacts of policy interventions. To follow is a discussion of the most relevant papers from Table 2.7, which are highlighted with asterisks (*).

Most studies that analyse the potential pathways to a resource-efficient European industry, have considered RE as an end in itself, rather than as a tool for achieving energy and emission goals. One noteworthy example is the large-scale, EU-funded POLFREE (POLicy options For a Resource-Efficient Economy) project. As part of this, Domenech et al. (2014) explored the policy options available to pursue RE across all economy sectors in the EU. The authors argue that, given the multi-faceted nature of RE, a cross-Directorate policy mix is needed. This rigorous and detailed analysis of the policy instruments available to improve RE is valuable for stakeholders interested in pursuing RE as an economic and environmental tool, but provides limited insights into the barriers and pathways to reshape RE into an energy and climate instrument.

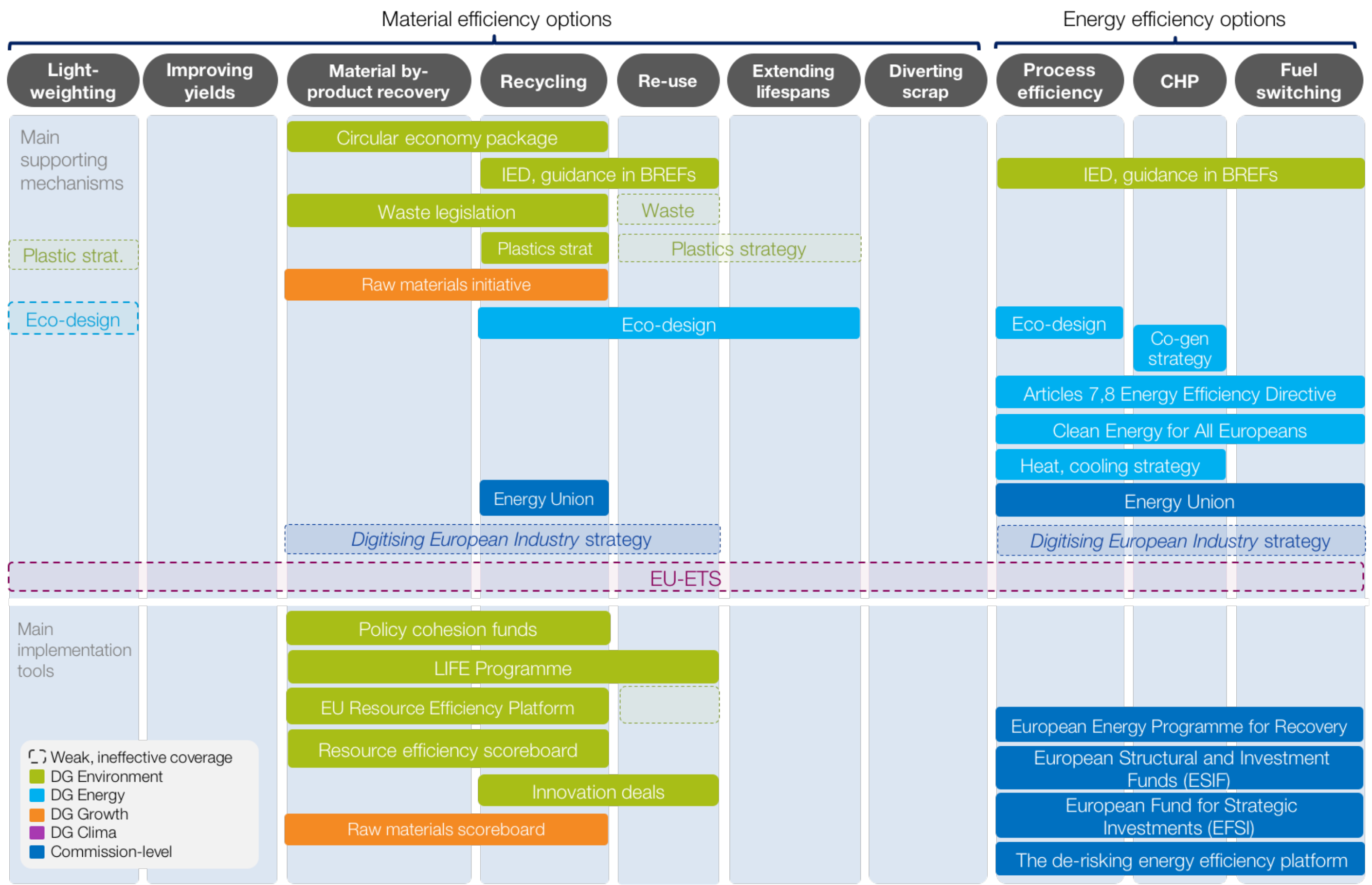

Figure 2.7: Overview of supporting mechanisms influencing individual ME and EE options

Table 2.7: Selection of papers analysing EU material efficiency policies

Author (date)	Description	Aim (to explain...)
Indicators analysis		
Shahbazi et al. (2017)	Identified ME indicators in manufacturing using bottom-up approach.	Classification of indicators
Etkins and Hughes (2016)	Reviews RE indicators in industry and policy	Classification of indicators
Valero et al. (2015)	Proposes a new thermodynamics-based, macro-level ME indicator	Proposal of new indicator
Huysman et al. (2015)	Macro-level RE indicators	Classification of indicators
Mudgal et al. (2012)	Evaluation of RE indicators available for target setting at the EU-level	Evaluation of indicators
Neuhoff et al. (2009)	Provides a theoretical analysis: reviews existing climate indicators and explores suitability.	Critical assessment of indicator choices
Barriers and drivers		
Circle Economy (2017)	Investigates levers to enable transition to a low-carbon circular economy. Uses a legal policy-mapping method and stakeholder consultations.	Drivers and proposals to move forward
Dunant et al. (2017)	Establishes cost of steel reuse through interviews across UK construction chain and proposes strategies to enable steel reuse at scale	Barriers/drivers in construction
Etkins and Hughes (2016)	Summarises state-of-the-art RE policies and measures across economy.	Best practices, barriers
OECD (2016)	Suggests key actions to improve the resource efficiency policies to be implemented through the G7 Resource Efficiency Alliance	Overarching policy analysis; guidance
Skelton (2013)	Multi-regional input-output analysis to analyse incentives for supply-chain collaboration to improve yield and light-weighting in steel sectors.	Barriers/drivers for steel
Policy agendas		
Cooper-Searle et al. (2017)*	Investigates why ME remains a small part of the UK policy agenda to reduce GHG emissions from cars (using multiple streams framework)	Barriers/drivers
Proposal of policy interventions		
Scott et al. (2017)*	Performs a policy assessment of Eco-design and proposes the inclusion of embodied emissions in product regulations and standards.	Provide solutions to incentivise ME in Eco-design
Aidt et al. (2017)*	Discusses economic theory and performs econometric analysis of policies targeted at reducing material demand	Provide solutions to incentivise ME
Skelton and Allwood (2017)*	Investigates whether high carbon prices would be sufficient to incentivise ME, through micro-economic theory and a policy analysis.	Provide solutions to incentivise ME in EU-ETS
Mehlhart et al. (2016)*	Investigates synergies of ME and identify energy savings potential from ME improvements across multiple sectors.	Technical potential and policy improvements
Neuhoff et al. (2016)*	Performs a policy assessment of EU-ETS and proposes a consumption charge as a pricing mechanism in this policy instrument.	Provide solutions to incentivise ME in ETS
Domenech et al. (2014)*	Investigates barriers to RE and models scenarios of future policy interventions (POLFREE project)	Proposes policy mixes and governance models

Mehlhart et al. (2016) – in a report commissioned by DG Environment – investigated the energy-saving potential of ME, proposing this as an option to achieve energy targets. The report identifies barriers for specific ME measures, and proposes interventions to tackle these. Two examples relevant to heavy industries are provided – the European ferrous sector and industrial symbiosis – for which high-level changes are proposed. For example, for the ferrous sector, they estimate that 265 PJ/yr can be saved by increasing steel recycling and propose general policy measures such as: demand-pull instruments to improve the cost-effectiveness of ME measures, or stimulating benchmarking to encourage technological diffusion.

Scott et al. (2017) conduct a similar analysis, and investigate ways in which EU product-specific energy efficiency policies could be extended to include aspects on material and product use in all sectors: transport, industry and buildings. The authors argue that product-based regulation, such as Eco-design, are more effective at integrating "material efficiency strategies within climate change mitigation policy". They contend that product policies can be more readily extended to include embodied emissions, which currently remain unaddressed in the ETS. This study provides an insightful contribution to the debate on the improvement of EU climate policies, re-emphasising the importance of incorporating embodied emissions.

Several studies analyse the economic aspects preventing the adoption of ME. Skelton (2013) investigates the barriers to both the uptake of ME in industry and its promotion within the policy community. In doing so, the author outlines the rationale for policy interventions and options available to policymakers. More recently, Neuhoff et al. (2016) and Skelton and Allwood (2017) specifically analysed the ETS. Neuhoff et al. (2016) propose the inclusion of a consumption charge, and Skelton and Allwood (2017) suggest the removal of distortive taxes and the implementation of carbon leakage exemptions that "are independent of the embodied carbon".

Cooper-Searle et al. (2017) use a public policy lens to look at the processes underpinning climate policy formation and gain insights into why ME is not a bigger part of the UK climate agenda. The authors used the Multiple Streams Framework (MSF) developed by Kingdon (1984) as a conceptual framework to structure their analysis. Valuable evidence is collected from interviews with stakeholders. These facilitate the portrayal of policymakers' and practitioners' views on ME, as well as their attitude towards potential interventions. Results suggest that many factors prevent policymakers from perceiving ME as an appealing option to reduce GHG emissions, including:

the absence of data and "modelling evidence on potential emissions savings, technical feasibility, costs of implementation and potential economic co-benefits"; the absence of united industry support; and the limited spare capacity available to British policymakers.

Neuhoff et al. (2016) and Skelton and Allwood (2017) provide valuable quantitative analyses of the economic and financial factors affecting the adoption of ME in industry. However, these studies largely focus on the ETS and also provide limited insight into the political and behavioural aspects taking part. In contrast, Mehlhart et al. (2016) examine the potential synergies between RE and EE policies in industry, but do not consider the complete policy landscape shown in Figure 2.6 or the interactions with other areas such as the ETS. Scott et al. (2017) analyse EE product policies and conclude these are the most promising for addressing the existing emissions reduction gap. This work, however, is based on a literature analysis and provides no empirical evidence. None of the above studies provide an explanation for the lack of attention given to ME in EU-level energy/climate policies, but rather use this as their motivation. The only example of a study assessing empirically the reasons behind the lack of attention given to ME in climate policies is that by Cooper-Searle et al. (2017). Yet, this focuses on the UK's automotive sector and thus provides limited insight into the agenda-setting process for strategies at EU-level.

2.4.3 Public policy theories: explaining the agenda-setting process

The complexity of policy formation has resulted in the development of a rich volume of conceptual frameworks that seek to explain why specific issues do or do not become part of specific policy agendas. These provide researchers with a simplified yet systematic method for understanding the behavioural, institutional and political factors that affect the agenda-setting process. This section reviews three policy frameworks that are appropriate to analyse the inclusion, or omission, of a technical issue (such as ME) in the EU's energy and climate policy agenda. These are: Rational Choice Institutionalism (RCI), New Institutionalism, and MSF (multiple streams framework).

Borrowing from neo-classical economics, *Rational Choice Institutionalism* traditionally assumes that individuals are homogeneous rational actors who compare the expected benefits and costs of their actions prior to adoption (Hindess (1984), Ostrom (1991)), and whose choices are constrained by institutions. Pollack (2006) contends that, in the EU, RCI has served as a means of formulating formal mathematical models, and of explaining endogenous preference formation – particularly relevant when assessing "the aggregation of individual preferences through domestic political institutions" (Pollack, 2006). For example, RCI can be insightful when conducting an analysis to explain why MS (Member States) delegate tasks to the EC or why there has been a growth in EU agencies.

This simplistic portrayal of the policy process and its actors, however, puts "politics in service of the economy" (Meadwell, 2005) and fails to capture actors' motivations, their decision-making process and the reconciliation of policy trade-offs seen in practice ((Norgaard, 1996)). Lindblom (1959) has long criticised RCI for its inability to explain incremental policy changes. Pollack (2006) concludes that RCI has limited applicability: it is most valuable within a specific policy domain, where individual's decisions are most relevant, where there is sufficient internal expertise on the matter analysed, and where institutional structures and rules are clearly defined.

These limitations have prompted modifications to the original theory by expanding on the motivations of actors, the role of institutions in shaping the interactions between actors, and the relevance of historical developments. These are typically categorised under the rubric of "new institutionalism" theories. Among the plethora of new-institutionalist viewpoints that emerged, Hudson and Lowe (2009) contend that the most prominent theory is that of historical institutionalism (HI). Central to HI is the understanding of temporal dimensions of policy change, that is, the relevance of policy legacy on new policy developments.

Historical institutionalists, such as Pierson (2000) and Mahoney (2000), support the idea that policies display *increasing returns* (opposing the 'diminishing return' view from economic theory), i.e. that mature policies are harder to reform. This idea has proved valuable in explaining the outcome of specific policy changes. For example, by focusing on pre-existing pension arrangements, Pierson (2001) was able to explain the decisions made by different countries regarding pension system reforms: states with long-standing state pensions only applied modest changes, whereas states with embryonic systems took more radical actions to favour their prioritisation.

Beyond HI, other new-institutionalist theories focused on investigating the effect of institutions on the interactions between actors. For example, to explain the relationships between policymakers in EU institutions, Princen and Rhinard (2006) – based on work by Cobb (1976) – proposed two types of institutional dynamics: *high* politics, where issues become part of a policy agenda from top-down interventions from political leaders; and *low* politics, where an issue is raised by junior members of staff in an organisation. The rationale for making this distinction is that the two routes have different features (see Princen (2009)). These are summarised in Table 2.8.

Table 2.8: Features of the high- and low-politics routes for agenda-setting (Princen and Rhinard (2006))

Features	High politics	Low politics
Originating actors (issue expansion)	High-ranking political figures, e.g. Commissioners	Low-ranking Commission experts, e.g. civil servants in specific units
Problems stream	Crises, symbolic events, public mood	Changes in indicators, policy feedback
Risk of issue entrance	High-level attention rapidly shifts to new issues causing political impetus to fade	Can be blocked by high-level politicians
Opportunity of issue entrance	Large political impetus for change once high-level politicians have committed	Solid 'self-sustaining dynamic' by slowly expanding EU activity upwards

To incorporate exogenous factors that remain unexplored in institutionalist theories, Kingdon (1984) developed a more pluralistic theory: the *Multiple Streams Framework* (MSF). Based on bounded rationality, this theory characterises the transience of opportunities available to bring problems to the attention of policymakers. To do this, Kingdon (1984) structures the analysis around three streams, that of *problems*, *politics* and *policy*. The author posits that for an issue to become part of a political (or public) agenda, thee three streams must converge during 'fleeting' moments, denoted as *policy windows*. Policy entrepreneurs are the actors pushing for policy solutions within these streams and they are key to understand the problem framing, the policy feedback, and the availability and characteristics of the policy solutions proposed. By defining a *policy* stream, this model is able to take into account the characteristics of the solutions, e.g. whether they are widely accepted or technically feasible.

Although originally informed by US policy developments, MSF has universal applicability and has been applied to understand EU agenda-setting processes. Today, MSF is viewed as "one of the most prolific and widely recognized" public policy theories (Jones et al. (2016)). Table 2.9 summarises some examples, and explains how these have been adapted to the EU context. In Table 2.9, the *policy stage* refers to the specific part of the policy process that the MSF was applied to. *Policy issue* describes the specific case that was investigated, and *adaptation* describes whether the definition of any of the streams, policy windows or entrepreneurs were adapted.

MSF has two main advantages: it is the only theory to explicitly consider the characteristics of policy solutions; it does not rely on an understanding of policy processes over long time periods (Sabatier et al. (1999)), which is beneficial for the study of ME (a relatively new topic). Yet, as argued by Brunner (2008), MSF is less appropriate for capturing institutional barriers, more

Table 2.9: Selection of MSF studies applied to the EU, expanded from Herweg (2016)

Study	Policy stage	Policy issue	Adaptation Streams	Window	Entre-preneurs
Bozzini (2017)	Entire process	Pesticide regulation	-	-	-
Fuchs (2017)	Decision-making	Environmental governance	No	No	Yes
Herweg (2016)	Agenda-setting	Natural gas regulation	Yes	Yes	Yes
Copeland and James (2014)	Decision-making	Economic reform	No	No	Yes
Bache (2013)	Agenda-setting	Quality of life	Yes	No	No
Grugel and Iusmen (2013)	Agenda-setting	Children's rights policy	Yes	No	No
Ackrill et al. (2013)	Entire process	Theory	Yes	Yes	Yes
Maltby (2013)	Agenda-setting	Energy policy integration	Yes	No	Yes
Ackrill and Kay (2011)	Decision-making	2005 Sugar reform	No	Yes	Yes
Borrás and Radaelli (2011)	Decision-making	Lisbon strategy governance	Yes	No	No
Kaunert and Giovanna (2010)	Decision-making	Counter-terrorist financing	Yes	No	Yes
Zahariadis (2008)	Entire process	General theory	Yes	Yes	Yes
Brunner (2008)	Agenda-setting	German emissions trading	No	No	No
Richardson (2001)	Entire process	General theory	Yes	Yes	Yes

specifically the "role of multi-level governance structures, learning processes, and the influence of networks". Brunner (2008) adds too, that Kingdon's theory is likely to underestimate "the importance of interests". Both of these aspects are instead better covered by institutionalist approaches.

This literature confirms that no single theory can capture all the factors influencing the formulation of policy agendas. In fact, Brunner (2008) recommends the use of more than one analytical framework, and Cairney (2007) contends that studies relying on several frameworks can provide more complete explanations of policy change and its drivers, especially if these studies "do not seek to confirm the value of one particular model". It is therefore posited that a combination of policy theories is needed to assess why ME has not been included in the energy and climate agendas; the exact combination of which will be determined from the evidence collected.

2.4.4 Proposed analysis: Incentivising material efficiency in the EU

The previous section confirms that a comprehensive, empirical explanation of why ME is omitted from energy and climate agendas in the EU – where the entire gamut of EU energy, climate and resource policies is considered – is still missing. It also shows that a combination of policy frameworks is likely to provide the richest explanation.

Therefore, this thesis seeks to fill two current knowledge gaps for ME policy. First, to provide empirical evidence that explains why ME is yet to become part of the energy and climate agendas – the relevant policy areas that could promote ME in heavy industry are to be investigated. Second, to explore interventions through which ME can be integrated into energy and climate strategies, and thereby to contribute to the discussion on how to facilitate the transition to a low-carbon heavy industry. In doing so, this work builds upon Skelton and Allwood's economic study on the ETS (Skelton and Allwood, 2017) and on Cooper and colleagues' analysis on the lack of attention given to ME in the UK automotive sector (Cooper-Searle et al., 2017). Based on the empirical evidence collected, Chapter 5 will detail how different policy theories are integrated to understand how to promote the introduction of ME policies for reducing energy use.

2.5 Defining the research questions

This chapter has reviewed the wide range of metrics, methods and applications available in the literature to measure and analyse the resource efficiency of industrial systems. It has also reviewed the energy, climate and resource-related policies developed in the EU, and investigated the potential relevance these could have in incentivising the uptake of RE. The final section of the chapter summaries the knowledge gaps identified in the literature, outlines the resulting three research questions (Section 2.5.1), and explores the research methodology required to deliver the thesis (Section 2.5.2).

2.5.1 Knowledge gaps

This literature has revealed three knowledge gaps:

1. As discussed in Section 2.1, industry-wide efficiency benchmarks are often defined in terms of energy intensities (GJ/t). Many ME indicators exist that measure the performance of specific interventions (e.g. recycling or re-using). Yet, these are not standardised and rarely compared across industries for environmental purposes. Exergy efficiencies have proved to be a credible alternative to measure how well industries use resources, but to date, these have not been used as industry benchmarks, and have rarely analysed the interactions of energy and materials together. To this end, exergy is a promising tool to measure the integrated efficiency of resource use. This can help incentivise ME in industry, more specifically the recovery of material by-products, which are currently not captured in any of the conventional EE or ME metrics.

2. Detailed and actionable information on resource use during production is key to encourage industry to improve RE. Previous studies (Section 2.3) either use control data for operational purposes such as reliability or safety, or jointly analyse resources but without applying this to the operations of plants over time. From the latter, a few examples exist that use Sankey diagrams to visualise their resource flows. However, no single study exists that constructs Sankey diagrams from control data to portray the exergy flows of real plant operations.

3. The widespread adoption of the integrated RE approach from gaps 1 and 2 hinges on the support of effective industrial policies. To date, the EU has provided limited support to the uptake of ME as a tool for reducing energy and emissions in industry. Understanding why ME has been overlooked by policymakers is a prerequisite for proposing ways of encouraging its adoption. Yet, Section 2.4.2 revealed that none of the studies in the literature provides a comprehensive explanation of why ME continues to be under-leveraged in the EU's energy and climate policies.

The ambitious overarching question of this thesis, "How can we help industry firms become more resource-efficient?" will be partially addressed through three specific research questions, based on the knowledge gaps identified above. These are:

Q1: How can energy-intensive industries measure and benchmark their energy and material efficiency in a unified manner?

Chapter 3 evaluates the use of exergy as an integrated measure of resource efficiency to benchmark heavy industries. The case study of the global steel industry is used to test the metric's effectiveness.

Q2: Can we gain a better understanding of resource efficiency using energy and material control data on a close-to-real time basis?

In **Chapter 4** control data from a Tata Steel basic oxygen steelmaking plant is used to analyse its operational resource efficiency. Resource flows are mapped using close-to-real-time Sankey diagrams measured in units of exergy.

Q3: Why is material efficiency not integrated into the EU's energy and climate strategies for heavy industries?

Material efficiency is currently overlooked in the EU as an energy- and emissions-saving tool; **Chapter 5** assesses why this is the case. A combination of interviews, policy documents and public policy theories form the basis of this analysis.

Together, these chapters aim to provide an in-depth exploration into the *site-level analysis of resource efficiency*. Chapter 6 will assess the extent to which the overarching research question was addressed, and will discuss the wider implications and conclusions from these three chapters (3, 4 and 5). Based on this, new research opportunities that arose from this thesis are presented, through which a more complete answer to the overarching research question could be provided.

2.5.2 Research methodology: defining the overall research approach

Before providing solutions to the above research questions, it is worth having an explicit discussion about the methodology behind the overall research – that is, the views that guide the approaches to inquiry of the following three chapters (Chapters 3-5). The choice of research methodology is important because it is the foundation on which other research decisions are based, including the selection of: data sources, analytical techniques (or methods) and their inherent assumptions. Much research has gone into characterising the various types of research paradigms and methodologies. This section, therefore, does not intend to provide a full description of these; instead, it explains how the research in this thesis was conceived and how it will proceed.

Research frameworks can be described as a combination of three elements, as proposed by Creswell (2014): (1) *philosophical worldviews*, that is, the fundamental set of beliefs held by a researcher – also denoted as *methodologies* or *paradigms*; (2) *research designs*, which relate to the choice of inquiry mode within qualitative, quantitative, and mixed methods approaches; (3) *research methods*, which involve the choice of specific steps and their relative order of execution within the chosen research approach. Figure 2.8 depicts the interconnection between these three elements and the options that exist within these.

In this thesis, the research framework can be considered to: (1) have a pragmatic worldview; (2) consist of different mixed method approaches and designs – both convergent parallel (quantitative and qualitative data is collected and analysed simultaneously) and explanatory sequential (where qualitative analyses build on quantitative ones); (3) employ a variety of methods including aspects from both qualitative and quantitative designs (e.g. collection of engineering data, design

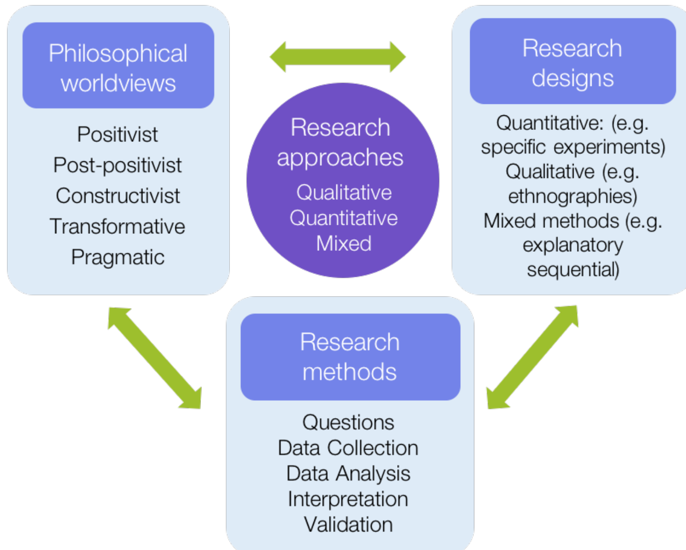

Figure 2.8: Research framework portraying the link between worldviews, research design, and research methods; modified from Creswell (2014).

of interviews, execution of thermodynamic analysis, or a review of policy documents).

Pragmatists are generally concerned with real-world applications. They seek to understand what works and focus on the *solutions* to specific problems (Patton, 1990). This problem- rather than method-centered worldview grants pragmatists the methodological freedom to employ "all approaches available to understand the problem" (Creswell, 2014). As such, it is only logical that this worldview lends itself to mixed-method approaches – as is the case for the research methods across each of the three results chapters (3,4 and 5).

The pragmatic nature of this thesis is, however, first and foremost reflected in the fact that much of its novelty is found in the specific combination of research methods applied to solve the identified problems, i.e. the improvement of industry's resource efficiency. Table 2.10 summarises the choice of research designs and methods. All three chapters conduct research for real engineering and policy applications. As opposed to positivist/post-positivist approaches (more commonly associated with scientific studies), pragmatism values the relevance of historical, cultural and social contexts. In this thesis, this is best represented through the use of semi-structured interviews, specifically in Chapters 4 and 5.

Table 2.10: Summary of research methods and designs

Chapter	Research design	Research methods
Chapter 3	Quantitative methods: testing theory and producing repeatable findings	Theory, Data collection, quantitative thermodynamic analysis, interpretation, validation
Chapter 4	Explanatory sequential mixed method (quantitative enriched by qualitative): based on quantitative analysis of resource use but enriched through semi-structured interviews with plant staff	Questions, data collection, triangulation, analysis, interpretation and validation
Chapter 5	Convergent parallel mixed method (qualitative and quantitative combined): includes the triangulation of semi-structured interviews, a policy document review and well-established policy theories	Questions, quantitative and quantitative data collection, analysis, interpretation and validation

Figure 2.9 below depicts the structure of this thesis, from Chapter 1 through to Chapter 6. This diagram summarises the steps involved in addressing the three research questions posed in Section 2.5.1, and describes how each of these components comes together to thread the overall narrative of this thesis.

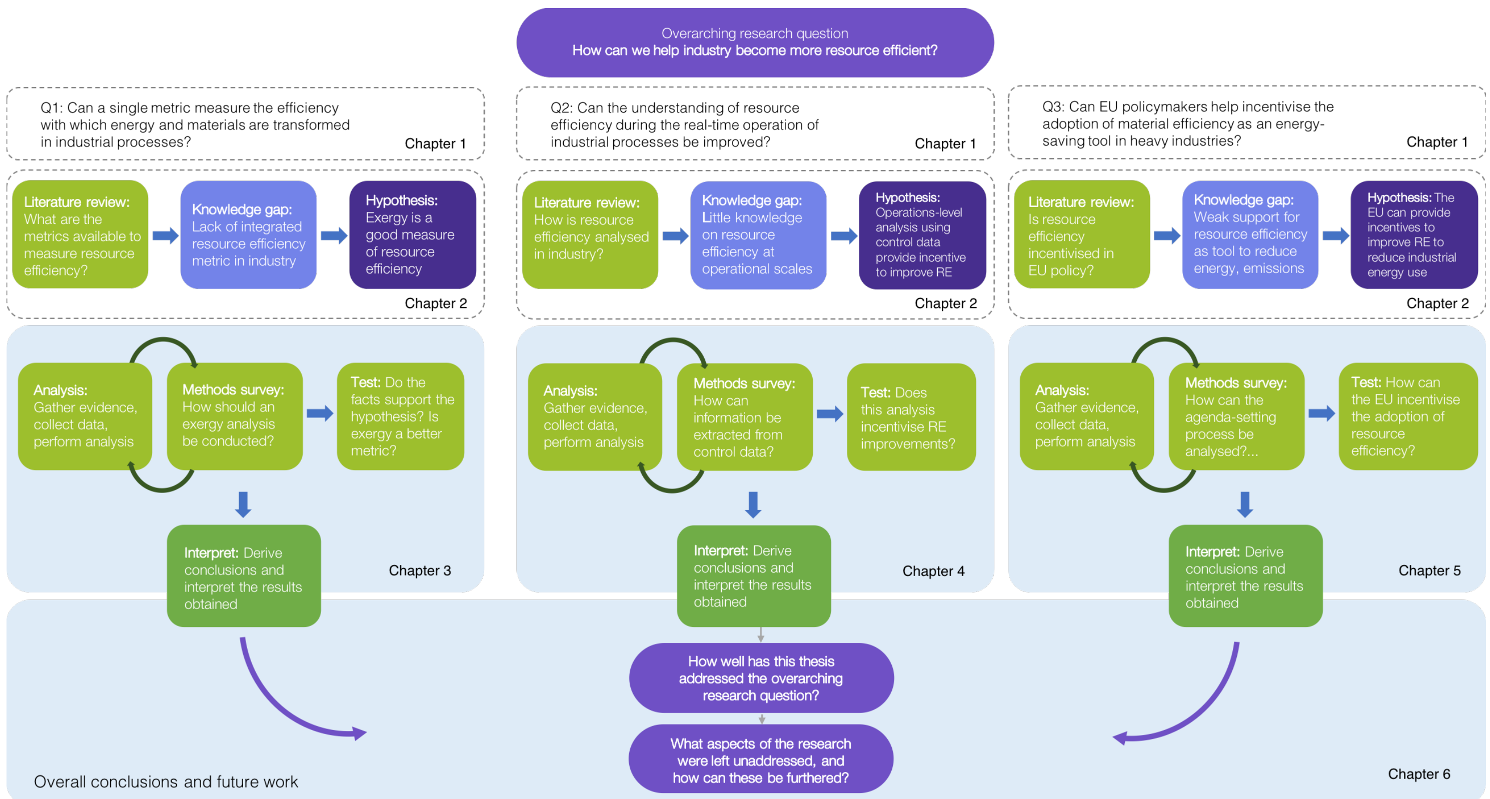

Figure 2.9: Research plan for this thesis. Chapter 1 begins by introducing the motivation behind this work – objective which defines this thesis' overarching research question. Three open-ended questions are also posed at this stage. An extensive and thorough literature review is then conducted to better define the knowledge gaps and to refine the original research questions. Based on this, three hypotheses are established (Chapters 3-5). Each of these is individually investigated and tested through practical case studies, the results of which are then interpreted.

"The exergy analysis of any chemical reaction allows for a rapid evaluation of alternative energy-production schemes, or various chemical-reaction schemes. In fact, these tools are so powerful we believe that they should be included in the standard toolkit for any engineer, industrial ecologist, and many other professionals dealing with sustainability issues." (Bakshi et al., 2011)

3

Measuring resource efficiency in heavy industries

Q1: How can energy-intensive industries measure and benchmark their energy and material efficiency in a unified manner?

Case study: Global steel production using worldsteel data

Part of the content of this chapter is based on a journal article titled "How resource-efficient is the global steel industry?", which was published by the journal *Resources, Conservation and Recycling*. My co-author, Leonardo Paoli, assisted me in processing the raw data; my co-author, Dr Jonathan Cullen, provided comments on draft versions of the article.

3.1 Introduction

In Section 2.1, we identified that conventional RE (resource efficiency) indicators used as industry benchmarks today do not provide an integrated understanding of the efficiency with which both energy and materials are transformed. They ignore the physical value of material by-products and focus on a single resource. This chapter investigates the use of exergy as a tool for more holistically comparing the RE of industry's energy and material use.

To enhance our understanding of the industry's resource flows, these flows are jointly mapped in the form of a Sankey diagram and measured in units of exergy – as proposed in Section 2.1. Doing this sheds light on the system's structure and scale. From these flows, the RE of plants as well as entire production routes can be quantified, and potential resource savings can be estimated.

This analysis is presented in four parts: Section 3.2 explains why the steel sector was chosen as the case study; Section 3.3 outlines the method used to map the exergy flows, compute the RE of the global steel sector and quantify potential resource use improvements available; Section 3.4 presents the results obtained; and Section 3.5 compares our results to previous studies, assesses the appropriateness of the metric proposed, and discusses the implications of these results.

3.2 Choice of case study

This chapter analyses the case study of the global steel industry. This was chosen for four reasons:

1. Steel is, and will continue to be, a ubiquitous material. It is used to manufacture the structural elements in buildings, rails, pipes, cars, trucks and ships, and is also found in mechanical equipment, metal goods, consumer packaging, and domestic appliances, among many other products. The volume of steel produced has continued to increase in the past couple of decades (worldsteel, 2014*b*). Studies suggest that this trend will remain unchanged; steel demand is likely to double between 2010 and 2050 (Cullen et al., 2012).
2. This extensive use of steel in society has had large, negative environmental impacts: steel production accounts for close to one-quarter of industry's CO_2 emissions (Cullen et al., 2012, IEA, 2017). The IEA (2016)'s 2ºC scenario for 2050 suggests that more than a third of the emissions reduction in industry (excluding power generation) will come from the steel sector, making steel the single largest contributor to industrial emissions reduction.
3. An analysis of iron- and steel-making processes can be directly applied to other metallurgical processes, including for example the aluminium, copper and lead industries – all of which require energy-intensive production processes. The analysis of chemical reactions (e.g. the blast furnace) is relevant to other energy-intensive industries such as cement, petrochemicals, and pulp and paper.
4. Today, exergy analyses have been applied to steel production (summarised in Table 3.10, Section 3.4): at country level, for the US (Masini and Ayres, 1996), China (Wu, Wang, Pu

and Qi, 2016), and the UK (Michaelis et al., 1998); for specific technologies (blast furnaces (Petela et al., 2002), electric furnaces or sintering processes (Bisio, 1993), smelting process Akiyama and Yagi (1988), Ostrovski and Zhang (2005)); across individual or a combination of reference plants (Costa et al., 2001, Szargut et al., 1988) and (de Beer, 2000). Yet no previous study captures the full picture of resource use and RE (in exergy) of the global steel industry.

3.3 Method

Three steps are required to quantify the RE of the global steel industry: (1) collecting energy and material data (Section 3.3.1); (2) converting this into exergy flows (Section 3.3.2); (3) defining and calculating the RE metric (Section 3.3.3). This data is then used to estimate the resource-use improvements available from implementing best practice performance worldwide (Section 3.3.4).

3.3.1 Gathering the data

This chapter analyses energy and material flow data across 38 steel production sites. This data was compiled through a series of company surveys collected by worldsteel over a four-year period between 2010 and 2014 (worldsteel, 2014*a*). It represents 9% of the total crude steel production worldwide, covering the regions of: Europe, China, India, North and South America, the Middle East and the Commonwealth of Independent States (CIS) countries.[1]

To improve data reliability and correct for misreporting of data – mainly from misunderstandings of survey terminology or system boundaries – worldsteel use a rigorous methodology (worldsteel, 2014*a*) with 15 checkpoints to ensure collected data from members lies within predefined ranges. Despite these checks, misreported data can still be present. However, the remaining incorrect data is likely to result in outliers, and can therefore be ignored in the savings calculations.

Figure 3.1 describes the number of samples analysed for each type of plant. Two sites were removed from the original data set – namely a smelt reduction site and a charcoal-fed blast furnace site – because these were single samples and are therefore not sufficient to provide representative global average values. Pelletising plants found in several sites were excluded for the same reason.

[1]Data from large steel producers in China and India may be under-represented.

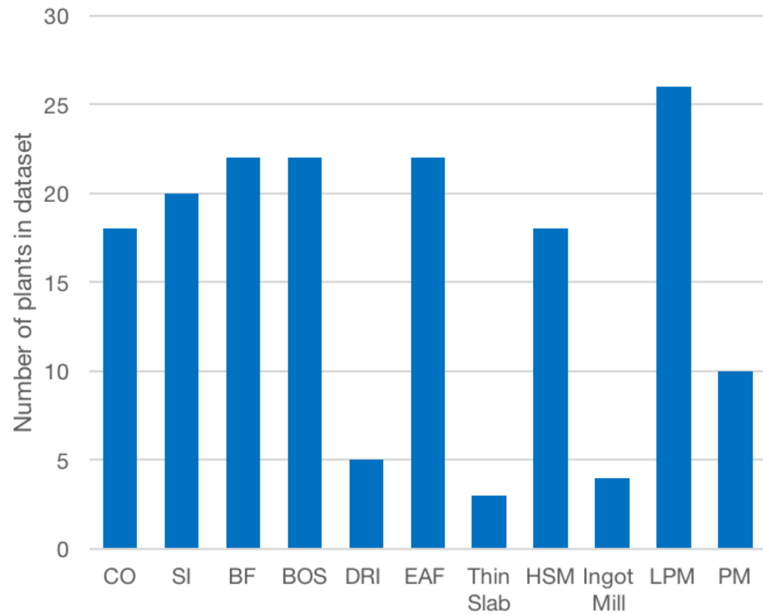

Figure 3.1: Number of samples analysed for each individual plant in the data set

Data was collected for two primary routes – the blast furnace-basic oxygen steelmaking route (BF-BOS) and the direct reduction-electric arc furnace (DRI-EAF) – and one secondary route: the scrap-based electric arc furnace (EAF). Currently, about 69% of global crude steel is produced via the BF-BOS route, whereas approximately 29% is produced through electric furnaces (a mix of directly reduced iron and scrap-based routes). Figure 3.2 depicts the processes and flows for the: BF-BOS route, which converts iron ore into steel; DRI-EAF route, where directly reduced iron is fed to the furnace; EAF, where scrap is the main input. Only on-site power plants are included in the boundary; off-site production and upstream transformation losses are excluded.

Steelmaking sites are not homogeneous and contain a variety of plant configurations. Products are frequently purchased and sold at intermediate stages. For example, some plants purchase coke to address production short fall, whereas others produce excess coke for export. To make sites comparable, mass and energy imbalances are classified as exports or imports, with individual plant exergy intensities attributed to exports and global average exergy intensities attributed to imports. The use of average EIs (energy intensities) for imported products can be disadvantageous for some sites if these sites happen to be buying products from plants operated more efficiently

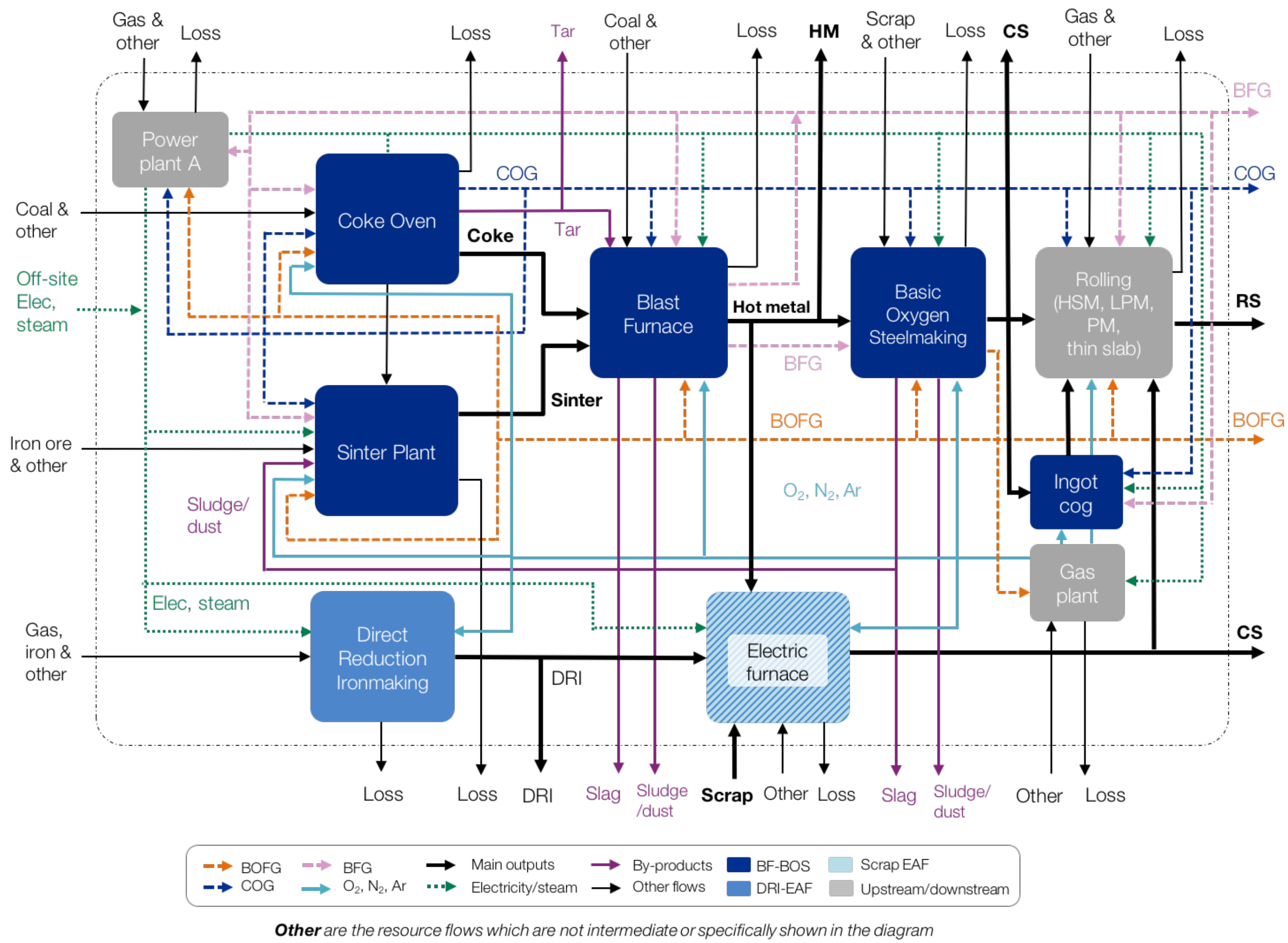

Figure 3.2: Schematic of the sector's processes and resource flows. Coke oven gas (COG), hot metal (HM)[a], blast furnace gas (BFG), basic oxygen steelmaking gas (BOSG), rolled steel (RS), crude steel (CS), directly reduced iron (DRI), hot strip mill (HSM), long product mill (LPM) and plate mill (PM).

[a]In this chapter, hot metal and pig iron are used as synonyms.

than reflected in the average. However, more detailed upstream data is required for the embodied energy use/resource efficiency attributed to the imported products to be improved.

Route-level analyses exclude rolling processes, as insufficient data was provided to perform a full mass balance over the entire gamut of rolling technologies (i.e. PM, LPM, HSM or thin slab rolling). Rolling processes, however, are analysed separately and included in the overall picture of the sector's resource flows. The raw data provided by worldsteel is in units of energy (joules) and mass (tonnes), and must therefore be converted into units of exergy before the resource flows can be mapped and the REs can be calculated.

3.3.2 Converting mass and energy balances into exergy flows

The exergy in a material can be divided into kinetic, potential, chemical and physical components. In metallurgical processes, the most relevant contributions to the exergy flows are the chemical – resulting from a difference in the chemical composition with respect to the reference state – and physical components – resulting from a difference in the system's temperature and/or pressure with respect to the reference state. The next sections detail how these are computed.

Calculating physical exergies

Physical exergies (b_{ph}) result from a difference in the system's temperature and/or pressure with respect to atmospheric conditions. The general expression for the specific physical exergy of matter (b_{ph}) is expressed in terms of enthalpies (H) and entropies (S). However, if information on enthalpies and entropies is not available, the physical exergies can be estimated by approximating these. For example, assuming a constant specific heat (C_p), Szargut et al. (1988) and Querol et al. (2013) employ Equation 3.1; this study uses this equation as an approximation for the physical exergy of materials (b_{ph}^{approx}).

$$b_{ph}^{approx} = C_p(T - T_o) - T_oC_p\ln(\frac{T}{T_o}) + T_oR\ln(\frac{P}{P_o}) \quad (3.1)$$

Exergy must be calculated relative to a reference state; the choice of this state is important as it affects the work that can be extracted from a process. In this study, the reference temperature and pressure used are $T_o=25^oC$ and $P_o= 101.325$ kPa respectively. Table 3.1 summarises the temperatures, pressures and specific heat capacities used for each relevant resource stream. The following additional assumptions are made: gases follow ideal behaviour; solids and liquids have constant C_p; outputs are at atmospheric pressure, except for high- and low-pressure steam (80 bar and 20 bar respectively) and blast furnace gas (BFG) at 20 bar (worldsteel, 2015*b*).

Table 3.1: Details on physical exergy (b_{ph}) calculations. Atmospheric pressure is assumed to be 101.3 kPa; coke oven gas – COG; blast furnace gas – BFG; basic oxygen steelmaking gas – BOSG.

Resource	Cp (kJ/kgK)	Temp. (ºC)	Pressure (kPa)	b_{ph} (GJ/t)	Sources (Data on temperature provided by (worldsteel, 2015*a*))
BOSG	0.9	1200	101.3	0.7	Data on gas composition by (worldsteel, 2015*a*)
COG	3.1	500	101.3	1.2	Data on gas composition by (worldsteel, 2015*a*)
BFG	1.0	350	2000	0.4	Data on gas composition by (worldsteel, 2015*a*)
BF, BOS slag	1.4	1200	101.3	0.9	Cp provided by (Monaghan and Brooks, 2002)
HP steam	2.5	500	8000	1.4	Pressure provided by (worldsteel, 2015*a*)
LP steam	2.4	300	2000	0.8	Pressure provided by (worldsteel, 2015*a*)
Hot metal	0.7	1300	101.3	0.5	Cp provided by (Lally et al., 1990)
Liquid steel	0.7	1300	101.3	0.6	Cp provided by (Lally et al., 1990, Valencia and Quested P.N, 2008)
Hot rolled steel	0.6	900	101.3	0.3	Cp provided by (Lally et al., 1990)
Coke	1.3	800	101.3	0.7	Cp provided by (Loison et al., 1989); temperature from (de Beer, 2000)
Sinter	0.9	700	101.3	0.3	Cp provided by (Tian et al., 2015), recorded at a temperature of 1173 K

The use of perfect gas equations to estimate the physical exergy of solids and liquids is a crude approximation. Yet this was compared to that obtained using enthalpies and entropies for liquid and hot rolled steel, and the difference is small (less than 15%).[2] The impact of this approximation is negligible if we consider that physical exergies are an order of magnitude smaller than their chemical counterparts. In fact, in studies of metallurgical sectors Masini and Ayres (1996) and Szargut et al. (1988) both ignore physical exergies altogether. Masini and Ayres (1996) argue that these are "of secondary — in fact negligible — importance when attention is focused on [...] chemical and metallurgical processes at the industry level".

Calculating chemical exergies

Chemical exergy (B_{ch}) represents the "exergy content of a substance at environmental pressure and temperature", which results from a difference in its composition and concentration relative to the components found in the environment (Szargut, 2005). As explained in Section 2.2.4, the

[2] Using the enthalpies and entropies reported by Kim (1975) for steel, physical exergy values of 0.47 and 0.24 kJ/kg are obtained; these are between 13-15% lower than our approximated values.

choice of this reference is key and non-trivial. For gases, liquids and solids Szargut (1986) defines a reference model based on mean concentrations in the atmosphere, hydrosphere (sea water) and lithosphere (the crust).

The composition of a material is the foundation of its chemical exergy. In defining his reference model, Szargut (1986) also tabulated a wide range of elements and compounds. Ayres and Ayres (1999) and Szargut (2005), among others, later expanded this list further and provided chemical exergy values for the most common materials in energy-intensive industries. Since a composition is required to calculate the specific chemical exergy of a material (b_{ch}), these authors had to estimate these: these are usually either global averages or the most commonly found compositions. For materials with compositions that are different from those contained in the standard tables, these should be calculated from first principles.

In this study, however, many different steel, iron, coal and coke (among other materials) compositions are aggregated to the global level. The average compositions tabulated by Ayres and Ayres (1999) and Szargut (1986) therefore provide suitable approximations for materials. Table 3.2 details the values adopted for this analysis.

Table 3.2: Chemical exergy of selected materials used in the steel industry

Materials	Value (GJ/t)	Source
Pig iron/ hot metal	8.0	
DRI/ steel / scrap	6.8	
BOS slag	1.5	Average values taken from Szargut (2005)
Oxygen	0.1	
Nitrogen	0.03	
Carbon dioxide	0.44	
Iron ore	0.4	
Pellets	0.2	
Sinter	0.3	
BF slag	1.2	
Coke	33.9	Average values taken from Ayres and Ayres (1999)
Coal tar	37.1	
Limestone	0.05	
Dolomite	0.2	
Flue dust	25.9	

The chemical exergy of standard fuels is instead derived from conversion factors based on low heating values (LHVs) in Nakicenovic et al. (1996). The conversion factor (*f*) for the average composition of coal (1.06) was used for all the coal types including, BF injection coal, coking coal, anthracite and EAF coal. Similarly, the *f* for crude oil (1.04) was used for both heavy and light oils, and "other gas" was converted using the *f* for natural gas (1.03). For the off-gases, blast furnace gas (BFG), coke oven gas (COG) and basic oxygen steelmaking gas (BOSG), LHV values were calculated using compositions from worldsteel (2015*b*) (see Table 3.3). The *f* for natural gas (1.03) was then used to convert these into exergy values.

Table 3.3: Low heating values and density of the industrial off-gases

Off-gas	LHV (MJ/kg)	Density (kg/m3)
COG	41.56	0.46
BOSG	6.69	1.26
BFG	2.44	1.35

Calculating exergy losses

Not all the exergy input into a process results in a useful output, and, unlike energy, exergy is not conserved. Some of this input is physically lost in the form of undesired materials – most commonly denoted as waste streams – and what remains becomes *irreversibilities*: losses caused by the increase in entropy of a given process. *Waste streams* include the chemical and physical exergy of material losses (i.e. yield losses), unused by-products, and emissions (e.g. CO_2). Irreversibilities include losses caused by the heat transfer across a finite temperature difference, combustion and chemical reactions, and the expansion and compression of fluids; combinations of these phenomena are present in all industrial devices.

In this study there are four main types of waste streams: iron (Fe) yield losses, carbon (C) yield losses, CO_2 emissions and unused by-products (more information on by-products in Section 3.3.3). In practice, Fe yield losses arise in the blast furnace (BF), basic oxygen furnace (BOF) and rolling plants. Yield losses are calculated by balancing the Fe flows across individual plants, for which average Fe contents are assumed: 65% for sinter/ore/pellets; 94% for hot metal/DRI; 99% for scrap/scales/hot rolled. Yield losses in coke ovens (CO) are found by balancing average carbon contents, while the calculation of chemical exergy for CO_2 emissions uses mass balances and average C contents (see Table 3.4).

Table 3.4: Carbon contents and sources for every stream analysed; measured per tonne of resource stream.

Resource (R) stream	Value (t C/t R)	Source	Resource stream	Value	Source
Coking / BF injection coal	0.81	(worldsteel, 2015*a*)	Natural gas	0.015	(IPCC, 2006)
Home / external coke / breeze	0.88		BFG	0.07	
Pet coke	0.87	(IPCC, 2006)	COG	0.01	
Pig iron / hot metal / scrap iron	0.04		BOSG	0.05	(worldsteel, 2015*a*)
Crude / rolled / scrap steel	0.01		LPG/ Waste tires	0.02 t C/ GJ	
Crude dolomite	0.13		Heavy/ light oil	0.02 t C/ GJ	(IEA, 2015*a*)
Limestone	0.12		Napthalenic oil	0.02 t C/ GJ	
BF gas dust/sludge	0.35	(worldsteel, 2015*a*)			
Tar/benzole	0.92				

The remaining exergy losses – i.e. those that do not end up in any output product or which are not part of either of the three above waste streams – are assumed to be irreversibilities. Information on the breakdown of irreversibilities requires equipment-level analysis in laboratory conditions, which is time-consuming. Instead, for this study, a reference plant loss breakdown from de Beer (2000) is used, where irreversibilities are attributed to combustion (40%), chemical reactions (30%), heat transfer (20%) and expansion/compression (13%).

Exergy flows for the entire steel industry are visualised in the form of a Sankey diagram. Here, process irreversibilities are depicted as outgoing flows, and are collated at the top of the diagram. Showing these allows us to highlight the origin of most of the process losses and to provide an idea of what fraction of the losses are realistically recoverable.

3.3.3 Measuring resource efficiency

Described generally, an efficiency provides a measure that relates the effect *obtained* from a process to the effect *supplied*. No unique method for defining the exergy efficiency of a process or system exists, as seen by the variety of definitions available (Brodyansky et al., 1994, Costa et al., 2001, Sorin and Paris, 1998, Szargut et al., 1988). However, based on the system boundary and purpose of this study – incentivising the adoption of RE improvement measures – the definition in Equation 3.2 is proposed. The numerator and denominator are both measured in joules of exergy, making the efficiency dimensionless. Here, the sum of the chemical and the physical exergies for the main product output (P), the material by-products (MB) and the energy by-products (EB), are expressed as $B_{\mathrm{P}}^{\mathrm{out}}$, $B_{\mathrm{MB}}^{\mathrm{recovered}}$ and $B_{\mathrm{EB}}^{\mathrm{recovered}}$ respectively; those for the energy and raw material (RM) inputs are expressed as $B_{\mathrm{RM}}^{\mathrm{in}}$ and $B_{\mathrm{E}}^{\mathrm{in}}$. *Recov* stands for recovered.

$$RE = \frac{\sum \left(B_{ch} + B_{ph}\right)_{\mathrm{useful}}}{\sum \left(B_{ch} + B_{ph}\right)_{\mathrm{total}}} = \frac{\sum B_{\mathrm{P}}^{\mathrm{out}} + \sum B_{\mathrm{MB}}^{\mathrm{recov}} + \sum B_{\mathrm{EB}}^{\mathrm{recov}}}{\sum B_{\mathrm{RM}}^{\mathrm{in}} + \sum B_{\mathrm{E}}^{\mathrm{in}}} \tag{3.2}$$

Equation 3.2 can be further disaggregated and expressed in a form suitable for the raw data provided by worldsteel: mass (M_o, M_{in}, M_B), energy (E_{in}, E_B), energy-to-exergy conversion factors (γ_F) and specific chemical/physical exergies (b_P, b_{in}, b_{MB}, b_{EB}).

$$RE = \frac{\sum b_P(M_o) + \sum b_{MB}(M_B) + \sum b_{EB}E_B}{\sum b_{in}(M_{in}) + \sum \gamma_F(E_{in})} \tag{3.3}$$

Rearranging this further, the RE – normalised by the mass of the main product (M_o) – can be expressed as per Equation 3.4, in terms of more familiar metrics of energy and material performance, such as energy intensity (EI) and material yield (α).

$$RE = \frac{\sum b_P + \sum b_{MB}\frac{(M_B)}{(M_o)} + \sum b_{EB}\frac{(E_B)}{(M_o)}}{\sum b_{in}(\frac{1}{\alpha}) + \sum \gamma_F(EI)} \tag{3.4}$$

Equation 3.4 summarises, mathematically, the strengths of the exergy-based RE metric. It not only allows us to capture the effect of improving the recovery of material by-products, but also includes the other three options available to improve RE: increase in material yields, improvement of energy recovery, and decrease in energy inputs.

Particular care is required when deciding which flows are *useful* as different interpretations of usefulness can lead to different efficiency results. For individual processes, only the outputs further used in other processes are considered useful, for example: flared BFG is a waste, whereas BFG used to generate electricity or as a fuel is considered useful. The usefulness of the three off-gases (BFG, BOSG, COG) and the BF sludge/dust is determined by comparing their outputs to the off-gases or BF sludge/dust fed to other processes. When data is not available, average recovery rates are assumed. For the BF and BOS slags it is assumed that 80% is recovered (worldsteel, 2016) – mainly for cement/concrete production. Tar, benzole and oil are assumed to be fully recovered in downstream processes outside of the sector. The BOS sludge/dust is not considered useful as this is often stockpiled on-site.

The calculation of RE for plants and routes, across sites, allows distributions of RE to be graphed. RE values are grouped into bins of two or more sites to avoid revealing proprietary data for individual plants. The shape and spread of the distributions provides an insight into the potential exergy savings available in each plant and production route.

EIs of processes and plants are computed, partly to facilitate comparisons with previous studies but chiefly to reveal the benefits from using a definition of RE that incorporates materials. The definition of $EI_{\text{by-prod}}$ is formulated as per Equation 3.5; this is the standard energy intensity definition used by worldsteel.

$$EI_{\text{by-prod}} = \frac{\sum E^{\text{in}} - \sum E^{\text{recov}}_{\text{by-prod}}}{M_{\text{prod}}} \tag{3.5}$$

M_{prod} represents the mass of the main product, and the terms $\sum E^{\text{in}}$, $\sum E^{\text{recov}}_{\text{by-prod}}$ refer to the sum of the energy inputs (in exergy) and recovered energy by-products, such as BFG or steam.

3.3.4 Quantifying improvements in resource use

Assessing the technical improvement potential of individual plants requires knowledge of: the scale of resource flow; the efficiency with which these flows are converted into products; and the potential efficiency improvement available. The technical IP for each plant (φ) can be expressed as the difference between resource inputs in current and target operation:

$$\varphi = B_{in}^{\text{current}} - B_{in}^{\text{target}} \tag{3.6}$$

Expressing this in terms of the output and efficiency, and assuming the resource output remains constant, results in:

$$\varphi = \frac{B_{out}^{\text{current}}}{RE^{\text{current}}} - \frac{B_{out}^{\text{target}}}{RE^{\text{target}}} = B_{out}\left(\frac{1}{RE^{\text{current}}} - \frac{1}{RE^{\text{target}}}\right) = B_{in}^{\text{current}}\left(1 - \frac{RE^{\text{current}}}{RE^{\text{target}}}\right) \tag{3.7}$$

In this study, two RE targets are defined: (1) best practice, where each plant is compared to the first decile plant, i.e. that representing 10% of the production volume; (2) best available, where each plant is compared to the best plant in the sample. These are both calculated using Equation 3.7 and assuming the technological status and resource input mix from 2010. Worldsteel resource data is considered to be representative of the global average, allowing it to be scaled up to the global level based on total steel production. This makes it possible to provide a conservative estimate of global resource use improvements available. To test the validity of this approach, Table 3.5 compares the scaled-up data and other statistics in the literature across several key parameters.

Table 3.5: Data validation through comparisons of specific results to other relevant studies

Resource flow	Unit	This study	Literature	% Diff	Reference
Total coal input	EJ (energy)	23.2	24.4	5	(World Coal Institute, 2007)
Fraction of EAF to BOF	%	27	29	7	(IEA, 2017)
Coke input into BF	EJ (energy)	12.4	12.3	1	(IEA, 2010)
Tar produced in CO	EJ (energy)	0.44	0.48	9	
BFG production	EJ	4.8	5.2	8	
COG production	EJ	2.8	2.8	1	

Further insight into the technical IP of the global steel industry is provided by breaking down potential resources savings into: recovery of waste gases currently flared; reductions in material yield losses; recovery of unused material by-products; capture of waste heat. Reductions in material yield losses are calculated assuming: a 5% increase in BF yield (to 95%); a 2% improvement in BOS yield (to 95%); 1-2% improvements in CO, HSM, LPM and PM yields (to 98%).

3.4 Results

This section presents a comprehensive analysis of the RE of global steel production, using the most up-to-date and representative resource data for 2010, and converting this to exergy to reveal opportunities for improvement. The results are structured in three parts: a global map of resource flows for the sector (Section 3.4.1); a RE assessment of plants and production routes (Section 3.4.2); an evaluation of the potential resource savings available globally (Section 3.4.3).

3.4.1 Mapping resource flows

Figure 3.3 shows the best estimate of global resource flows in the steel sector in 2010, from coking (left) to rolling (right). Material and energy flows are presented in a Sankey diagram, where the thickness of each line represents the scale of the flow in units of exergy. Each node represents a plant, and colour is used to indicate the resource type. The resulting map reveals the complex interactions between energy and materials in steelmaking. Presenting results in Sankey diagram form allows the scale of resource flows to be compared in relation to one another, providing a powerful way to highlight possible interventions and their prioritisation.

The total resource input to the steel industry in 2010 is 24.7 GJ/tcs (gigajoules of exergy per tonne of crude steel). The BF-BOS route has an average resource input of 29.8 GJ/tcs, whereas the DRI-EAF and the scrap-only EAF routes have values of 17.2 and 10.3 GJ/tcs respectively. The EAF route makes up under a third of total crude steel production, but with less than a tenth of the total exergy input, even after accounting for the exergy in the scrap input. Coal contributes just under 60% of the total exergy input of all energy carriers, surpassing the inputs of electricity and natural gas. The integrated BF-BOS plants generate 36% of on-site electricity and 93% of on-site steam requirements.

Steel scrap is the largest raw material input with a value of 1.8 GJ/tcs (exergy). About 0.4 GJ/tcs of this (20% of the total steel scrap) is generated internally by the industry: in the BF, the BOF and in downstream rolling and fabrication processes. Surprisingly, nearly half of all the scrap (0.7 GJ/tcs) is fed to the primary route (i.e. the BOS plant), contributing 10% of the exergy input and 12% of the mass of the route. Cold iron is the second largest material input; it is generated as a by-product from the BF and recycled back to the steelmaking processes: 40% to the EAF and 60% to the BOS.

The useful outputs from global steel production consist of steel, energy by-products and material by-products. The exergy value of the steel output (5.7 GJ/tcs) is less than one-quarter of the total exergy input, giving an indication of the RE of steel production. The largest un-utilised output flows are: the flared BFG (1.2 GJ/tcs); the chemical exergy (0.7 GJ/tcs) of BF Fe losses; the waste heat (0.5 GJ/tcs) from BFG; and the flared COG (0.4 GJ/tcs). These figures reveal that there is still potential to improve the recovery of the three off-gases.

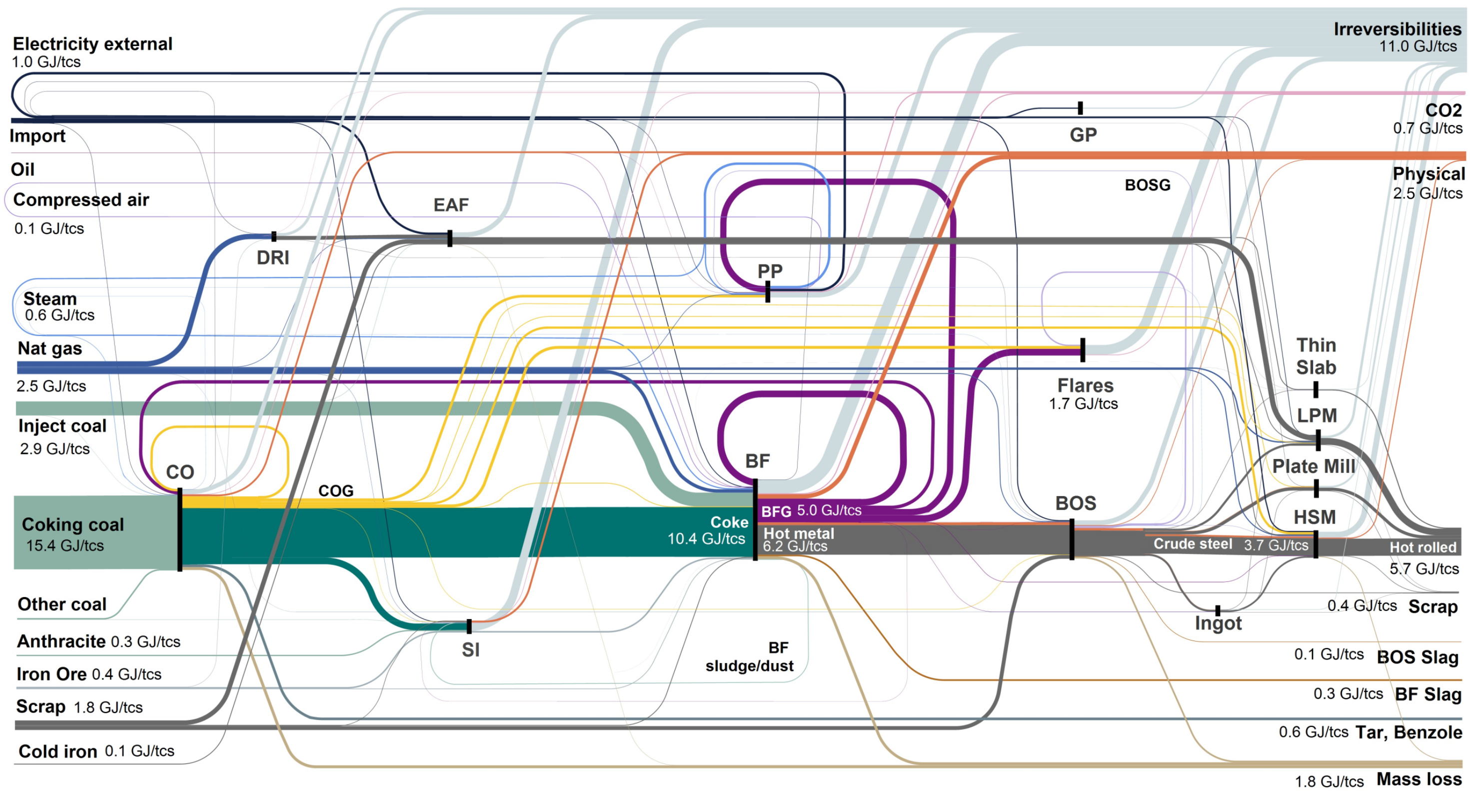

Figure 3.3: Global resource flows in the steel industry for 2010, in the form of a Sankey diagram and measured in units of exergy. This figure captures the relative scale of resource flows across the three main steel production routes. The BF is a great example of how exergy captures the upgrades in material quality (hot metal from iron ore) through downgrades in energy (coal to heat). The Sankey diagram reveals there is still potential to improve the recovery of both energy and material by-products, as well as that of waste heat. Coke oven (CO), sinter (SI), blast furnace (BF), basic oxygen steelmaking (BOS), direct-reduction ironmaking (DRI), electric arc furnace (EAF) and hot strip mill (HSM). These numbers assume final energy numbers for electricity, i.e. not including the energy used to produce the electricity.

Figure 3.4 depicts the destination of the three waste gases. Chemical exergy is currently recovered from the BFG (75%), COG (80%) and BOSG (61%) either as a direct fuel substitute or an input to electricity generation. These three off-gases already contribute 90% of the exergy input to on-site power plants. The remainder is flared, wasting the equivalent of 7% of the total global exergy input to the steel sector. Alongside this, physical exergy in the form of waste heat is lost mainly from the BF, CO and SI. This equates to 2.5 GJ/tcs. A full breakdown of the individual physical exergy of output flows is presented in Table 3.6, where the results are compared to previous studies.

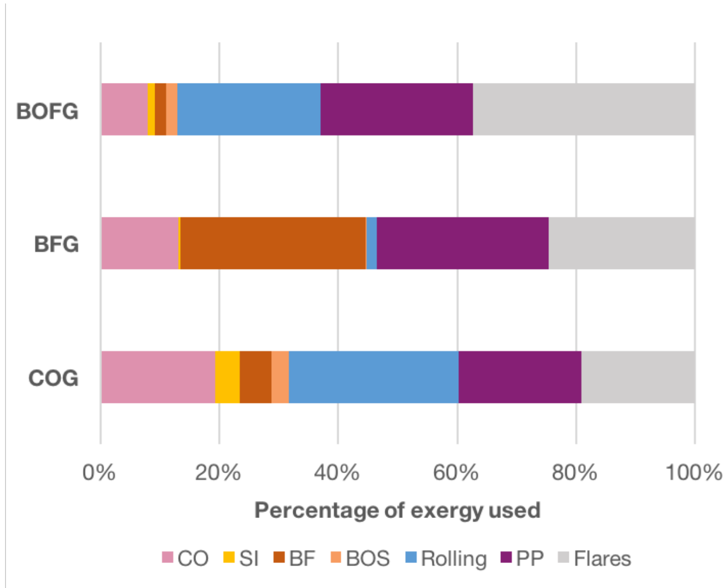

Figure 3.4: Destination of waste gases within the steel industry

Failure to capture material by-products represents a significant loss of exergy. Around 0.02 GJ/tcs (out of 0.1 GJ/tcs) of BOS slag, some 20 Mt per year, is stockpiled. Similarly, the BF produces 0.3 GJ/tcs of exergy as slag, some 360 Mt, of which about 10% is stockpiled. BF sludge/dust, 0.2 GJ/tcs and 28 Mt, appears to be fully recovered as feedstock in sinter plants, whereas close to 2 Mt of BOS sludge/dust is thought to be stockpiled. Attempts to recover BOS sludge/dust have proved challenging due to the high Zinc contents (Trung et al., 2011).

In total, 1.8 GJ/tcs of chemical exergy is lost as "yield losses" and these include carbon, iron and steel lost across all three production routes. Most material lost from the BF, BOS, EAF

Table 3.6: Comparison of physical exergy results. E – energy; B – exergy. RS – rolled steel.

Resource flow	de Beer (2000)		IEA (2008)		Li et al. (2010)		This study	
	E	T (ºC)	B(GJ/trs)	T (ºC)	E	T (ºC)	B(GJ/tcs)	T (ºC)
Coke	0.24	1100	0.14	1100	0.6	1000	0.2	800
COG	0.24	700	0.12	850	0.2	700	0.1	500
Sinter cooler gas	0.97	350	0.28	100-350	-	-	-	-
Sinter exhaust gas	0.23	350	0.12	100-350	0.7	300	-	-
Sinter	-	-	-	-	0.9	800	0.3	700
WHR in hot stove	-	-	0.33	250-400	-	-	-	-
BFG	0.82	500	-	-	0.8	200	0.7	350
BF slag	0.39	1300	0.26	1500	0.6	1500	0.3	1200
BOSG	0.29	1200	0.12	1600	0.2	1600	0.04	1200
BOS slag	0.02	1500	0.01	1600	0.2	1550	0.08	1200
Cast steel slab	1.39	1600	1.06	1600	-	-	0.5	1300
Hot rolled steel	1.04	900	0.62	900	0.6	900	0.3	900
Total	5.5		3.1		4.9		2.5	

and rolling processes, however, is thought to be re-circulated internally; these re-enter the sector in the form of the cold iron and scrap (often denoted as *internal scrap* or *own-arisings*) input. These internal remelting loops of iron and steel are energy-intensive and generate unnecessary additional CO_2 emissions before the steel even makes it to a product.

Irreversibilities sum to 11.0 GJ/tcs with 4.0 GJ/tcs lost in combustion, 3.2 GJ/tcs in chemical reactions, 2.3 GJ/tcs in heat transfer mechanisms and 1.4 GJ/tcs in expansion and compression. Table 3.7 provides a loss breakdown for each process. The largest share of irreversibilities is associated with combustion processes and chemical reactions, which are difficult to avoid without redesigning the process. Heat transfer and expansion/compression losses can be reduced through improved component design and by modifying temperature profiles.

3.4.2 Quantifying the resource efficiency of plants and production routes

Table 3.8 summarises the EI, exergy intensity (ExI) and RE results for the three steelmaking routes and nine plants. The overall ExI and RE of the global steel sector are 24.7 GJ/tcs and 32.9% respectively, including all three routes – averages weighted by production volumes – and with the addition of the rolling processes. The BF-BOS route is shown to be the least efficient,

Table 3.7: Exergy losses for seven processes, divided into the exergy in the mass loss, in CO_2 emissions and irreversibilities; measured in gigajoules per tonne of crude steel. CO – coke oven; SI – sinter; BF – blast furnace; BOS – basic oxygen steelmaking; EAF – electric arc furnace; HSM – hot strip mill; PP – power plant.

Exergy loss	CO	SI	BF	BOS	EAF	HSM	PP	Total
Mass loss	0.7	0.09	1.4	0.5	0.01	0.1	0	3
CO_2 emissions	0.2	0.2	0.3	0	0	0.03	0.2	0.9
Total irreversibilities	1.2	1.8	2.8	0.8	0.9	0.7	1.3	11

with an average RE of 29.1%. This is less than half the efficiency of the scrap-based EAF route (65.7%). Still, the BF-BOS route involves the more complex reduction of iron-ore to steel.

Table 3.8: Energy and exergy intensities, and REs (average, maximum and minimum) for individual plants and production routes. Routes do not include the rolling plants, and upstream electricity production is excluded.

		EI (GJ/t of product)			ExI (GJ/t of product)			RE (%)		
Plant	Product	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
CO	coke	8.0	5.0	12.1	8.2	7.2	12.0	85.3	78.1	90.7
SI	sinter	2.0	1.2	2.8	2.5	1.7	3.6	10.8	7.7	14.8
BF	hot metal	14.7	11.6	21.8	21.4	18.7	26.3	64.6	50.5	81.8
DRI	DRI	11.9	11.0	13.6	12.9	11.6	14.6	62.2	54.4	68.6
BOS	crude steel	0.2	-0.4	1.9	9.4	8.8	10.7	80.2	64.2	93.1
EAF		2.7	2.0	3.9	10.9	9.4	13.0	62.5	52.7	75.0
HSM		1.6	0.4	2.0	8.6	7.4	9.2	80.5	76.5	91
PM		2.8	1.6	5.3	10.4	9.2	13.2	73.1	61.6	81.2
LPM		2.5	0.3	5.9	9.6	7.1	13.0	77.3	55.6	94.8
Production route										
BF-BOS route	crude steel	26.3	20.5	33	29.8	25.3	37.7	29.1	23.1	33.0
DRI-EAF route		11.2	4.2	16.3	17.2	12.5	23.4	40.5	28.9	54.1
Scrap-EAF route		2.8	2.1	3.8	10.3	9.7	12.0	65.7	56.4	69.6
Global industry	crude steel	22.6	-	-	24.7	-	-	32.9	-	-

On its own, the BF plant (64.6%) is more resource-efficient than the EAF plant (62.5%). This rivals the most efficient combustion technologies available (i.e. diesel engines, gas turbines). However, once upstream coking and sintering plants and downstream steelmaking (BOS) are included, the combined RE is reduced to 29.1%.

The granularity of the data collected makes it possible to go beyond simple efficiency averages and min/max ranges, to characterise RE distributions for plants and production routes. Figure 3.5 shows the variability of RE for individual plants, weighted by production volume. The shape of most distributions varies across plants and is either bi-modal or skewed. This results from the use of different technologies, the varying amount of by-products recovered, differences in operational practices, and the potential randomness caused by only including a limited number of sites. The following sections describe each of the efficiency distributions in more detail.

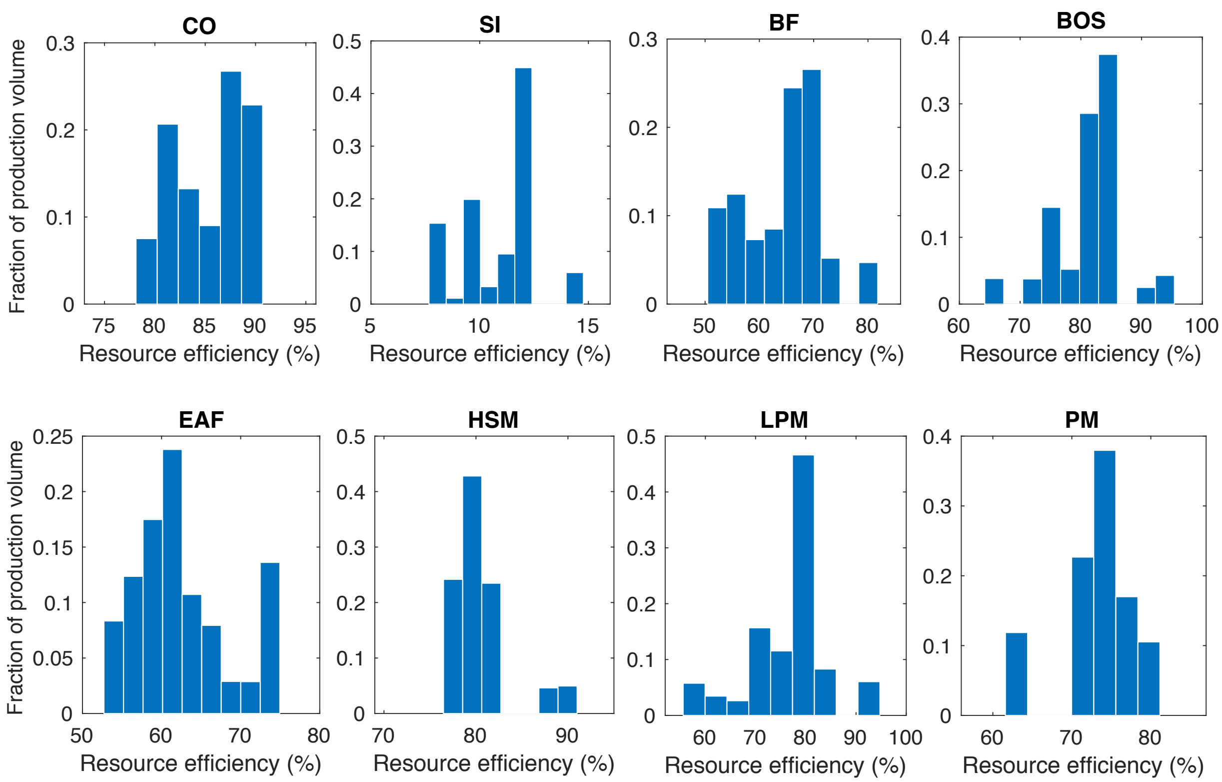

Figure 3.5: Distributions of resource efficiencies for eight plants: CO, SI, BF, BOS, EAF, hot strip mill (HSM), long product mill (LPM) and plate mill (PM). The DRI, ingot, and thin slab are not portrayed because the small number of plants compromises confidentiality.

Coking and sintering

The CO and SI plants exhibit the narrowest distributions (ranges of 13% and 7%). The fact that these two plants both involve energy-intensive processes, explains why industry is searching for ways to avoid these processes altogether (e.g. smelt reduction).

The CO has a narrow RE range (78-91%) which can be explained by the similarity in high-value fuel inputs and the consistent recovery of material by-products (tar and benzole) and COG (80% with a standard deviation of 36%) across the sites. The bi-modal distribution is thought to arise from technology differences, particularly the implementation of coke dry quenching (CDQ), found only at some sites. Improving the recovery of COG and steam presents the best solution for tightening this small RE gap in CO plants.

SI plants are the most resource inefficient processes across all three steelmaking routes (REs range from 7 to 14%). Although recovering waste heat from SI plants is the measure with the highest energy-saving potential, its implementation across sites is not explicitly captured in the RE distributions presented here (no information was available on this). Instead, the heterogeneity across sites is likely to result from differences in: the amount and type of solid wastes input in the sinter mixture; the amount of air leakage on wind main(s); the implementation of combustion and variable speed drive controls; and in the depth of the sinter beds (worldsteel, 2014*a*).

In the past, pellet plants have been proposed as more energy-efficient alternatives to SI plants (Hooey et al., 2014). Yet, in exergy terms, SI plants are advantageous because they are able to recover BF/BOS sludge, slag and other metallurgical wastes generated on-site. Reductions in the quality of iron ore fed to SI plants is known to increase their energy use (Hooey et al., 2014, worldsteel, 2014*a*). In the near future, decreases in the availability of high-quality iron ores may further incentivise improvements in the EE of sinter plants. If these EE improvements were to materialise and SI plants continue to use on-site metallurgical wastes, their REs may become comparable to or better than those of pellet plants. Optimal solutions will ultimately depend on the site's local conditions.

Blast and electric furnaces

In contrast to the CO and SI plants, the BF and EAF have wide bi-modal distributions, with ranges of 31% and 22% respectively. In the BF, the variation in RE results from two factors. First, the inherent flexibility of the process, which can use a wide range of fuels. Second, the large number of technologies available for improvements, the different combinations of which cause varying levels of RE. The main improvement technologies include: the injection of pulverised coal or other injectants, such as tar or natural gas; the adoption of combustion monitoring and controlling systems; the installation of top recovery turbines; and the recovery of BFG as a fuel. From these, the largest RE variations arise from the use of BFG top-gas recovery (standard deviation of 22%). Currently, the amount of BFG recovered and the electricity produced and consumed in BFs varies substantially across sites. Differences in the recovery of slag and sludge are not captured as no information on the rates for the individual sites was available.

The EAF shows a wide range of REs and a bi-modal shape. This results from the DRI-to-scrap input ratio, where the peak at the high-end (74%) represents scrap-based EAF plants, and the peak at the low-end (62%) the DRI-fed plants. Combined with these differences in burden types, there are three other factors causing the variation in RE: the existence of multiple melting practices worldwide; the wide range of EAF types; and differences in the fuel inputs. The main technologies relevant to the operation of EAFs are: improved monitoring and control (mainly for electricity and gas); improved flue gas monitoring; and scrap preheating or bottom stirring.

Basic oxygen steelmaking

The BOS plant shows a symmetrical distribution which is close to normal. This wide variation in RE (nearly 30%) mainly results from differences in the percentage of BOSG recovered; the recovery of BOSG averages 61% with a standard deviation of 46%, which is the largest variation of the three off-gases. Other differences arise due to discrepancies in the batch waiting times (and therefore in the fuel consumption of pre-heating) and in the ratio of scrap-to-hot metal input. The most relevant improvement options available to BOS plants include the recovery of BOF dust/sludge, the increase in the calorific value of the BOSG recovered through better management of ladle lids, and the increase in the ratio of scrap input (mainly operational aspects).[3]

Hot-strip, long-product and plate mills

Out of the three rolling processes, the PM is the least resource-efficient (with an average of 73.1%) followed by the LPM (77.3%) and the HSM (80.5%). The low RE of plate mills could be a consequence of their often low productivity in comparison to HSMs and LPMs – low productivity translates into higher energy use (worldsteel, 2018). The LPM shows the broadest RE range of the three. This can be explained by the fact that this plant category actually encompasses a wide range of process types – including rod/bar, section and wire-rod mills – each of which may have different production schedules and require different qualities (worldsteel, 2018).

[3]Increases in scrap ratios in the BOS reduce the energy needed to produce steel overall; it reduces the demand for hot metal. However, high scrap ratios (above 35%) can cause operational difficulties in BOS plants.

The small RE variation across HSMs results from: the consistently high heat-recovery rates for the reheating furnaces; low levels of electricity use, in part due to the widespread implementation of advanced control systems; the relatively uniform size of the mills across sites. The data set reveals a few highly-efficient plants (at $\sim$ 90%), which likely result from the reporting of low electricity inputs – only a small number of the plants in the data set have implemented a large number of improvement measures (over 18) (worldsteel, 2014*a*). Some of these technologies include: air-to-fuel ratio controls to improve combustion efficiency; air preheating; the recovery of heat from waste gases; the use of regenerative burners or walking beam furnaces; and hot charging.

Production routes

Figure 3.6 portrays the RE distributions for the three steelmaking routes. These show that heterogeneity exists in all three, indicating there is still technical potential for improvement. The BF-BOS route has a uniform distribution with three peaks in efficiency, ranging from 20.5% to 33.0%. Despite the wide distributions observed in the REs of the BF and BOS processes, the BF-BOS route shows a relatively narrow RE range. This emphasises that benchmarking entire routes can provide a more realistic understanding than benchmarking – as is often performed – individual plants. It is unlikely that a given site contains all the most efficient plants: there are trade-offs between different technologies, and plants must choose which to implement based on their specific local conditions.

The small RE variations that do exist mainly result from the implementation of CDQ, off-gas recovery systems, or hot-connect between the BOS plant and the HSM. Although independent of plant size, variations also arise from differences in the proportions of imports/exports of intermediate products for each site.

The DRI-EAF route shows a normal-like distribution and has a greater range in RE compared to the other two routes. This arises from three differences: the shares of metal inputs, i.e. the DRI-to-scrap ratio for each site; the types of technologies (e.g. HyL III versus MIDREX process); and the degree to which fuel-utilisation measures are installed. This ratio of iron inputs is known to have a significant effect on the energy intensity of the EAF process – with higher fractions of scrap resulting in greater efficiencies (worldsteel, 2014*b*). The scrap-EAF route shows a positively skewed distribution, suggesting a smaller gap for incremental improvement.

3.4.3 Estimating improvements in resource use

Table 3.9 summarises the resource savings (in exergy) available from making individual improvements to plants, and from moving to best practice and best available operations. Three key

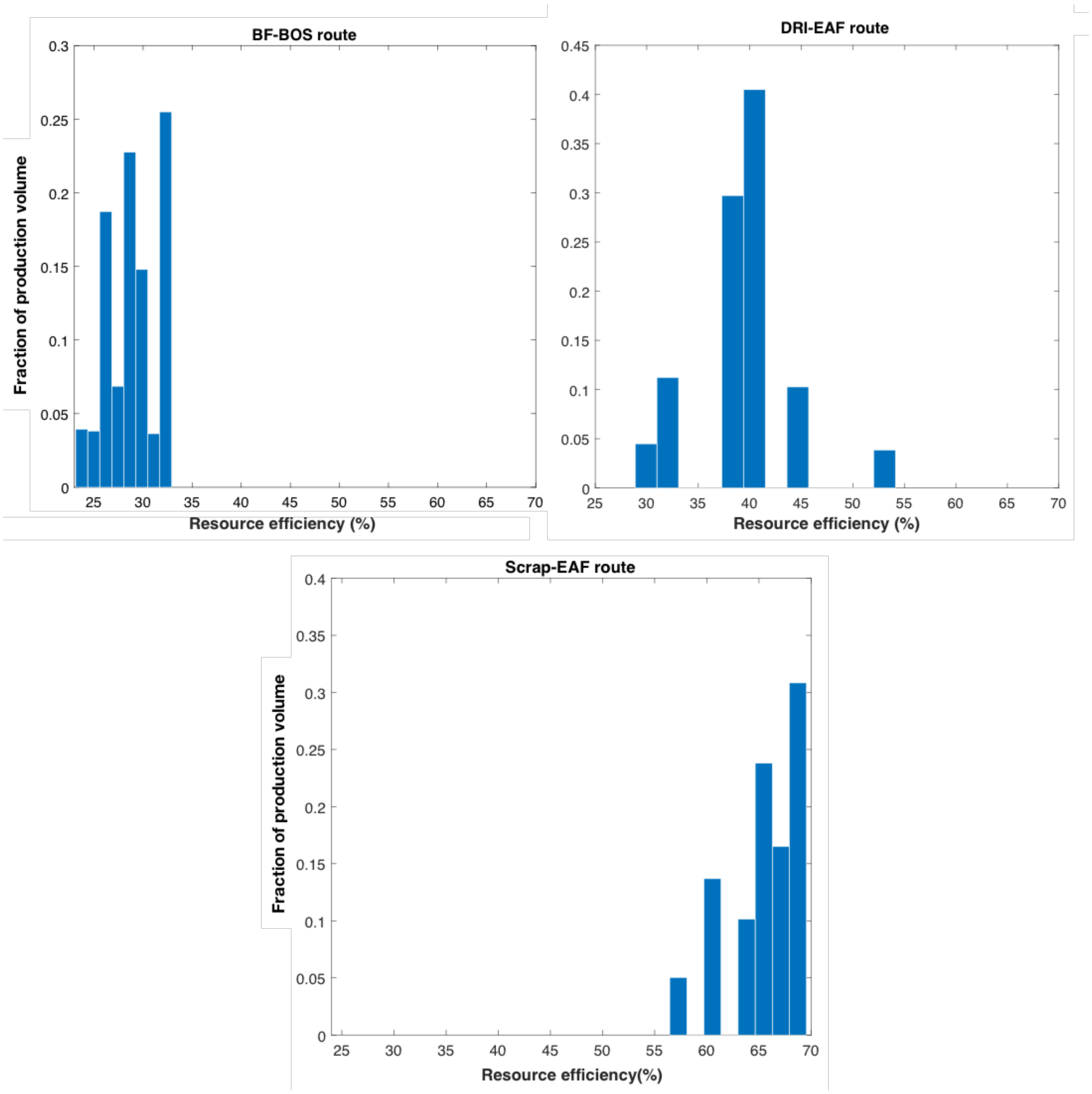

Figure 3.6: Distributions of RE across the three production routes

opportunities for reducing resource inputs are introduced: recovering flared off-gases and material by-products; moving to best available operation; shifting from ore-based to scrap-based production. Plant- and route-level values are different as rolling is not included in the routes.

Table 3.9: Global resource savings available in the steel industry; WHR – waste heat recovery; MBR – Material by-product recovery. This table is subject to rounding errors

Individual improvement options (EJ of exergy/yr)				Best Practice (Best Available)		
Plant	Off-gas recovery	WHR	MBR	Yield loss (direct)	IEA (2008) (EJ of energy/yr)	This study (EJ of exergy/yr)
CO	0.4	0.2	-	0.1	0.4 (0.6)	0.9 (1.1)
SI	-	0.3	-	-	-	0.2 (0.9)
BF	1.2	0.7	0.04	0.4	1.2 (1.5)	2.0 (4.5)
DRI	-	-	-	-	-	0.1
EAF	-	0.2	0.01	0.1	0.25	0.1 (0.5)
BOS	0.1	0.7	0.03	0.1	0.25	0.6 (1.3)
Rolling	-	0.3	-	0.1	0.3 (0.4)	0.5 (1.3)
Total	1.7	2.5	0.09	0.8		4.4
BF-BOS	1.7	2	0.07	0.7	-	3.4 (4.1)
DRI-EAF	-	0.1	0.01	0.1	-	0.5 (2.3)
Scrap EAF	-	0.1	0.01	0.1	-	0
Total	1.7	2.2	0.09	0.9	2.3-2.9	3.9 (6.4)

The current practice of flaring off-gases results in the loss of 1.7 EJ of exergy: 1.2 EJ of BFG, 0.4 EJ of COG and 0.1 EJ of BOSG. Globally, a maximum of 2.2 EJ/yr of waste heat could be recovered in addition to this – an amount greater than the final energy use of the EU28 steel industry in 2015. From this 2.2 EJ, up to 1.8 EJ is available from solids such as slags, crude steel, coke and sinter. Recovering heat from solids is more challenging than from gases or liquids. However, recent technology advances have made commercial recovery a reality for slag (Zhang et al., 2013), coke, and sinter (Carpenter, 2012). Exploiting this technical potential requires policy intervention, as current return on investment rates are too low to drive take-up for most European companies (Banerjee et al., 2012). Similarly, fully recovering off-gases requires substantial site-level modifications and large investments in infrastructure to install new piping and gas holders.

Moving from current to best available operation in primary production can save up to 6.4 EJ/yr globally, equal to about 25% of the sector's total exergy input and 40% of the total primary energy input to EU (28) industry in 2015 (Eurostat, 2016). The largest fraction of this improvement comes from the BF-BOS route, as this is the most energy-intensive of the three. Within this route, the BF plant yields the largest energy savings through improved operational excellence, alongside increased recovery rates of BFG, slag, and sludge/dust, and reductions in coal/coke inputs.

Reducing the cooling and heating cycles of the main outputs, such as coke, sinter and steel, provides another opportunity to reduce exergy losses – as already suggested by de Beer (2000) in 1998. Improving the amount of hot charging between the BOS and the hot rolling facility is particularly promising. In the BF-BOS route, reducing Fe yield losses can save up to 0.8 EJ/year; later stages of production should be prioritised as these save an increasing amount of embodied upstream exergy losses.

A shift from ore- to scrap-based production is key for reducing resource use and mitigating emissions in the steel industry. Currently, scrap-based EAF consumes one-third of the exergy required for BF-BOS, and is more than twice as resource-efficient. Assuming steel demand doubles by 2050 (Waugh, 2013) and scrap steel from recycling accounts for half of all demand (limited by available scrap for recycling) (Pauliuk et al., 2013), then switching from ore-based to scrap-based production could result in almost 8 EJ in exergy input savings.

This shift does not necessarily mean the demise of the BF-BOS route, as this can accept over 30% scrap input (Bradaric et al., 2016) (out of the total metallic charge), and currently 44% of the global scrap is melted in BOS plants. In addition, in 2050 half of all steel demand is still expected to come from ore-based production (Pauliuk et al., 2013), so any shift towards secondary production needs to be accompanied by parallel exergy savings in the BF-BOS as part of a push to best available operation.

3.5 Discussion

This section will compare the results obtained in this study of the global steel industry's resource use and efficiency to previous exergy studies (Section 3.5.1), and discuss both the associated implications for the future of steelmaking (Section 3.5.2) and the effectiveness of the exergy-based metric (Section 3.5.3).

3.5.1 How do these values compare to previous studies?

To validate the current analysis and to evaluate today's RE in the context of historical developments, the efficiencies and resource savings estimated here are compared to previous studies.

Table 3.10 summarises the main studies found in the literature, which provide efficiencies.

Table 3.10: Exergy efficiency values found in the literature (CO – coke oven; SI – sinter; BF – blast furnace; BOS – basic oxygen steelmaking; EAF – electric arc furnace; DRI – direct iron reduction; PP – power plant).

Reference	Scope	CO	SI	BF	BOS	EAF	DRI	PP	BF-BOS	DRI-EAF
Szargut et al. (1988)	Case study	78.5	-	28–59	85–92	52.2	-	-	29–30	34
Akiyama and Yagi (1988)	Japan	82.0	25.3	51-84	-	-	-	-	-	-
Masini and Ayres (1996)	US	83–90	4.3	44.8	67.6	-	-	-	36.1	-
Bisio (1993)	Case study	-	-	-	-	41.9	-	-	-	-
de Beer (2000)	Theoretical	-	-	-	-	-	-	-	29-48	-
Costa et al. (2001)	Mix of plants	68–85	12–24	52–80	75–85	67–69	65–68	-	30–56	28–49
Wu, Wang, Pu and Qi (2016)	Case study	78	16.6	42.2	49.8	-	-	27	-	-

The third column in Table 3.10 shows that the REs reported for coke ovens (CO) fluctuate over time, with some recent studies (Wu, Qi and Wang, 2016) reporting lower values than studies conducted 30 years ago (Akiyama and Yagi, 1988). This variation can be explained by the fact that these studies analyse different coking technologies, with and without CDQ (plants with CDQ have higher REs) and assume different chemical exergies for coal and coke. Our results show higher REs that have narrower ranges than those found in the literature, suggesting that improvement measures – mainly CDQ – are now more widely adopted. For sintering, our RE (10.8%) is lower than in most previous studies (12–25%), except for the 4.3% reported by Masini and Ayres (1996). Our results consider the sinter to be the sole useful process output, and assume no heat is recovered; this may therefore underestimate the true global average RE for sintering.

Discrepancies in the REs (in exergy) for the BF and the BOS mainly arise from differences in the assumptions made on the recovery of waste gas, BFG and BOSG respectively. For example, the RE of 64.6% for the BF in this analysis is much higher than the 42.2% quoted for the Chinese network (Wu, Wang, Pu and Qi, 2016). When information on the amount of BFG recovered is missing, some studies report ranges rather than single values, e.g. Akiyama and Yagi (1988) and Costa et al. (2001). These results suggest that, on average, global BF and BOS plants are still able to improve their RE by improving the recovery rate of these off-gases.

Earlier studies on EAFs report REs at the lower end of the range reported here. Our result for the global average EAF (62.5%), however, mainly reflects the fact that our average EAF plant represents a mix of processes with different inputs, ranging from 100% scrap to 100% DRI. Scrap-only EAFs have a higher RE (65.7% from Table 3.8). This is comparable to that reported by Costa et al. (2001) and reflects the accomplished improvements in the technology since the 1960s (American Iron and Steel Institute, 2001) – compared to Bisio (1993) and Szargut et al. (1988), who also assume 100% scrap input. These improvements in RE have primarily resulted from reductions in electricity consumption, and increases in steel productivity. This suggests that, today, the potential for improvement of EAFs is limited.

The average RE of the BF-BOS route is 29.1%, less than that reported by Costa et al. (2001), de Beer (2000) and Masini and Ayres (1996). There are two reasons why the RE reported by Masini and Ayres (1996) for the US in 1988 is higher than today's average: the shares of primary and secondary production for the US in 1988 were 53% to 47%, a lot higher than today's global average; and most of the iron ore was pelletised rather than made into sinter, the latter having a lower RE than the former. Costa et al. (2001) and de Beer (2000) use indicative and reference data respectively, and their analysed plants therefore have higher efficiencies. The RE for the DRI-EAF route (29-54%) calculated here lies within those reported by Costa et al. (2001); although, the two are not directly comparable, as Costa et al. (2001) based their analysis on a single DRI technology, COREX. The lack of comparable global exergy studies on the steel industry makes it impossible to evaluate historical improvements in resource efficiency.

Previous energy studies on the sector, however, facilitate comparisons in terms of energy intensity. For example, in 1998 and based on data for 1994, de Beer (2000) estimated that the EI of the global steel sector was 24 GJ/tcs (tonne of crude steel). Our results show that in the past sixteen years, the EI of the sector has decreased by at least 1.4 GJ/tcs to 22.6 GJ/tcs worldwide. This reduction is likely to be larger if we consider that de Beer (2000) fully credited the recovery of off-gases and did not account for the actual amount recovered, as we have done in this study.

The estimated resource savings can be compared to three studies: the IEA's last detailed study on industrial energy and emissions (IEA, 2008), the IEA's 2010 Energy Technology Perspective report IEA (2010*b*), and a study by Saygin et al. (2011). In 2008, the IEA (2008) predicted that 2.9 EJ of primary energy could be saved by shifting current BF-BOS production to best practice technologies. Our analysis estimates greater potential savings in primary production (6.4 EJ/yr) for two reasons. First, the IEA neglects the savings from the sinter plant and the BFG recovery, which are included here. Second, our study includes ME options – mainly in the BF, BOS and rolling – such as yield improvements or the recovery of material by-products.[4] The IEA (2008) also estimate that an extra 2.1 EJ could be saved by increasing the use of recycled steel. Our calculation suggests these savings could amount to 8 EJ/year if the chemical exergy of the steel scrap input is considered.

In 2010, the agency provided a more detailed breakdown of the energy savings that were available for the global steel industry in 2007 (IEA, 2010*b*). Figure 3.7 depicts these savings disaggregated into countries and improvement options. But again, the 4.1 GJ/t of crude steel savings predicted by the IEA does not include the entire gamut of ME measures relevant to upstream production plants, such as the recycling of scrap, improvements in iron yields, reduction in raw material inputs or the recovery of slag and sludge.[5]

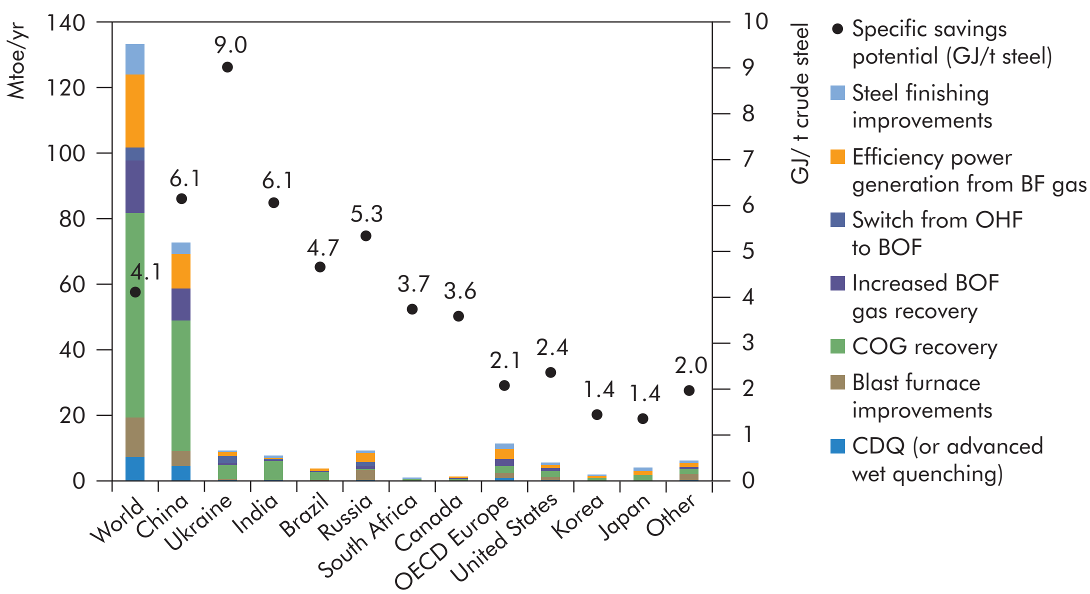

Figure 3.7: Energy savings available in the steel industry in 200, based on Best Available Technologies (BATs). Image obtained from IEA (2010*b*); CDQ – coke dry quenching, COG – coke oven gas; BFG – blast furnace gas.

[4]The value of flared COG reported by the IEA (2008) for China in 2005 (250 PJ) corresponds to about 60% of the value calculated in this study (430 PJ); percentage which is comparable to the fraction of global pig iron produced in China.

[5]This estimate was updated to 4.4 GJ/t crude steel in IEA (2012*b*).

Saygin et al. (2011) predict that shifting to best practice technologies in the steel industry could yield savings of up to 7.3 EJ/year. In their study, however, the authors combine savings available in both primary and secondary production, and these can therefore not be directly compared in isolation. In this study, combining the savings available from implementing best-practice technologies in the primary production routes, and the shift to scrap-based production would suggest that savings of over 14 EJ/year are possible. In practice though, savings are likely to be smaller, as improvements in BF-BOS sites cannot materialise if these are substituted with EAFs.

3.5.2 What are the implications for the future of the global steel industry?

This RE analysis reveals that the scrap-based EAF is twice as resource-efficient as ore-based steelmaking. These results provide an additional rationale to pursue the scrap-EAF route as a low-carbon solution for the steel industry; in addition to requiring less than half of the energy input, this route also consumes fewer resources overall. Discouragingly though, the recipe for mitigating emissions in the steel industry is not so simple. Evidence suggests that the shift to scrap-based production will be hindered primarily by the future availability of scrap (Pauliuk et al., 2013) and by quality restrictions inflicted by the entrapment of metal elements (Daehn et al., 2017).

In its most recent study, the IEA (2017) predicted that by 2060, BOFs will be faced out completely, and that by 2040, ore-based production will only provide 20% of the global hot metal production. To achieve the agreed CO_2 emission reductions in its *Beyond 2-degrees* scenario, the agency continues to hinge on the implementation of disruptive technologies. It estimates that over 40% of steel in 2035 will need to be produced through innovative smelt reduction technologies – this reaching over two thirds of production in 2050. This is likely to be an overly optimistic (if not unrealistic) scenario for the steel industry, not least because smelt reduction currently produces less than 1% of steel worldwide and 2035 is less than 20 years away.

Given the limitations on scrap use and the slow deployment of innovative technologies such as carbon capture and storage or smelt reduction, an obvious alternative for BF-BOS production – the most energy-intensive route – is to shift to DRI-EAF steelmaking. Despite not being as resource-efficient as scrap-based plants (∼41% versus ∼66%), the DRI-EAF route is, on average, more efficient than ore-based routes (∼29%). If the embodied energy extant in the scrap is considered, the benefits become even greater, as energy has already been input to create the scrap in the first place. This is especially relevant for countries with a long tradition in steelmaking such as the UK, as suggested by Serrenho, Mourão, Norman, Cullen and Allwood (2016), where end-of-life scrap is more widely available.

Yet the substitution of ore for scrap is also possible in the BF-BOS route. In fact, our results show that globally almost 44% of the scrap (in exergy) ends up in the BF-BOS route. Scrap can be input into sintering plants and blast furnaces, but mostly ends up in BOS plants. Bradaric et al. (2016) and IISI (1998) say that BOFs can take up to 30-35% scrap input (in terms of the metallic charge), but plants consuming above to 40% are not unheard of (Bradaric et al., 2016, Wang et al., 2009). Pushing scrap limits in BF and BOS plants is not without problems: product quality and operational reliability can be compromised, as the "weights of the scrap are very important for cooling, as well as yield" (Short et al., 2014). Another key aspect is that it remains uncertain how much of this scrap has been generated internally from low material yields – before the steel becomes a product at all – and how much of it is end-of-life scrap. For this option to truly yield a more resource-efficient and less carbon-intensive industry, end-of-life scrap must be prioritised and internal arisings minimised (Cullen et al., 2012, Milford et al., 2011).

The need to maximise the use of end-of-life scrap is unquestionable. Which processes the scrap will or should be used in, however, remains unclear. Looking forward, it seems that all three steelmaking routes will be vying for the available end-of-life scrap. Yet, in practice, other aspects may hinder the shift from BF-BOS production to secondary steelmaking, and some BF-BOS sites are likely to remain in operation in the medium term. Both governments and companies have reasons to keep BF-BOS sites open: committed investments, the need to maintain jobs, or to localise production and ensure security of supply. This study shows that moving current performance to best practice in the BF-BOS and the DRI-EAF routes can, together, save between 3.9 and 6.4 EJ/year (exergy) – with almost two thirds of the savings arising solely from the BF-BOS route.

In the absence of rebound effects, this improvement is possible because of the technological heterogeneity that exists across sites (refer to Figure 3.5). de Beer (2000), European Steel Association and European Steel Technology Platform (2014), worldsteel (2014*a*) and EC (2011*a*) provide detailed lists of technologies that can help steel producers achieve best practice, suggesting that improvements in primary (including both ore-based BF-BOS and DRI-fed EAFs) and secondary steelmaking (scrap-based) should therefore go hand in hand.

3.5.3 How good a measure of RE is the proposed exergy-based metric?

Measuring RE in exergy units has multiple benefits:

1. *This consolidates energy and material efficiency options into one metric.*

   An examination of Equation 3.4, and Figures 3.8 and 3.9 reveals that the RE metric is capable of capturing differences in energy input and material output in the same way as the conventional EI metrics. However, unlike with EIs, the RE metric can reflect differences in raw material input ($\sum b_{in}(M_{in})$) and material by-product recovery ($\sum b_{MB}(M_B)$).

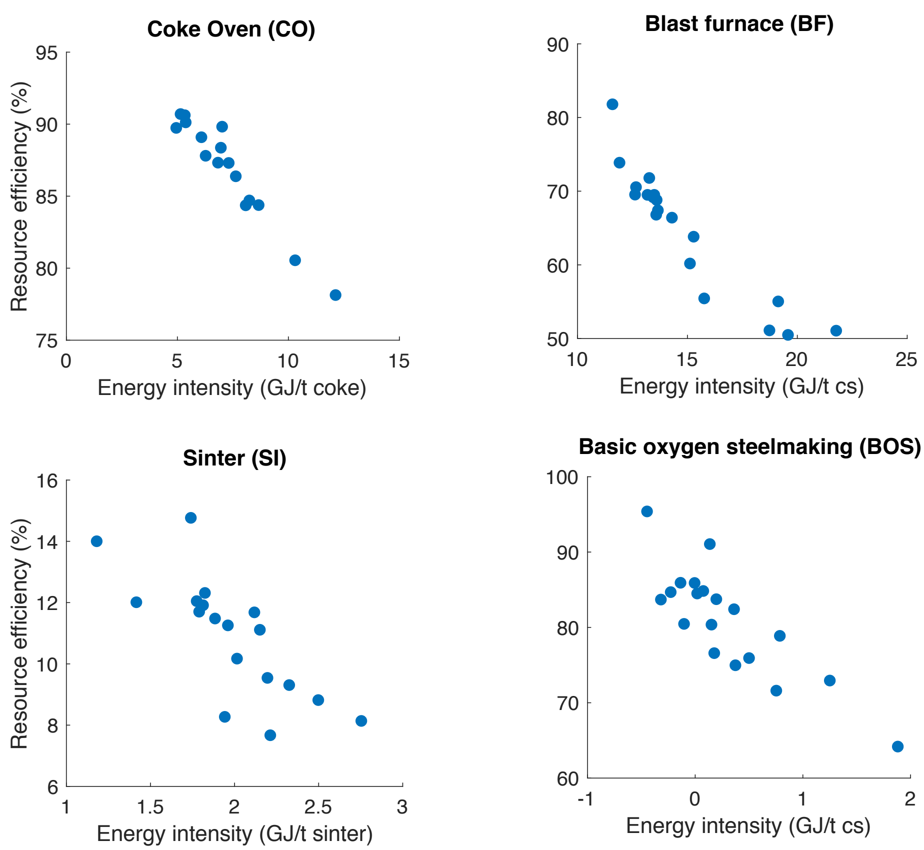

Figure 3.8: Resource efficiency versus energy intensity for individual plants

For processes where energy (inputs, outputs, by-products) makes up the main flows and where metal yield loss is the sole material-related factor, EIs and REs provide similar insights. This is the case for the CO and the BF plotted in Figure 3.8 for example – with Pearson correlation coefficients of -0.96 and -0.93 respectively. Conversely, for processes where material inputs (as opposed to their energy) compose a higher fraction of the total resource use (measured in exergy) and the output products are mainly materials, the cor-

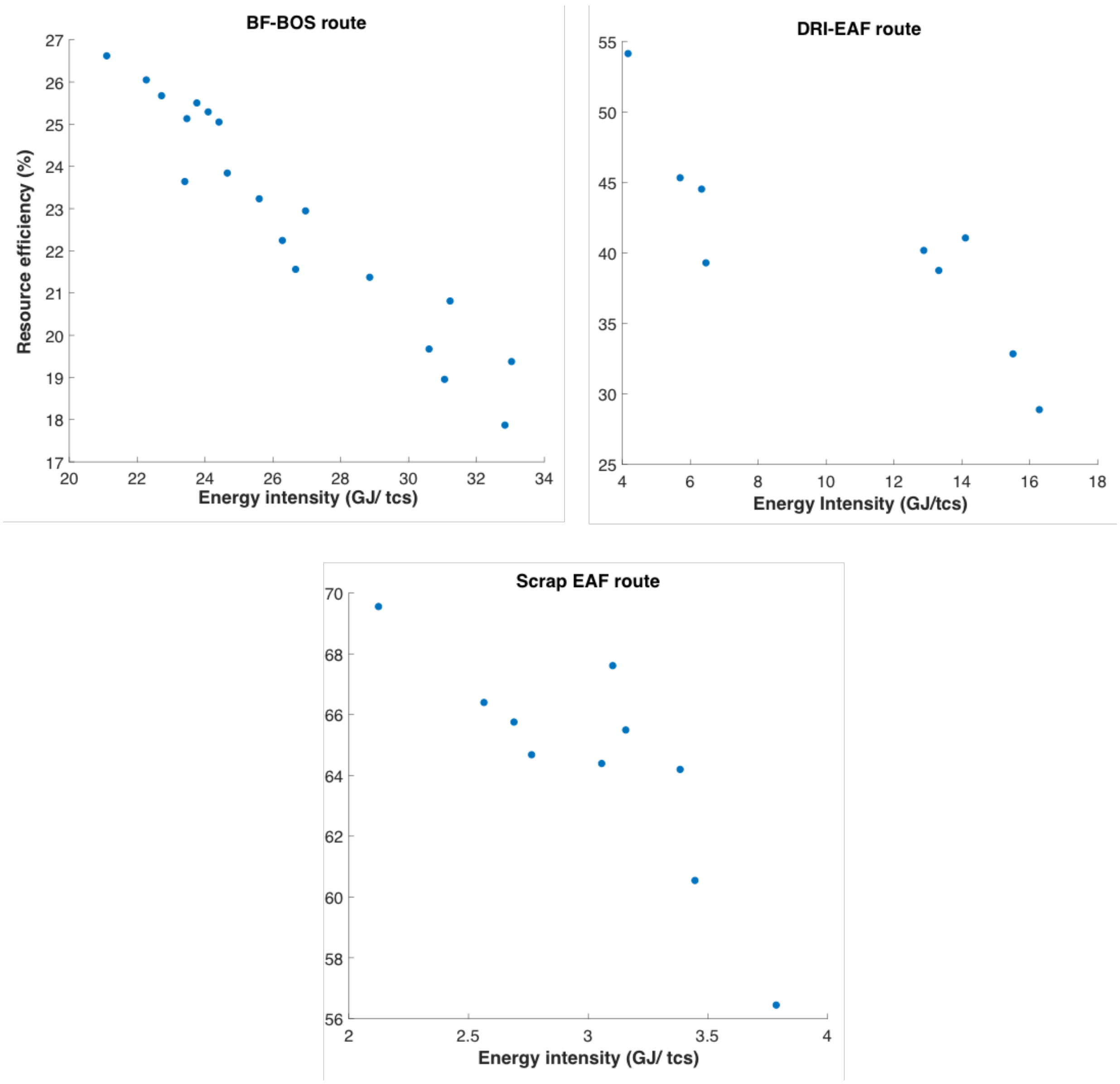

Figure 3.9: Relationship between resource efficiency and energy intensity for the three routes

relation between RE and EI is not as strong: -0.77 for the SI and -0.84 for the BOS.

For production routes (Figure 3.9) the correlation between RE and EI is relatively high: -0.96 for the BF-BOS route and about -0.83 for both the DRI-EAF and the scrap-based EAF routes. This results from the fact that the differences across sites currently results from differences in the recovery rates of the waste-gases, and the fuel inputs. With improved data on the recovery of material by-products, the correlation between the two metrics is expected to decrease for the BF-BOS route, where differences in the amount of slag and sludge recovered in the BF and BOS processes would only be captured in the RE metric.

2. *This can be applied to multiple industry sectors.*

   Across the literature, the method of exergy has been applied to analyse resource use in a bounty of industry sectors – from metallurgical (Masini and Ayres, 1996, Szargut et al., 1988) to chemical (Sorin and Paris, 1998, Szargut et al., 1988) to manufacturing processes (Gutowski et al., 2009). In addition, as outlined in Section 2.1, Renaldi et al. (2011), Tanaka (2008) and Lior and Zhang (2007) have sought to standardise exergy efficiency definitions across different processes and sectors. This suggests that the use of exergy is a promising alternative to benchmark industry processes and sectors.

3. *This facilitates comparisons across different processes.*

   By virtue of being dimensionless, the exergy-based RE makes it possible to compare across processes/routes in other industries. For example, it is possible to compare the RE of a copper furnace and a steel blast furnace. As with any efficiency metric, these comparisons must be made across processes with similar physical/chemical transformations, and not across fundamentally different processes whose efficiency definitions are likely to be different.

4. *This reveals real process losses.*

   Exergy captures both the First and Second Laws of Thermodynamics and therefore reveals the irreversibilities in real processes and the quality of resource flows, including both chemical and physical properties. Understanding the irreversibilities generated in production plants can guide efforts to improve technology designs.

5. *This is usable at different system levels, from process, to plants, sites or regions.*

   Exergy has been used in a myriad of applications at multiple system levels. The possibility of using the same method at different levels of aggregation makes it a suitable tool with which to bridge technical engineers and high-level decision-makers. Energy managers can use the resource flow maps and the exergy-based measures of RE to shed light on inefficient processes and to prioritise investments. Similarly, policymakers can use this information on resource use and RE as an instrument to set sector-specific priorities and targets.

An integrated RE measure is valuable to other fields related to climate action. One example is green finance and more specifically its definitions of 'green' investments. Currently most green investment definitions limit their scope to three interventions: energy efficiency, carbon capture and storage, and supply technologies (e.g. biofuels, renewables and nuclear energy) (Inderst et al., 2012). This RE metric provides a promising tool to quantitatively assess the 'greenness' of resource-efficient solutions – which have been hitherto excluded – thereby incentivising ME as part of the wider umbrella of green investments.

One of the main challenges in using exergy is the calculation of the chemical and physical exergies. To resolve this, academics have tabulated the chemical exergies for many of the resource flows involved in the production of energy-intensive materials (Ayres and Ayres, 1999, Szargut, 1986). For the physical exergies, additional information on pressures and temperatures may be required, although these are widely available in the literature too. Tabulated values would provide good approximations for industry-wide benchmarking exercises. With improvements in data availability, more detailed calculations using custom compositions are possible.

Although exergy is a good proxy for the RE of bulk materials production, it must be acknowledged that it may not be a good reflection of the value of final products, especially in downstream processes producing specialised steels. Yet, its ability to incentivise the better use of materials and to capture the upgrades in material quality (or utility) through expenditures of high-grade fuels and low-quality raw materials, make it a worthwhile undertaking. Not least because the upstream production of bulk materials causes its lion's share of industrial emissions.

The choice of system boundary is an unavoidable decision that can impact a metric's effectiveness and its associated interpretations. The RE metric described here is designed to encourage stakeholders to invest in measures that fall within their control. It therefore avoids the need to allocate upstream energy use to downstream processes, instead energy use can be attributed to the process directly. The prioritisation of ME actions downstream and across wider system boundaries, however, should consider the embodied energy of these materials. For a given amount of material reduction, the further down in the supply chain it is, the greater the associated energy savings (Allwood et al., 2012). In general, the best way of addressing the subjectivity associated with boundary choices is for researchers to be as transparent as possible about their underlying assumptions. They should also be explicit about the reasoning behind their choice and the impacts these can have on the usefulness of their metric.

3.5.4 Research evaluation: has the research question been answered?

The literature review in Chapter 2 identified the need to develop new metrics that can provide an integrated, and therefore more complete, measure for the conversion efficiency of energy and materials in industry. To address this, Chapter 3 strives to answer the following question: *How can energy-intensive industries measure and benchmark their energy and material efficiency in a unified manner?* The research presented in Sections 3.1 to 3.5 answers this question by developing an integrated exergy-based metric that measures energy and material efficiency on a single scale. The metric has been tested using steelmaking data from 38 plants (globally) and shown to be an effective metric for comparing RE between plants and routes, with worldsteel adopting the metric into its benchmarking methodology.

In summary, the RE metric proposed here can:

- incentivise the adoption of both energy and material efficiency options. This, by virtue of quantifying the input and output of material as well as energy flows. This metric is particularly relevant to promote the recovery of material by-products, which is currently often neglected in all other performance metrics.
- reveal both the irreversibilities in real processes and the quality of resource flows. This is possible because such an exergy-based RE captures both the First and Second Laws of Thermodynamics. Understanding the scale and structure of resource flows and their irreversibilities can guide efforts to improve technology designs.
- facilitate the consolidation of energy and materials into a single metric, and therefore be an ideal alternative to benchmark industry processes and sectors as a result of its dimensionless nature, i.e. it ranges between 0 and 100.

Chapter 6 builds on the insights presented in this Chapter and assesses the wider implications of the results obtained. Further research developments, which would support the widespread adoption of the proposed resource efficiency metric in industry are also outlined.

3.6 Chapter Summary

This chapter develops a holistic measure of resource efficiency that can incentivise the adoption of both energy and material efficiency options. It shows that exergy facilitates the consolidation of energy and materials into a single metric, and can therefore be key in incentivising the recovery of material by-products. This, alongside the dimensionless nature of the metric, makes it an ideal alternative to benchmark industry processes and sectors.

The adoption of this exergy-based RE metric is a step towards understanding the interactions of resources and process efficiencies in industry systems. To fully operationalise exergy as a cross-sector benchmarking method, efficiency definitions must be standardised for different types of industry processes. More detailed resource data will help us understand how yield losses, the recovery of by-products and the reduction of energy use affect RE, and will make it possible to quantify the improvement potential in recovering waste heat, for which no data is available.

Results from the analysis on the global steel industry reveal that the sector is 32.9% resource-efficient and that secondary steelmaking is twice as efficient (65.7%) as ore-based production (29.1%). The steel sector has two options to improve its resource efficiency in the short-to-medium term. First, it can shift some of the existing primary production plants to best practice. Several options are available to facilitate this shift, from the improvement of off-gas recovery, to the reduction of yield losses, to the recovery of slag and slurry. Second, the sector can increase its use of end-of-life scrap. As capacity to do so is available in all three production routes, steel producers will need to decide how far they reduce their iron ore/ hot metal charge: whether only a little (in the BF-BOS), a moderate amount (DRI-EAF) or all the way (scrap EAF). It is the responsibility of the governments to decide which option to incentivise.

This global study of the RE of the steel industry offers three main contributions. It provides:

- a holistic resource analysis that considers both energy and material efficiency improvement options side by side.
- the most recent and comprehensive investigation of energy and material use in the global steel industry, including resource efficiency distributions for plants and production routes.
- the first comprehensive comparison of current, average exergy-based RE with best practice and best available operations for the global steel industry.

"In 1862, Bessemer took out a patent for the employment of a pair of converting vessels [...] forming such an extremely practical and efficient set of apparatus for carrying on the process, that although very many clever men have since done their best to improve upon these plans, the essential portions area retained in the most approved plants of the present day." (*J B Lippincot & Co*, *1877*)

4

Assessing the resource efficiency of industry processes during operation

Q2: Can we gain a better understanding of resource efficiency using energy and material control data on a close to real-time basis?

Case study: Tata Steel UK, Basic Oxygen Steelmaking plant

Part of this Chapter is based on a conference paper titled "From control data to real-time resource maps in a steel-making plant". An extended version was published in the journal *Applied Energy*, with the title "Control data, Sankey diagrams, and exergy: assessing the resource efficiency of industrial plants". The research was done in collaboration with Dr Richard Lupton and with help from Chris Barnes and Chris Williams from Tata Steel.

4.1 Introduction

The introduction to this thesis (Chapter 1) revealed that reducing material use in energy-intensive industries – measures under the rubric of ME (material efficiency) – is indispensable to achieve the agreed targets on CO_2 emission reductions (Allwood et al., 2011). In a series of studies, Cullen et al. (2012) and Cullen and Allwood (2013), among others, showed that these industries are currently wasteful; around half of all steel and aluminium produced is either scrapped in production, or used unnecessarily in over-specified products. Not all of these losses are recoverable, but there are significant practically achievable solutions to reduce existing material losses in energy-intensive industries (Cooper et al., 2014, Milford et al., 2011, Serrenho, Mourão, Norman, Cullen and Allwood, 2016). In fact, as articulated by IEA (2015*c*), in these industries, energy savings from ME measures have the potential to deliver larger savings than EE (energy efficiency).

To realise these opportunities, however, individual industry firms must identify and prioritise ME interventions at actionable time-frames and scopes, that is, within boundaries directly controlled by them. For this to happen, a detailed awareness of resource flows is needed. It is therefore crucial that firms have the appropriate instruments to jointly analyse and visualise energy and materials; these must be complex enough to capture the nuances of real operations yet simple enough to be easily communicated to decision-makers.

Chapter 3 demonstrated the benefits of using an integrated exergy metric to measure industry's RE (resource efficiency) and to compare energy and material efficiency options side-by-side. It also evidenced the ability of Sankey diagrams to condense extensive amounts of flow data and structure, as well as to reveal resource losses in large, complex systems. With the soaring capabilities of digital devices, the decline in the price of electronics and the improvements in data analytic methods, there is an opportunity to automatically extract available control data to analyse resources and to visualise resource use at actionable scopes for plant managers.

Exploiting the value that resides in a plant's control data could help reduce the amount of time, expertise and money needed to conduct energy and material audits, the scale of which is currently viewed as problematic by energy-intensive industries in the EU (EC, 2012*a*). Moreover, the EU has demonstrated its political support for the shift to a data economy – fostering the potential of digital data to improve industry and society as a whole. As part of its *Digitising European Industry* strategy, the EU has committed to spend EUR 300 million on the next generation of digital industrial platforms, in particular through "new reference architecture models leading to smart factories and services" (EC, 2016*a*). And yet reviewing the literature in Section 2.3 uncovered that at the plant-level, no study uses control data to jointly analyse the EE and ME of production plants in units of exergy. A tool providing a holistic picture of energy and materials that is representative of real-time operations is therefore yet to be provided.

This chapter aims to provide such a tool by capitalising on three previously developed methods: (1) the well-established exergy approach to combine the analysis of energy and materials; (2) the use of control data collected on a real-time basis through plant meters; (3) Sankey diagrams as a means to transparently depict the combined flows of energy and materials. The analysis is explored using the case study of a TataSteel basic oxygen steelmaking (BOS) plant.

More specifically, this RE tool must: (1) improve the current understanding of the facility's integrated energy and material flows at the operational scale; (2) provide a single metric to track the integrated resource efficiency of the production system; (3) use available sensor data as much as feasibly possible; (4) ensure that plant managers, technicians and decision-makers have access to data granularities, which are appropriate for their management remit; (5) be based on a transparent and repeatable method, that can be scaled up and across to other areas of the site.

The rest of the chapter is structured as follows. First, the method used to analyse and visualise the resource efficiency of the BOS plant is explained (Section 4.2). Second, Section 4.3 describes the results obtained for the resource flows and REs, as well as the resource savings available from implementing EE and ME improvement measures. This section also discusses the benefits of the new RE metric by comparing it to conventional energy-intensity metrics (Section 4.3.4). Last, the analysis results and their associated implications are further discussed (Section 4.4).

4.2 Method

This section outlines the method used to analyse and visualise the RE of the TataSteel BOS plant. The use of control data to produce maps of resource flows and measures of RE is described comprehensively. For it is this, rather than the specific results obtained for this case study, that we are most interested in. The method is described in five steps: the outline of the process structure and raw data (Section 4.2.1); the pre-processing of this raw data (Section 4.2.2); the balancing of resources (Section 4.2.3); the conversion of resource flows into exergy and the calculation of resource efficiencies (Section 4.2.4); and the visualisation of resource flows (Section 4.2.5). From this, improvement options are evaluated (Section 4.2.6). The Python code written to read, clean, balance and analyse the resource data can be accessed at Lupton and Gonzalez Hernandez (2018).

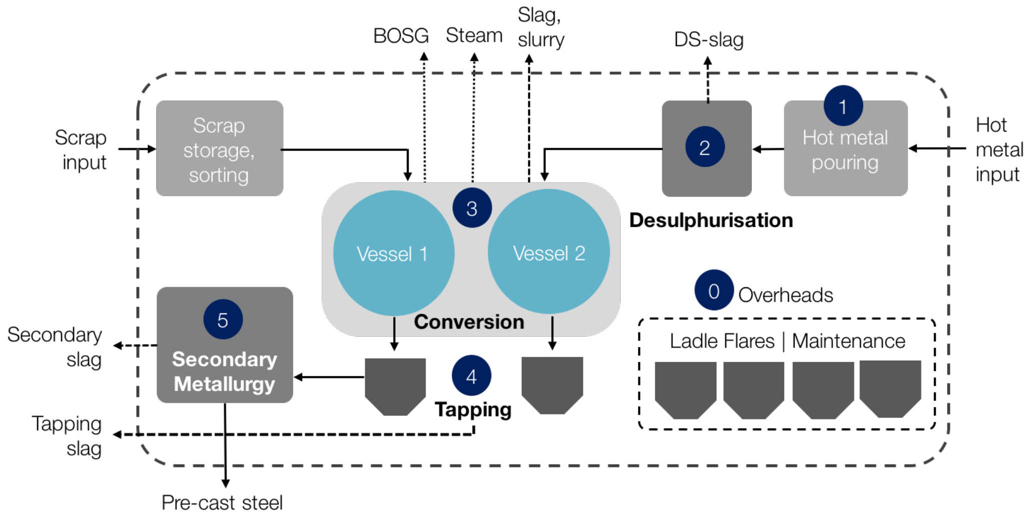

Figure 4.1: BOS plant process structure and system boundaries

4.2.1 Describing system boundaries and raw data inputs

Basic Oxygen Steelmaking, also known as the *Bessemer* process, is an oxidation process that reduces the carbon content in iron from 4.5 wt.% to 0.05 to 0.25 wt.% in steel. In doing so, it produces by-products such CO, CO_2, SiO_2, MnO and iron oxides (released as product gases or trapped in slag). Four key processes within the TataSteel BOS plant are studied in detail (portrayed in Figure 4.1): the desulphurisation of the hot metal, where lime and magnesium are added to reduce the metal's sulphur content; the oxidation process in the converter; the tapping of the steel from the converter, where additions are sometimes added; and the refining of the steel – denoted as *secondary metallurgy* (SM), where the steel grade is defined through additions of ferro-alloys, carbon and top slags either in degassers or argon stirrers.

Information on the structure of the resource flows can, in theory, be obtained from process flow diagrams. Yet, in practice, diagrams with the right level of information are rarely available, and it is necessary to rely on conversations with on-site experts to define the wire structure underpinning the plant's internal resources. Figure 4.1 shows the system structure analysed in this study.

Production plants collect resource data from several sources, and at multiple time-scales and system levels. This discrepancy in the data sampling rates is exacerbated by the analysis remit,

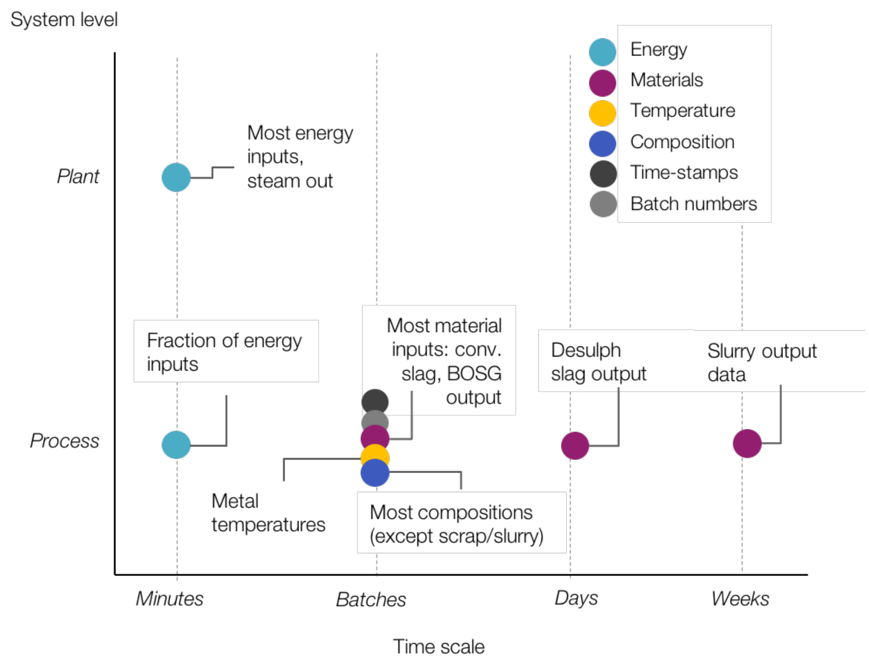

Figure 4.2: Data availability described in terms of time scales and system levels; *conv.* – converter; *BOSG* – BOS gas; *Desulph* – desulphurisation.

which includes multiple units and resource types. Figure 4.2 summarises the time-scales and levels at which data is measured in the BOS plant. Six types of control data were collected: mass flows, energy flows, physical properties (e.g. temperature and pressure), composition, time-stamps and batch-numbers. Additionally, a control log provides start and end times for each process.

Energy data, both at plant- and process-level, are metered continuously and are available on a per minute basis. Most energy flows are metered only at plant-level, with little data collected on the energy use of individual processes. Plant-level energy meters measure: the input of natural gas (NG), electricity, nitrogen, oxygen and coke oven gas (COG), as well as the output BOS gas (BOSG) and steam in the converter. Electricity and nitrogen are fed to all four processes, whereas oxygen is input to the converter only, and the gas inputs are solely used for the pre-heating of ladles (e.g. overheads). At the process-level, only a fraction of the COG and NG inputs to the ladle pre-heaters (or flares) is metered.

All other material inputs are measured discretely, at the point when the material is charged to the process. The main material flows are the hot metal input, intermediate steel flows, and the refined steel output. Other minor material inputs include fluxes (e.g. magnesium, dolomite or lime), additions such as ore or ferro-alloys, and steel scrap. The remaining material flows primarily include by-products such as slags and slurry. Every material flow is allocated to a batch number and given a time and location stamp. This information allows materials to be directly attributed to specific processes or batches, which is not the case for the energy flows.

Figure 4.2 reveals that the availability and format of the composition and physical data is more inconsistent. Most *composition data* is available on a batch-level; i.e. for the hot metal, steel, BOSG, and converter slag. For the rest of the materials, including scrap, fluxes, additions, other slags and slurry, only an *averaged* composition is available. Data on the *physical properties* of materials is only available for the metal flows (per batch) and the steam outputs (per minute).

4.2.2 Pre-processing the raw data inputs

In measuring production performance, managers and engineers must gather the disparate data just described and process it before meaningful information can be extracted from it. The data will need to be aggregated to different time-scales and scopes, depending on the purpose of the analysis. Highly aggregated data (at a level of weeks, months or years) is commonly used at high-management levels to understand general trends and the overall amount of savings available. Engineering staff, however, typically work with detailed data at time-scales of minutes, hours or days to solve safety, stability and reliability issues. This suggests that, for this analysis, a wide range of time-scales and scopes are available, and it is not immediately obvious which will provide more insights into the RE of production operations.

To establish appropriate system levels and to facilitate the integration of this approach into the company's practices, 13 participants working in the steel industry were interviewed. Eight were based on-site and five were based off-site in sustainability teams. Participants were responsible for a range of different tasks, from the operation of individual processes to the management of entire work areas or business units. Semi-structured interviews lasting between 45-60 minutes were conducted; later transcribed to perform further analyses. The interviewees were asked about ten questions, within which two or three were posed regarding the time-scales and scopes involved in the decisions they would typically take; see Table 4.1 for some examples.[1]

[1]These interviews were conducted as part of a larger interview process, looking at RE and policy. A more

Table 4.1: Pre-prepared questions for the semi-structured interviews

nº	Question
1	How often do you review performance?
2	What type of decisions do you make regarding resource use?
3	What level is data aggregated to, to make the business case for investing in an improvement option?
4	What is the time-scale of the data used in the performance reviews?

From these interviews it was concluded that, for each scope, data needs to be reported at multiple temporal scales. Based on this evidence it was possible to establish a simplified framework to define the multiple tiers of analysis required. These tiers, shown in Figure 4.3, align with the characteristics of the management roles in which decisions on RE improvements are made (depicted in Figure 4.3a). The four tiers are namely: operators, front-line level, mid-level and high-level management. Figure 4.3a depicts the type of data handled by the various management tiers, and the types of questions each of these is responsible for answering. Figure 4.3b shows that, for example, for mid-level managers, who typically review performance on a daily and weekly basis, it is necessary to display data both at a batch level (a few hours) as well as daily and weekly.

Because the main aim of this chapter is to serve as a proof-of-concept for the integrated approach tested in Chapter 3 (at operational scales and using control data), it is sufficient to apply the analysis to a selection of time-frames and scopes. Given the data provided by TataSteel, and the time available to conduct this research, the scope of the analysis was limited to two levels: at the highest resolution, each process is analysed in batches (at the level of hours), and at the lowest resolution, the entire plant is analysed on a daily basis, starting from midnight. This choice is sensible for two reasons. First, because front-line managers are the first tier at which production performance is evaluated (see Figure 4.3a); below this, at the minutes-level, safety, reliability and product quality are the sole operational concerns. Second, because it is across batches, rather than across hours, that operational variations are most likely to be observed.

Allocating process times and aligning system levels

Section 4.2.1 revealed that raw data is available at multiple aggregation levels. Therefore, for flows across the BOS plant to balance, the aggregation levels of the raw data need to be aligned to the appropriate time-scales and scopes first.

detailed description is provided in Section 5.2.3.

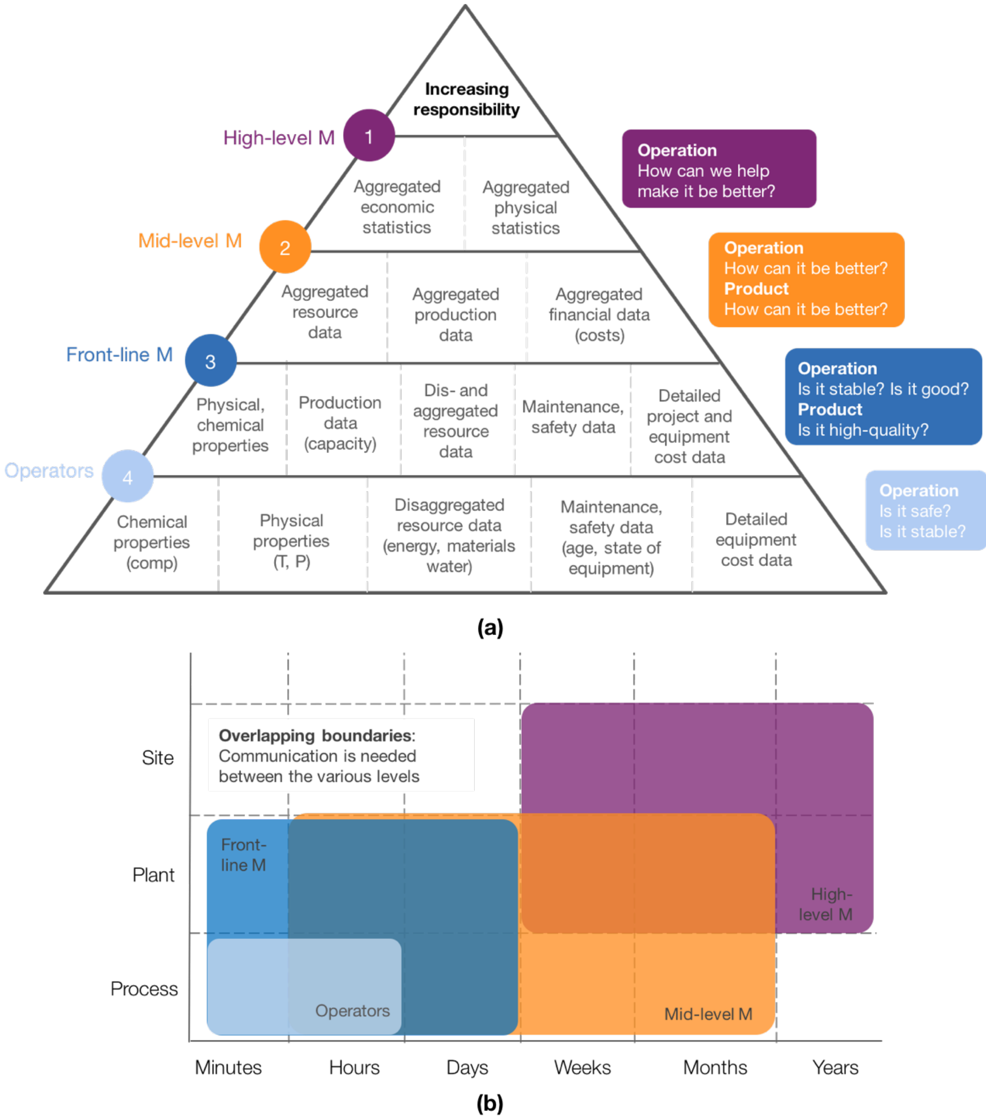

Figure 4.3: (a) Pyramid portraying the type of information and decisions taken at the four management levels; (b) Time-scales and scopes of the multiple tiers of the analysis; M – management.

For the plant-level energy inputs to balance across individual processes at a scale of days and batches, they need to be further disaggregated, i.e. allocated down. Information on batch timings was re-processed from available control log files to give a list of start times and end times for each process, and each batch; see Figure 4.4. Three types of times were recorded: waiting times (t_w), start times (t_{in}) and process duration times (t_p). These timings were used to build a binary matrix describing when each process is active, for each minute (depicted in Figure 4.5a). From this, it was possible to estimate how much energy each process uses.

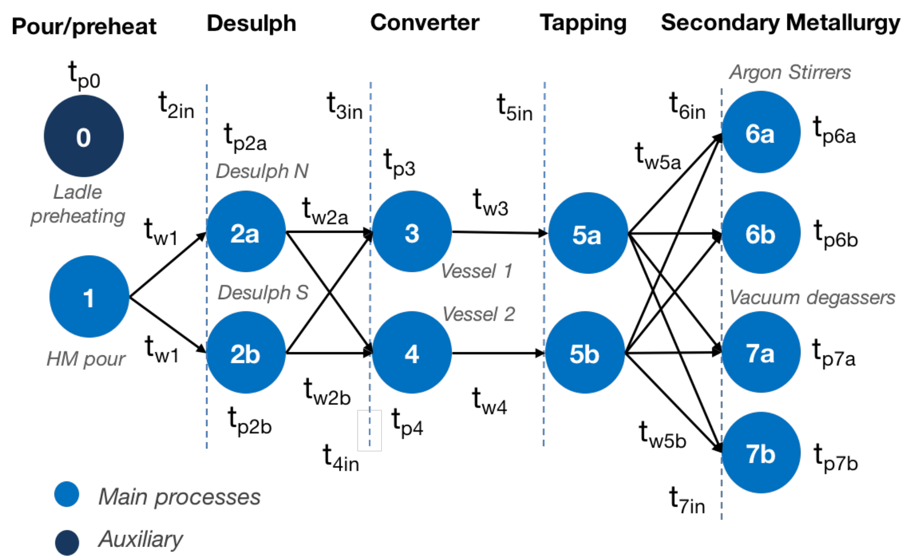

Figure 4.4: Flow chart showing the structure used to establish batch timings

An ordinary least-squares regression was used, for which we assumed that process consumption profiles varied linearly between the start, middle and end of the process (based on the processed batch timings). The regression explains about 10% of the electricity, NG and nitrogen use, and over 85% of the steam inputs; the remainder is classified as daily overheads. Figure 4.5b depicts the actual fluctuations of the energy inputs (black) and the assumed shapes (red). Figure 4.5c and d are snapshots illustrating the amount of steam and electricity allocated to certain processes. Unlike energy inputs, which are metered every minute, some materials are measured at high temporal aggregation levels. For example, the slurry and the DS slag are measured weekly and hourly. To balance flows at batch-level across processes, these flows have to be allocated down temporally. In the absence of better information, they are assumed to be distributed linearly across batches. The same assumption is made when flows are aggregated to the daily level.

Filtering the raw data

Large volumes of unstructured data often contain errors. In the analysed plant, raw data is logged into the control system in two ways: automatically or manually. Both can cause errors in the

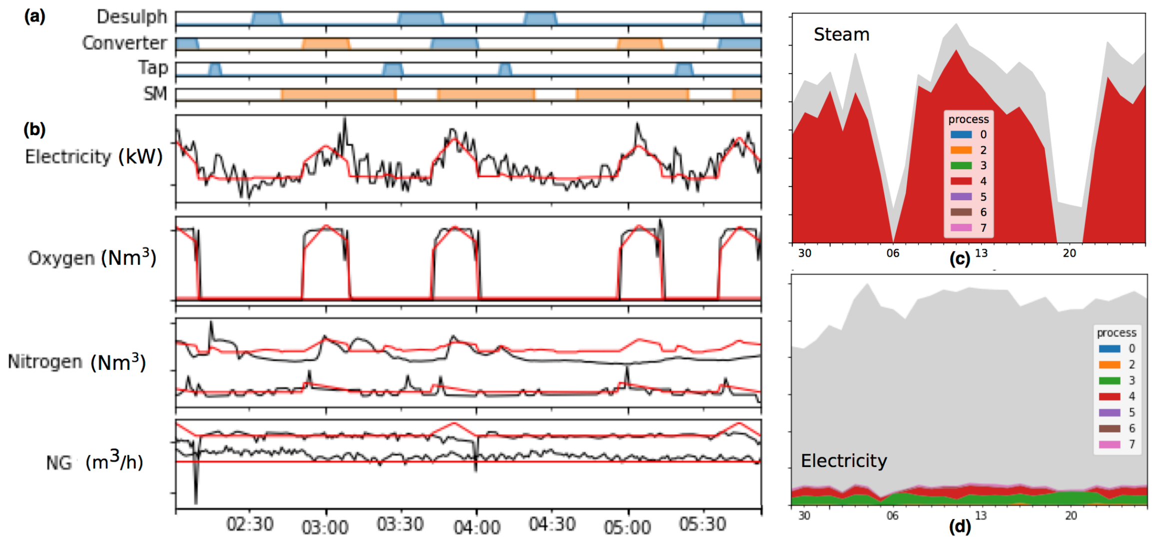

Figure 4.5: Allocation of energy flows to specific batches and processes. (a) Activity matrix depicting which and when specific processes are on or off; (b) Snapshot of energy input flows across time, red lines indicate modelled flows whereas black depict the true values; (c) Portion of steam flows explained through the allocation regression; (d) Portion of electricity flows explained through the allocation regression.

data, either in the form of wrong or missing values. For example, the operator may input the wrong value for a given flow in a given batch, or the right value but for the wrong batch number. Similarly, for a flow in a given batch, the control system may fail to log a flow value altogether.

In the BOS plant, iron and steel is only lost in batches, in which either the quality of the steel output is considered inappropriate or operational difficulties are experienced. In some cases this results in entire batches needing remelting. In others, where yield losses are dropped on the ground, the lost iron or steel is left to cool and then sent to an on-site metal recovery plant. Here, the lost metal is crashed and later re-fed into the BOS plant as scrap. For these batches, where yield losses are generated, the data is logged manually and this is therefore specially prone to errors. For this initial analysis, 'faulty' batches containing multiple errors were excluded.

For the remaining batches, different mechanisms were devised to filter the missing or conflicting data points depending on the type of data. All of the data inputs can contain errors, including the time-stamps and batch numbers. Table 4.2 outlines further details for specific resource flows. Different steps are taken depending on the process for which the data is incomplete. For example,

Table 4.2: Process of filtering out wrong/conflicting data inputs

Data type	Missing data	Check	Filled in with
Composition	Slag Slurry Scrap Hot metal	Are batch-level compositions available?	**Yes:** take previous composition; **No:** take average composition
Mass	Tap weights	Was the previous/following batch logged?	**Yes:** take value for previous batch; **No:** take average value
	Slag weights		**Yes:** take value for previous batch; **No:** take average slag-to-tap weight ratio
	Hot metal weights	*For converter:* check that oxygen was input	**Yes:** take value for previous batch; **No:** discard batch
Physical properties	Temp./press.	Check previous batches	**Yes:** take previous; **No:** take average
Identifiers	Batch numbers	Check previous and following batches in heat log	If error remains unclear, remove batch from dataset
	Time-stamps	*For converter:* use oxygen data; *For rest:* check log for other processes; or whether inputs were recorded	*For converter* – **Yes:** take average; **No:** remove batch; *For rest* – **Yes:** if tapping, remove batch; if desulph or sm, use average. **No:** remove batch

for desulphurisation and tapping, when the control log appeared incomplete, this was validated across with the mass data. In some cases, this indicated that no desulphurisation took place, in others, it reflected a logging error. If mass had been input, but no times had been recorded in the control log, then the duration for the previous batch would be used. If this was missing too, then average duration times would be used. Batch times would then be further validated across the time-stamps reported in the material data, which indicate the time at which the material was charged (and not that at which the process was initiated). These missing or conflicting values in the raw data must be resolved before data for all batches and days can be balanced, i.e. before the model described in Section 4.2.3 can be applied [2].

[2] The logging of data for SM is more faulty and required special care – partly because there are four units that can be used to refine steel. In occasions, a single batch will be refined through both, either for intentional quality reasons or unintentional operational issues. For batches going through more than one SM unit, the beginning of the first unit was taken as the start-time and the end-time was taken as the end of the last unit.

4.2.3 Outlining the resource flow system structure

The exercise of tracing resource flows is denoted as material and energy flow analysis (MEFA). The main feature of MEFAs is that they are governed by the principle of material and energy conservation. Assuming that the storage of mass is negligible (in this case this is small compared with the steel flows), this balancing principle can be expressed mathematically as per Equation 4.1. Here, x is any substance that is conserved; k_I and k_O are the flows that are input and output respectively. By definition, resource flows need to balance at each point in time.

$$\sum_{k_I} x_{input} = \sum_{k_O} x_{output} \tag{4.1}$$

Figure 4.6 portrays the structure of the resource flows, each of which is colour-coded according to the type of data input. Calculations relevant to all processes are described first. Aspects specific to individual processes are subsequently described by navigating this figure. The flow numbers in Figure 4.6 are used to help the reader identify these more easily.

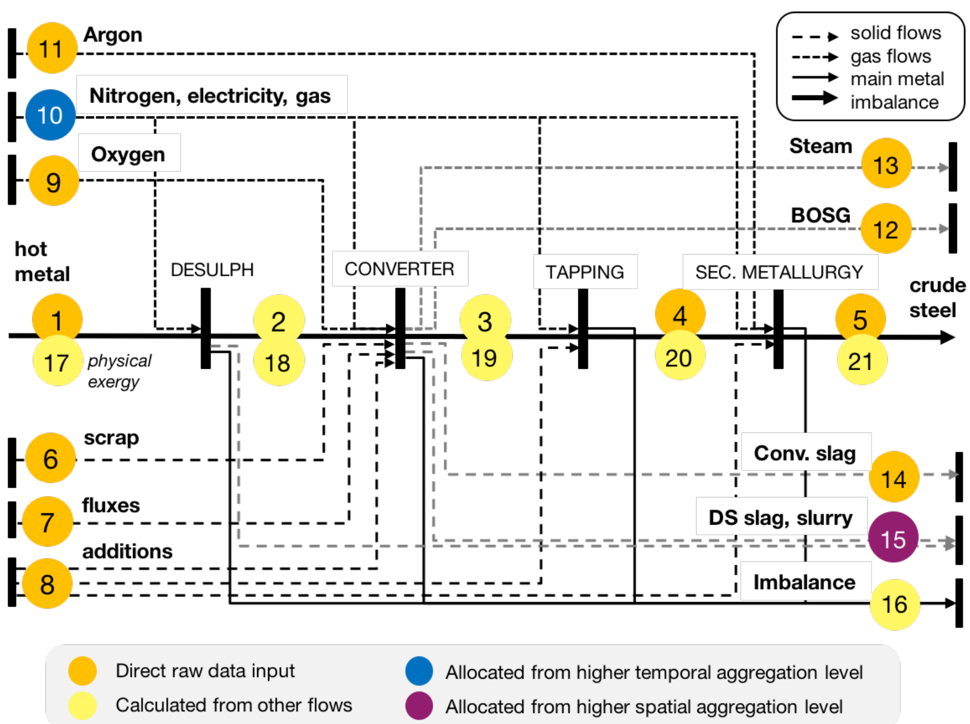

Figure 4.6: Resource flow wire structure. Colour is used to distinguish between the various ways in which the mass values were obtained for the different flows.

General assumptions

Three main assumptions are made that apply to all processes: (a) the nitrogen and argon input into the processes is assumed to be vented; (b) energy inputs that cannot be allocated to individual processes are assumed to be consumed as overheads; (c) the difference between inputs and outputs is denoted as the *imbalance* (positive imbalances are assumed to be irreversibilities, whereas negative imbalances are assumed to capture the errors in the chemical exergy of scrap).

Process-level calculations

Desulphurisation (desulph): During desulphurisation, the sulphur content in the hot metal (HM) is reduced through the input of lime and magnesium (MG). HM is input (1) alongside two energy inputs (10) – electricity and nitrogen (NIT), both of which are allocated from plant-level metering. Outputs include desulphurised hot metal (DSHM) and (15) desulphurisation slag (DSLAG). This slag is skimmed from the metal before this is poured into the converter. In mass units, this is described by Equation 4.2.

$$m_{\mathrm{MG}} + m_{\mathrm{lime}} + m_{\mathrm{HM}} + m_{\mathrm{NIT}} = m_{\mathrm{DSHM}} + m_{\mathrm{DSLAG}} + m_{\mathrm{NIT}} \tag{4.2}$$

Secondary metallurgy (SM): Although the last process, SM is considered first because SM data is used to back-calculate the tapping steel (TST) input and converter output flows (3). Here, steel is refined (4) before it is cast. Steel can be refined using two types of processes, namely argon stirring or vacuum degassing. These involve different types of processes, but for the modelling exercise, the relevant difference is that argon stirrers consume argon (AR), whereas the degassers use steam. Equation 4.3 describes the flows for the two processes combined, where RST stands for refined steel. All data inputs (8, 10, 11) are known except for (3) and the secondary slag (SSLAG). The former is calculated by assuming this to be the same as (5), i.e. that the metal yield is equal to 100%. The latter is calculated as the difference between inputs and outputs.

$$m_{\mathrm{ADDS}} + m_{\mathrm{TST}} + m_{\mathrm{AR}} + m_{\mathrm{TSLAG}} + m_{\mathrm{NIT}} + m_{\mathrm{steam}} = m_{\mathrm{RST}} + m_{\mathrm{SSLAG}} + m_{\mathrm{NIT}} \tag{4.3}$$

Converter: The converter has multiple material inputs – including scrap (6), fluxes (7), additions or ADDS (8), and DSHM (2) – and material outputs, namely converted steel (CST), converter slag (CSLAG) and slurry (14, 15). It consumes NIT, electricity (10), oxygen (9) denoted as OXY, and produces BOSG (12) and steam (13). Air (17), which is sucked into the BOSG, is included in the mass balance and calculated using the data provided on the BOSG composition; the nitrogen portion of the gas is assumed to be equal to the air input. Equation 4.4 summarises these flows.

$$\begin{aligned} m_{\text{ADDS}} + m_{\text{fluxes}} + m_{\text{DSHM}} + m_{\text{scrap}} + m_{\text{OXY}} + m_{\text{NIT}} + m_{\text{air}} = \\ m_{\text{CST}} + m_{\text{CSLAG}} + m_{\text{slurry}} + m_{\text{steam}} + m_{\text{BOSG}} + m_{\text{NIT}} \end{aligned} \tag{4.4}$$

Tapping: During tapping, the steel from the converter is poured into a ladle. In doing so, some CSLAG is carried over (15). During this process, NIT and electricity are consumed (10) and additions are often input (8). The resource flows are summarised in Equation 4.5.

$$m_{\text{ADDS}} + m_{\text{CST}} + m_{\text{CSLAG}} + m_{\text{NIT}} = m_{\text{TST}} + m_{\text{TSLAG}} + m_{\text{NIT}} \tag{4.5}$$

The tapped steel (TST) is assumed to be equal to the input to SM. The tapping slag (TSLAG) is calculated as the difference between refined (RST) and converted steel (CST).

4.2.4 Converting energy and material flows into exergy units

In metallurgical processes, the physical (B_{ph}) and chemical (B_{ch}) are the most relevant components of the exergy. Therefore, this analysis only considers the chemical exergy (for which differences in composition and concentration are the driving forces) and the physical exergy (for which differences in pressure and temperature are the driving forces) of energy and materials.

Chemical exergy

As described in Chapter 3, Section 3.3.2, the chemical exergy of many materials has been previously tabulated assuming specific material compositions (Ayres and Ayres, 1999, Szargut, 1986) – usually the most commonly found. These standard tables serve as good approximations when there is no information about the compositions of the analysed materials. However, when detailed knowledge of the chemical composition is available, these can be calculated from first principles. In this study, the compositions of the hot metal input, and the steel and slag output vary even across individual batches, and it is therefore important to capture these variations. This section describes how custom-fit chemical exergies are calculated for these materials.

Chapter 3 also explained that for every element involved in a chemical reaction, its reference species – that for which chemical exergy is equal to zero – is defined as the *most common component* *of the natural environment* that contains the considered element.[3] For gases, liquids and solids these are defined based on mean concentrations in the atmosphere, hydrosphere (sea water) and lithosphere (the crust)[4]. For elements that do not occur naturally in the environment (e.g. Fe or Al) a *reference reaction* must be formulated. This reaction consists of only reference substances (influent and effluent reference species). For example, the reference reaction for Calcium (Ca) consists of a reaction with CO_2 and O_2 as influent and $CaCO_3$ as the effluent reference species. From this reference reaction the standard chemical exergy of an element ($b^o_{ch,el}$) can be computed using Equation 4.6 (Szargut, 2005):

$$b^o_{ch,el} = -\Delta_r G^o + \sum_k b^o_{ch,k} - \sum_j b^o_{ch,j} \tag{4.6}$$

where $\Delta_r G^o$ refers to the standard free energy of the reference reaction, and $\sum_k b^o_{ch,k}$ and $\sum_j b^o_{ch,j}$ represent the sum of the standard chemical exergies of the effluent and influent reference species respectively. Once the chemical exergy for elements has been quantified, it is then possible to determine the chemical exergy of compounds ($b^o_{ch,comp}$) through Equation 4.7 (Szargut, 2005):

$$b^o_{ch,comp} = -\Delta_f G^o + \sum_{el} n_{el} b^o_{ch,el} \tag{4.7}$$

where n_{el} is the number of moles of the elements in the compound and $\Delta_f G^o$ the Gibbs standard free energy of formation of the compound. Values for $b^o_{ch,comp}$ and $b^o_{ch,el}$ are found in work by Szargut (2005), Szargut et al. (1988) and Ayres and Ayres (1999).

The chemical exergies of compounds can then be combined to calculate the chemical exergy of solutions, for which Equation 4.8 can be used.

$$b_{ch,mix} = \sum_i n_i b_{ch,i} + RT_o \sum_i n_i ln(a_i) \tag{4.8}$$

Here, $b_{ch,i}$ is the chemical exergy of the component, n_i is the number of moles in the ith component, a_i stands for the activity of the component, R is the gas constant (0.008135 kJ/mol·K) and T_o is the temperature of the reference environment (298 K). For ideal solutions, the activity (a_i) can be substituted by the molar fraction. Reuter et al. (2005) argue that the b_{ch} of metal alloys can be

[3] Szargut (2005) posits that the reference species of the different elements are independent of each other.

[4] Errors in the calculations of chemical exergies can result from differences in the composition of the earth's crust in different regions, as well as from changes in the ambient temperature and pressure.

calculated using Equation 4.8; this assumption is adopted here. Equation 4.8 was therefore used to calculate the chemical exergy of the hot metal, the outputs of BOSG, converter slag and steel. Table 4.3 shows an example calculation for the chemical exergy of a steel slab.

Table 4.3: Calculations for the chemical exergy of a steel slab of a given composition; φ is the mass fraction of each element; a is the product of the mass fraction and the chemical exergy of the element (i.e. $\sum_i n_i b_{ch,i}$).

Slab	φ	$b_{ch,i}$ (kJ/mol)	a	n*ln(n)	Molar mass (kg/kmol)
Fe	0.95	374.3	356.0	-0.05	55.8
C	0.02	409.9	7.4	-0.07	12.0
Si	0.01	855.0	11.1	-0.06	28.1
Mn	0.02	487.7	8.3	-0.07	54.9
P	0.00	861.4	0.9	-0.01	31.0
Sum	1.00		383.6	-0.25	54.6
Chemical exergy (GJ/t)					7.01

For materials with no composition data, averaged values were used. These were obtained from tabulated results (Ayres and Ayres, 1999, Szargut, 2005). Tabulated values of specific chemical exergies are used for most of the additions, fluxes and scrap inputs, input gases (i.e. nitrogen, argon, oxygen, air), all other slags and slurry.

For fuels, for which no composition is available, calculating B_{ch} is simpler than for materials. The inherent similarities between fuel heating values and their chemical exergies (within 10%), make it possible to directly convert from one to the other. Academics, such as Nakicenovic et al. (1996), have defined conversion factors (f) for the main energy carriers. Nakicenovic's conversion factors are used for NG and electricity.

Physical exergy

There are two ways of calculating a material's physical exergy: directly or indirectly. In both cases, it is important to define a reference state as this affects the work that can be extracted from a process.[5] The direct method involves using values of enthalpies (h) and entropies (s), as depicted in Equation 4.9, where h_o and s_o are those at ambient conditions. The *IAPWS* Python package

[5] The reference temperature and pressure used are T_o=25^oC and P_o= 101.325 kPa respectively.

(Gomez Romera, 2016) was used to calculate h and s for the steam flows in each batch; these are calculated using inputs of minute-level metered data on steam temperatures and pressures.

$$b_{\text{ph}}^{\text{direct}} = (h - h_o) - T_o(s - s_o) \tag{4.9}$$

The indirect method consists of expressions that approximate the enthalpies and entropies of the substances. Different equations are used depending on the conditions and assumptions made. For example, assuming a constant specific heat (C_p), Szargut et al. (1988) use Equation 3.1, as per Chapter 3, Section 3.3.2. This is used to calculate the b_{ph}^{approx} of the metal flows. Table 4.4 shows example calculations for the physical exergy of the liquid steel and the hot metal flows of three batches, just before and after the converter process.

Table 4.4: Example of physical exergy calculations for given production batches; the values for Cp were obtained from (Lally et al., 1990, Valencia and Quested P.N, 2008)

batch	material	T (ºC)	P (kPa)	C_p	b_{ph}
1		1895.0			0.74
2	liquid steel	1876.8	101.325	0.71	0.73
3		1924.6			0.76
1		1657.5			0.58
2	hot metal	1597.6	101.325	0.68	0.54
3		1604.9			0.55

Exergy losses

As explained in Chapter 3, Section 3.3.2, the destruction of exergy is often denoted as *irreversibilities*. These result primarily from heat transfers occurring across finite temperature differences, combustion and chemical reactions, and the expansion and compression of fluids. Combinations of these phenomena are present in all devices. In this study, irreversibilities are determined by calculating the difference between the total exergy inputs and the total exergy outputs.

The ability to quantify the energy lost in any real process is one of added benefits of exergy. Representing the exergy irreversibilities as output flows in the Sankey diagrams, despite not physically being there, allows the exergy flows to comply with the format required for conventional MEFAs. Based on these exergy flows, it is now possible to calculate the RE of the system and its processes. Table 4.5 (spread across three pages) gives more detailed explanations of how the mass flows, chemical and physical exergies were calculated for each stream, including the exergy losses. Flows are described individually according to their source, target and material type.

Selecting a definition of resource efficiency

Exergy efficiency – as described in Equation 4.10– is commonly described as the ratio of useful exergy output to the total exergy inputs (Brodyansky et al., 1994, Szargut et al., 1988). The numerator and denominator are both measured in joules, and the useful exergy output can never exceed the exergy input, so these always range between 0 and 1. Many definitions of efficiency are possible as a judgement must be made for each process in order to distinguish between products (useful outputs), by-products and wastes.

$$RE = \frac{\sum \left(B_{ch} + B_{ph}\right)_{\text{useful}}}{\sum \left(B_{ch} + B_{ph}\right)_{\text{total}}} \tag{4.10}$$

In this study, the term *useful* refers to resources that are fed into other processes, e.g. the collected BOSG is considered useful, but that flared is considered waste. Overall, wastes include material losses, such as unused by-products (e.g. stockpiled slag or sludge) and emissions. Table 4.6 depicts the specific RE definitions adopted for each process and for the BOS plant as a whole. It becomes useful to distinguish between wastes and irreversibilities when defining the potential for improvements: wastes can be reduced or recovered, while irreversibilities are often unavoidable.

The EI (energy intensity) of the BOS plant is computed to allow comparisons with the exergy-based RE. To protect the company's proprietary data, the EI is normalised to its absolute maximum (EI_{norm}), as expressed in Equation 4.11.

$$EI_{\text{norm}} = \left(\frac{E_{\text{inputs}} - E_{\text{by-prod}}}{M_{\text{prod}}}\right) EI_{\text{max}}^{-1} \tag{4.11}$$

4.2.5 Visualising the resource data

In this study, Sankey diagrams are used to visualise the mass (in tonnes) and exergy (in gigajoules) of resources. An open-source, Python tool developed by Lupton and Allwood (2017*a*), *floWeaver*, was used to construct these diagrams (the code can be found at (Lupton and Paoli,

Table 4.5: Description of material, energy, and exergy analysis for individual flows

Source	Target	Material	Description (mass)	Description (exergy)
Overheads (allocated to days, rather than batches)				
COG	Preheat	COG	Obtained by aggregating plant-level, minutes-scale energy control data – COG data was collected using process-level meters specific to the ladle preheaters	Obtained from literature – worldsteel average value: 38.7 GJ/t
NG	Preheat	NG	Obtained by aggregating plant-level, minutes-scale metered NG data into periods of days	Obtained from Nakicenovic et al. (1996); Exergy conversion factor= 1.03
Preheat	Loss	Exergy losses	-	Calculated from imbalance of inputs to outputs
NG	SM	NG	Obtained by aggregating plant-level, minutes-scale metered NG data into periods of days	Obtained from Nakicenovic et al. (1996); Exergy conversion factor= 1.03
NG	Converter	NG		
Utilities				
Steam	SM	Steam	Obtained by aggregating plant-level, minutes-scale metered data and allocating it using state-based model across processes	Obtained from Szargut (1986): steam chemical exergy = 0.75 GJ/t
Oxygen	Converter	Oxygen	Obtained by aggregating plant-level, minutes-scale metered (only input to converter)	Obtained from Szargut (1986): Oxygen chemical exergy= 0.12 GJ/t;
Nitrogen	Desulph	Nitrogen	Obtained by aggregating the plant-level, minutes-scale metered data and allocating to processes using state-based model	Obtained from Szargut (1986): N_2 chemical exergy= 0.026 GJ/t;
Nitrogen	Converter	Nitrogen	Same as above	
Nitrogen	Tapping	Nitrogen	Same as above	
Nitrogen	SM	Nitrogen	Same as above	
Electricity	Desulph	Electricity	Same as nitrogen	Conversion factor=1 (Nakicenovic et al., 1996)
Electricity	Converter	Electricity	Same as nitrogen	
Electricity	Tapping	Electricity	Same as nitrogen	
Electricity	SM	Electricity	Same as nitrogen	
Desulph (Material inputs)				
DS.Fluxes	Desulph	DS. Fluxes	Calculated from the sum of Magnesium, Doloflux, and Lime obtained from metered material data	Obtained from Obtained from Szargut (1986); Lime= 0.05 GJ/t ; Doloflx= 0.18 GJ/t; Mg= 26.1 GJ/t;
Hot metal	Desulph	Hot metal	Obtained from metered material data	Calculated using metered composition for each batch from first principles (using Eq 4.8)
Hot metal	Desulph	Hot metal physical	-	Calculated from Eq. 3.1. Ts and Ps obtained from metered data; Cp = 0.68; R= 0.08134 MJ/kgK.

Source	Target	Material	Description (mass)	Description (exergy)
Desulph (Material outputs)				
Desulph	stockyard	DS Slag	Obtained from estimated DS Slag data from plant	Obtained from literature; (Szargut, 1986)
Desulph	Converter	DSHM	Obtained by subtracting all the inputs from all the outputs	Calculated using metered composition for each batch from first principles (using Eq 4.8)
Desulph	Converter	DSHM physical	-	Same as for Hot metal physical.
Desulph	Loss	Exergy losses	-	Calculated from imbalance of inputs to outputs
Converter (Material inputs)				
Fluxes	Converter	Fluxes	Calculated from the sum of Iron ore, Doloflux, and Lime obtained from metered material data	Obtained from literature – Szargut et al. (1986); Scrap chemical exergy= 6.75 GJ/t; Iron ore= 0.42 GJ/t; Lime= 0.05 GJ/t ; Doloflx= 0.18 GJ/t
Scrap	Converter	Scrap	Obtained from metered material data	
Converter outputs				
Converter	Tapping	Conv steel	Obtained by assuming equal to input to tapping	Calculated from first principles using composition data for refined steel (available for each batch).
Converter	Tapping	Conv steel physical	-	Same as Hot metal physical, but updating Cp = 0.71MJ/kgK.
Converter	stockyard	Slurry, grit	Obtained from estimated and metered weekly slurry and grit data, and linearly divided across days	Calculated from first principles using averaged slurry composition data
Converter	stockyard	Slag	Obtained from estimations of slag production from material data (available at a batch level)	Calculated from first principles using metered composition data available for each batch
Converter	Output	Steam	Obtained by aggregating process-level, minutes-scale metered data– converter vessel is only process producing steam	Using Eq.3.1 and temperatures and pressures from metered energy data; Cp = 0.75/1.35; R= 0.08134 MJ/kgK.
Converter	Output	BOS gas	Obtained from metered material data	Calculated from first principles using metered composition data available for each batch
Converter	Output	BOS gas physical	-	Assumed to be at atmospheric conditions, so equal to 0.
Converter	Loss	Exergy losses	-	Calculated from imbalance of inputs to outputs

Source	Target	Material	Description (mass)	Description (exergy)
Tapping (Material inputs)				
Additions	Tapping	Additions	Obtained from metered material data; Calculated from the sum of Aluminium Pebbles, Carbon, High- and Low-Carbon Fe V, Fe Ti, Fe Cr, Slag and Si Mn	Obtained from the literature: Aluminium= 29.4 GJ/t; Carbon= 34.2 GJ/t; Fe V= 9.8 GJ/t; Fe Cr= 10 GJ/t; Fe Ti= 17 GJ/t; Si Mn= 13.8 GJ/t; Calculated from first principles: HiFeMn, LoFeMn= 10.2, 9.8GJ/t.
Tapping (Material outputs)				
Tapping	SM	Tap steel	Obtained from metered data (although metered value includes slag)	Calculated from first principles using metered composition data available for each batch (composition assumed equal to refined steel)
Tapping	SM	Tap steel physical	-	Same as Conv. Steel physical
Tapping	Stockyard	Tapping slag	Difference between refined steel and tapping input	Composition equal to that of the converter slag
Tapping	Loss	Exergy losses	-	Calculated from imbalance of inputs to outputs
Secondary Metallurgy (Material inputs)				
Additions	SM	Additions	Sum of Aluminium Pebbles, Carbon, High- and Low-Carbon Ferromanganese obtained from metered material data	Same as for tapping additions, and converter scrap input
Scrap	SM	Scrap	Obtained from metered material data	
Secondary Metallurgy (Material outputs)				
SM	Output	Refined steel	Obtained from metered material data	Calculated from first principles using metered composition data available for each batch
SM	Output	Refined steel physical	-	Same as Conv. Steel physical
SM	stockyard	Secondary slag	Assumed equal to additions	Composition equal to that of the converter slag
SM	Loss	Exergy losses	-	Calculated from imbalance of inputs to outputs

Table 4.6: RE definitions of the four processes and BOS plant; nit. is nitrogen, and elec. is electricity

Process	Useful outputs		Total inputs	
	B_{ch}^{useful}	B_{ph}^{useful}	B_{ch}^{total}	B_{ph}^{total}
Desulph	Desulphurised hot metal	Desulphurised hot metal	Hot metal, lime, magnesium, nit., elec.	Hot metal
Converter	Converted steel, recovered BOSG	Converted steel, steam	Desulph. hot metal, scrap, fluxes, additions, nit., elec.	Desulph. hot metal
Tapping	Tapped steel	Tapped steel	Converted steel, additions, nit., elec.	Converted steel
Secondary Metallurgy	Refined steel	Refined steel	Tapped steel, additions, nit., elec., steam, argon	Tapped steel
Plant	Refined steel, recovered BOSG	Refined steel, steam	Scrap, lime, magnesium, fluxes, additions, nit., elec., NG, COG, argon	Hot metal

2017)). Alongside the Sankey diagrams, histograms were used to depict the entire range of REs across batches and days. These were plotted in Python using *Matplotlib* package (Hunter, 2007).

The Sankey-diagram tool developed by Lupton and Allwood (2017*a*) allowed us to depict individual daily and batch-level SDs – for processes and the entire plant – across the 29 days and 900 batches respectively. Using *floWeaver* (Lupton and Allwood, 2017*a*) makes it possible to easily toggle between different units, i.e. from mass to exergy. Resources flows were combined into groups if these, on their own, were too small to be visible on the diagrams. The groupings change depending on the scope analysed – these are summarised in Table 4.7.

Table 4.7: Sankey diagram groupings

Level	Group name	Materials included
Batch	Slag	Converter, DS, tapping and secondary slag
	Slurry	Sludge and grit
	Scrap	Eight types of scrap inputs
Daily	Overheads	Electricity, COG, NG
	Fluxes	Lime, magnesium, dolomite, ore
	Additions	Ferro-alloys, carbon, silicon manganese
	Nitrogen	Nitrogen 6 bar and 16 bar

Templates were constructed to define the standard layouts of the SDs. These were then used to depict the flows for all other iterations of batches and days. To prevent flows from overlapping in any instance, it was necessary to construct a fictitious SD containing the largest possible flows for each individual stream. This layout was built using the *floWeaver* software, and later imported into the Python code, where the videos depicting the resource flows across all batches were constructed. In total, six template layouts were designed for: the process-level across batches for mass (1) and exergy (2); the process-level across days for mass (3) and exergy (4); and the plant-level across days for mass (5) and exergy (6).

The graphical representation of resource balances through Sankey diagrams supports the strategic dialogue, which is required in identifying improvement opportunities and challenges, and in aligning actions among stakeholders. SDs describe a system using arrows of thickness proportional to their flow magnitude, thereby presenting a useful snapshot of a system's behaviour at a given time. One of the main advantages of SDs is their flexibility to depict different types of information using a wide range of features.

4.2.6 Calculating the resource use improvements

To exemplify how this analysis can facilitate the comparison between energy and material efficiency measures, improvements available from the following options were calculated:

- From within ME options:
  - The recovery of converter slag for further use in other processes across batches
  - The recovery of other slag for further use in other processes across batches
  - The recovery of slurry for further use in other processes across batches
- From within the EE options:
  - Increasing the amount of BOSG recovered across batches
  - Decreasing the amount of overheads (gas, electricity) consumed daily

Three aspects must be considered when quantifying the size of these improvements: (1) the current RE of the process; (2) the scale of the flows; (3) the limit for improvement. The value of the improvement limit depends on the criteria used to define it, i.e. whether it is based on economic, technical or theoretical considerations. In this analysis, only technical engineering limits are considered. Table 4.8 summarises the limits for each of the improvement measures listed above, including the reasoning behind the choice of these.

Table 4.8: Description of limits of improvement measures. Worldsteel average sourced from worldsteel (2016); t*st* stands for a tonne of steel.

Improvement option	Limit	Reasoning
Converter slag recovery	90% of mass	10% higher than worldsteel average
Other slag recovery	90% of mass	As for converter slag
Slurry recovery	90% of mass	Assumed limits equal to slag
BOSG recovery	85% of vol. produced	$\sim$ 5% above maximum observed
Reduction in overheads	To 0.09 GJ/t*st*	10% below minimum observed

By measuring resource flows in units of exergy it is now possible to compare the improvements available from both EE and ME. As explained by Bakshi et al. (2011), it is useful to consider the point of view developed in the *resource accounting* literature when interpreting the meaning of these improvements: the chemical exergy of the material by-products (the intrinsic) expresses the theoretical amount of exergy that can be saved if these materials are further input in other processes. The intrinsic exergy of materials is independent of the process that produced it, and therefore does not include the exergy embodied in making it (i.e. the process losses).

4.3 Results

The method just described was applied to study the RE of a TataSteel Basic Oxygen Steelmaking plant. Tracing resource flows and quantifying the efficiency with which these are transformed is the first step of this analysis. Resource flows are mapped using both units of mass and of exergy: Section 4.3.1 describes the mass analysis, whereas Section 4.3.2 presents the results obtained from the exergy analysis. Based on these, Section 4.3.3 outlines the resource-use improvements that are available throughout the 29 days. The added value of integrated RE values is then investigated by comparing these to conventional EI metrics (Section 4.3.4).

4.3.1 Mass analysis: from control data to balanced Sankey diagrams

As described in Section 4.2.4, mass flows are the foundation from which exergy flows are constructed. Figure 4.7 depicts, for a given batch, a Sankey diagram of the resource flows – measured in mass – across the four internal processes. Unsurprisingly, the metal inputs (hot metal), intermediate products (desulphurised hot metal, and converted and tapped steel) and final outputs

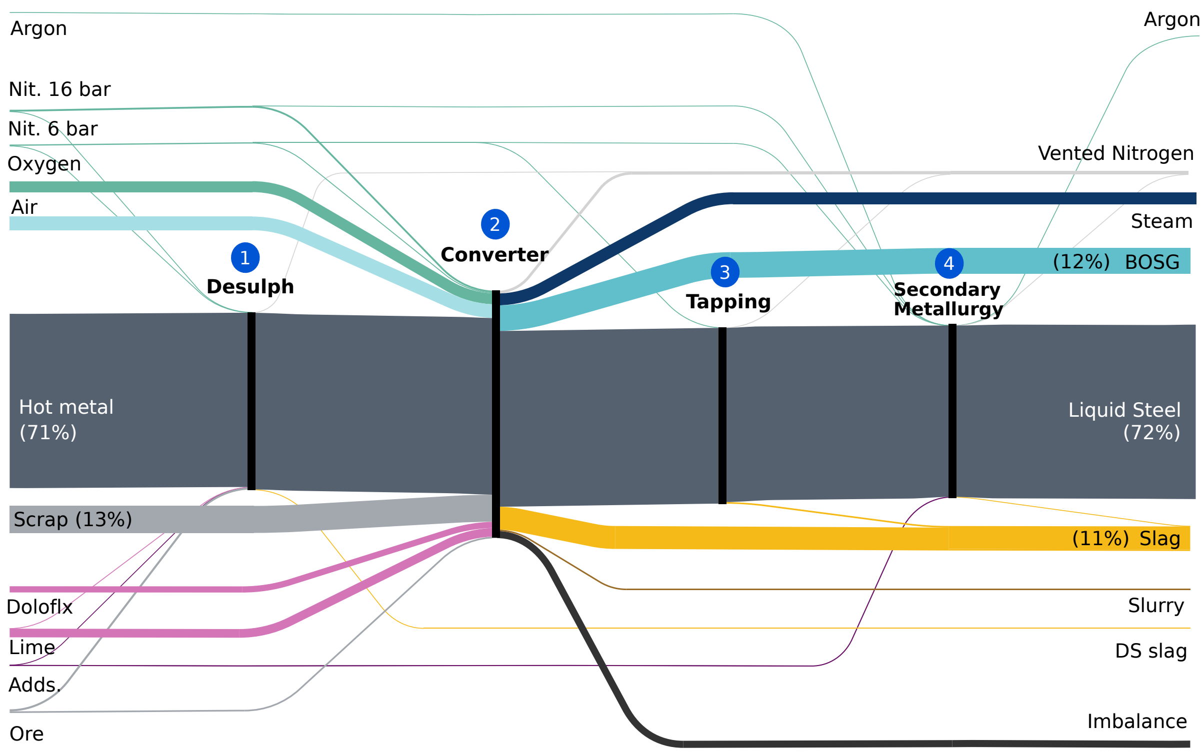

Figure 4.7: Resource flow diagram for a given batch (measured in mass). Hot metal and scrap are the largest material inputs, and BOSG and slag are the largest by-products.

(refined steel) are the largest mass flows in the BOS plant. The scrap, converter slag and BOSG each comprise between 10 and 17% of the total mass input; this varies across batches and days.[6]

The data for the flows has been cleaned from errors and allocated to specific processes where appropriate. As a result, the flows in this specific batch almost fully balance; there is only a small imbalance in the converter process. In fact, across the 29 days, daily mass imbalances (shown in Figure 4.8) range between -2.5% and 0.5% of the total mass input daily (-0.9% on average). At batch-level, mass imbalances are larger and range between -8.5% and 1% (average of -2%).

The most likely sources of this mismatch are: (1) the allocation of slurry and DS slag from days/weeks to individual batches; and (2) errors in the measurement of some materials, mainly

[6] A short video depicting the BOS plant's internal mass flows for a subset of batches can be viewed at: https://www.dropbox.com/s/ix530l08hf52ebd/1802_video_apen.mp4?dl=0. Drawn using Lupton (2017).

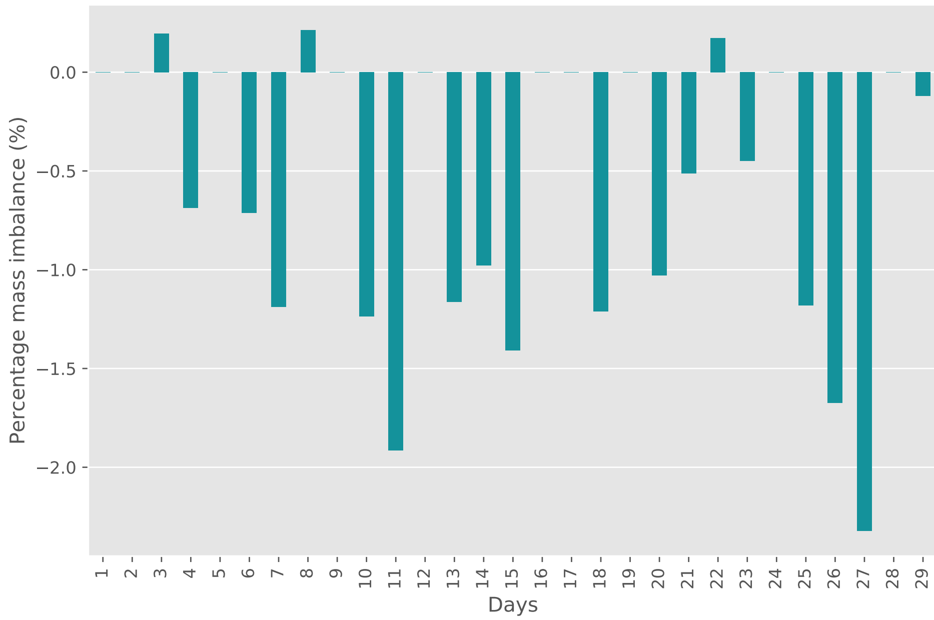

Figure 4.8: Daily mass imbalances in the BOS plant, measured relative to the total daily mass input

the steel flows and the inputs of scrap, fluxes and additions. Although this mass imbalance will also be apparent in the exergy flows, it is useful to investigate this in mass units first. Additional uncertainties are incorporated when flows are measured in units of exergy. This is mainly because chemical and physical exergy contents represent approximations, and these are especially inaccurate when no composition data is available, e.g. for scrap inputs.

4.3.2 Exergy analysis: an integrated resource efficiency analysis

Figure 4.9 shows the resource flows and efficiency for the BOS plant measured in units of exergy. The Sankey diagram (Figure 4.9a) portrays the flows for a specific day, and the RE distribution across the 29 days is highlighted in Figure 4.9b. Both diagrams reveal several insights into the BOS plant operation. The chemical exergy content of material flows dominates that of the energy flows, with the hot metal and scrap inputs, and the steel output, being the three largest flows.
The diagram shows there are two main energy by-products: steam ($\sim$ 2% of total exergy input), which is currently recovered in a super-heater and exported to other on-site plants; and BOSG ($\sim$ 10% of total input), which is divided into two, that currently flared (light blue) and that already recovered for further use on-site (dark blue). As the chemical exergy of this gas is signif-

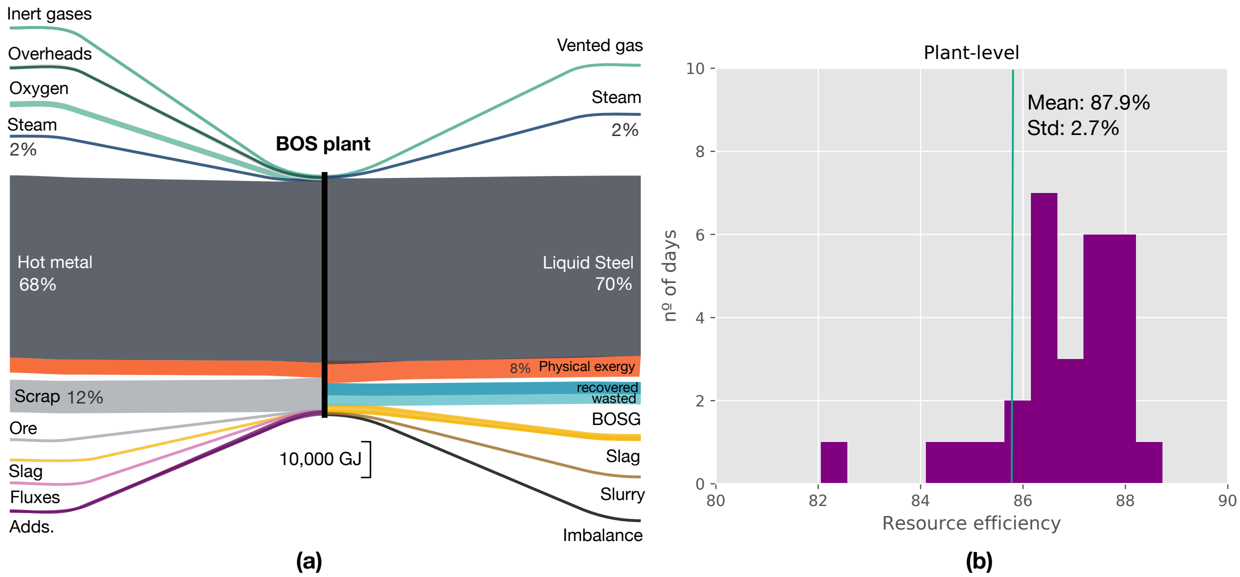

Figure 4.9: (a) SD of plant-level resource flows for a given day, measured in units of exergy; (b) Daily-level REs for the entire plant across the 29-day period.

icant, every effort should be made to recover its chemical content. Slag (2-4% of total input) and slurry ($\sim$ 1% of total input) are the two material by-products. The physical exergy of the refined steel represents 6-7% of total exergy inputs – harnessing this saves the plant energy, particularly when transporting the steel between the BOS and rolling facilities. Process irreversibilities (in the *imbalance* term) represent about 2-5% of the total exergy input. These losses are largely unavoidable, although a fraction of them may be reduced by further optimising process conditions.

The RE of the BOS plant (Figure 4.9b) has a skewed bi-modal distribution, ranging from 82.5 to 88.4%. Across the 29-day period, the BOS plant has a mean RE of 87.9%, with an absolute standard deviation (STD) of 2.5%. The bi-modal shape arises mainly due to the differences in the amount of BOSG collected. The heterogeneity results from variations in: the difference in grades produced, the scrap-to-iron inputs, waiting and duration times between and of processes, and the consumption of overheads (e.g. NG or electricity). The differences in the daily steel-to-slag and steel-to-slurry ratios have no influence over this RE as they were not recovered for further use during this time period. Although the minimum RE in Figure 4.9b appears to be an outlier, the short time period studied makes it difficult to judge whether this is the case.

At batch-level, the RE ranges from 75% to 96%, with a bi-modal shape, as depicted in Figure 4.10. By comparing Figure 4.10 and Figure 4.9b it is possible to deduce that batch-level variations appear to be averaged out when aggregated to the daily scale. Overall, the heterogeneity observed daily and across batches shows there is still potential for improvement. To investigate this further, the resource flows and efficiencies of the processes are analysed.

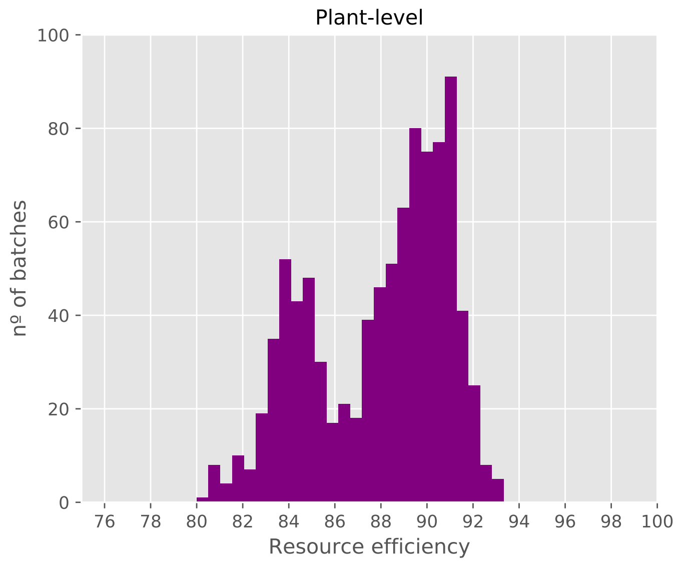

Figure 4.10: Resource efficiency distribution for the BOS plant (on a batch-level)

Figure 4.11a portrays a detailed view of the BOS plant, disaggregated into four processes. The Sankey diagram depicts the resource flows for a specific batch, and the histograms portray the RE variation for each process across the 29 days.[7] Disaggregating the plant-level RE shows its variance comes from the converter (2), as the majority of fuels, by-products, and irreversibilities arise here. In fact, Figure 4.11b shows that across the 29 days, the converter is the least resource-efficient process. The converter has a mean RE of 91.6%, and is the most variable process, with an absolute STD of 2.5%. In contrast, the desulph, tapping and SM processes have mean REs of 98.9%, 98.5% and 98.2% respectively, with small STDs (0.3%, 0.7% and 0.4%).

Figure 4.12 depicts the remaining daily exergy imbalances. In this case, imbalances range from

[7] A video of these internal exergy flows for a subset of batches can be viewed at: https://www.dropbox.com/s/ix530l08hf52ebd/1802_video_apen.mp4?dl=0. Drawn using Lupton (2017).

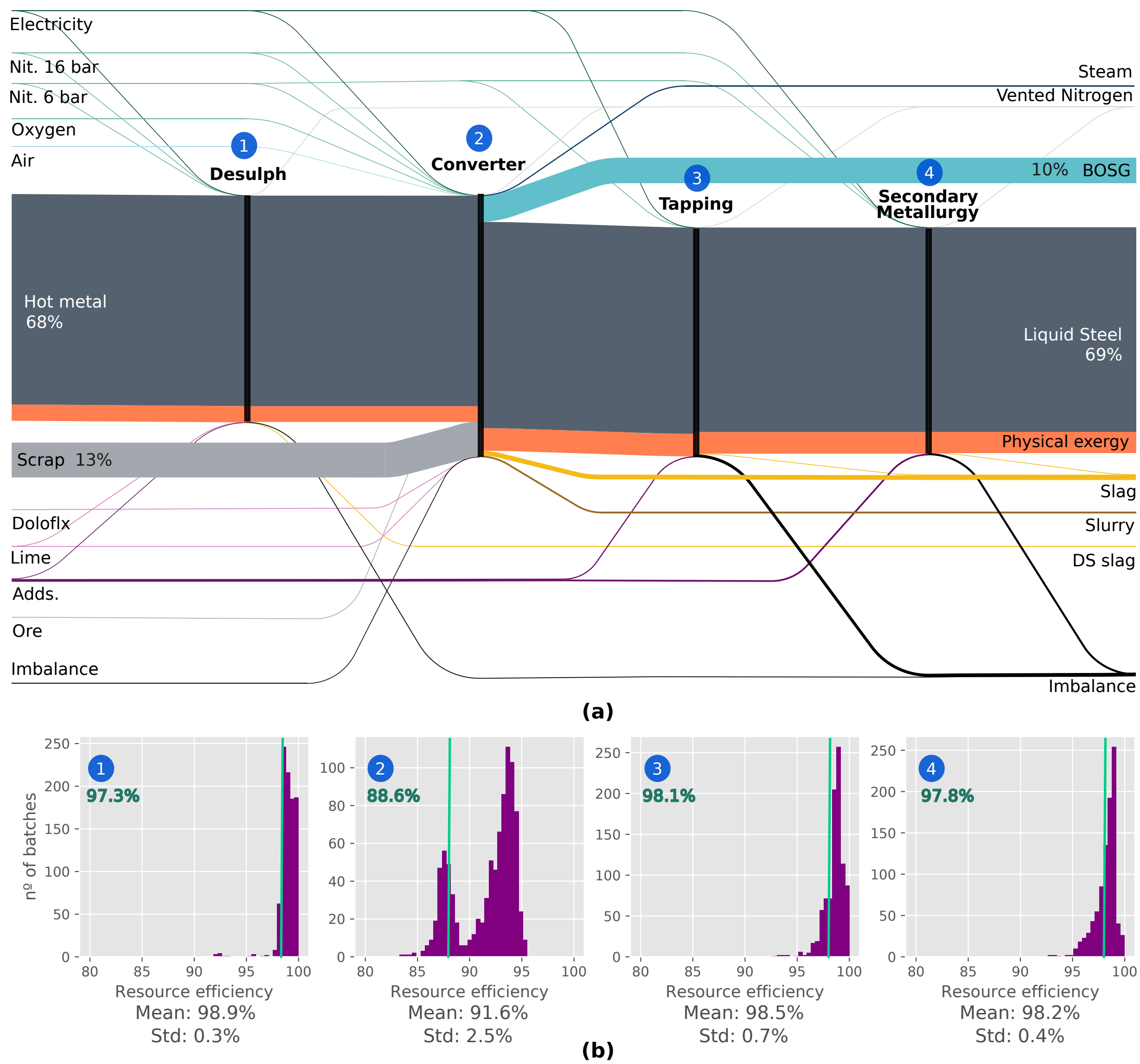

Figure 4.11: (a) SD for a specific batch (measured in exergy); (b) Histograms of the RE variations across batches for each of the four processes. Values in green reflect the REs of the batch in (a). The means and standard deviations (Std) across the 29 days are depicted below the histograms.

-3.5% to just above 1.5% (average -1.6%). At batch-level, exergy imbalances are greater and range between -10% and 4% (average -3%). Again, for the exergy flows, most imbalances are negative – that is, there appears to be missing inputs to match the quantified outputs. The mass imbalances described in Section 4.3.1 explain part of the discrepancies in exergy flows. The remainder is likely to arise from other sources, such as: the errors associated with allocating highly aggregated material (e.g. slurry, DS slag) and energy (electricity, NG or nitrogen) data; or the lack of disaggregated composition data for the scrap input or the slurry output, which then force us to use averaged, and therefore inaccurate chemical exergies for these.

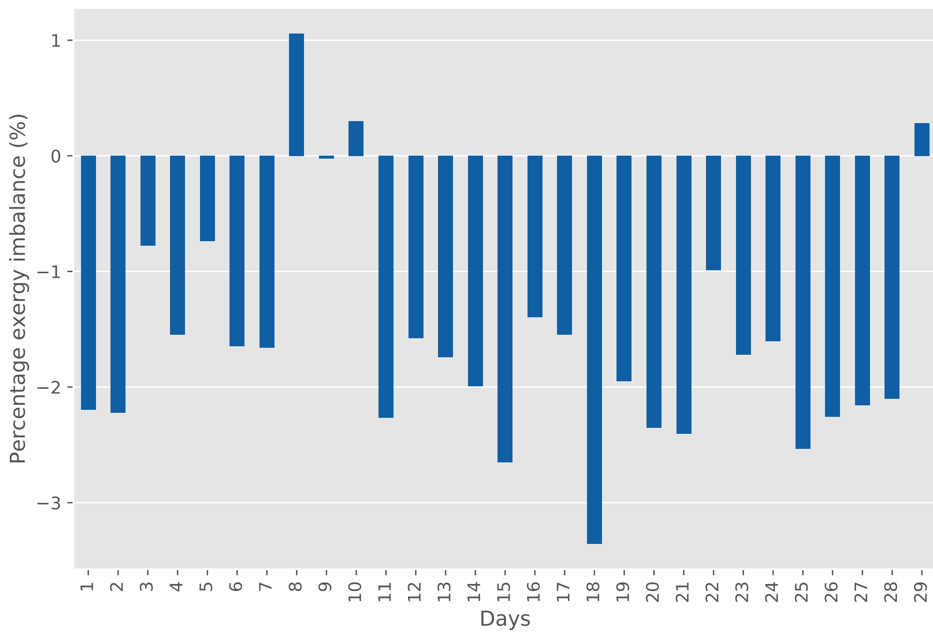

Figure 4.12: Daily exergy imbalances in the BOS plant, relative to the total daily exergy input

4.3.3 Reducing resource use: potential improvements

Based on the constructed exergy flows and the computed REs, it is now possible to estimate the resource savings available from improving ME and EE. Figure 4.13a illustrates the current RE variations of the processes across time, and the resource use improvements available from energy-related (Figure 4.13b) and material-related options (Figure 4.13c). For confidentiality reasons, the resource use improvements are measured in relative terms, i.e. as a percentage of the total daily exergy input.

The implementation of the measures outlined in Section 4.2.6 results in resource-use improvements equivalent to 7.1% of the resource inputs (in exergy) across the 29 days. Energy-related options (Figure 4.13b), those which efforts have been focused on historically, provide over 60% of the resource-use improvements (4.4% of total exergy input). In parallel, material-related options yield the remaining 2.8% available (Figure 4.13c).

Figure 4.13b reveals that the recovery of BOSG yields the largest improvement in utilisation: up to about 8% of the total daily exergy input. This potential, which is the most variable – ranging from 1% to 8% of the daily exergy use – is greatest in the first week during which most of the BOSG was wasted ($\sim$ 7-8%). For Days 1 to 7, in which part of the BOSG *is* recovered, the EE and ME options are comparable in size (about 2.7% of the daily exergy input). The amount of BOSG that can be recovered is primarily limited by two main aspects: the recovery infrastructure, such as the gas holders and the site-wide piping; and the variations in the energy demand of the processes in which this would be further consumed. Reducing the amount of overheads used daily for each tonne of steel results in savings equivalent to 0.2-2.6% of the total inputs (with an absolute STD of 0.5%). As overheads are mainly used for the preheating of ladles, its consumption is likely to be affected by the process durations and the in-between waiting times.

From within the ME options, in Figure 4.13c, the recovery of converter slag provides the largest improvement in resource utilisation, equivalent to about 1.6-2.5% of the daily exergy inputs (0.2% STD). This steelmaking slag is commonly used internally within sinter plants. Further re-using the tapping and secondary slag provide 0.1-0.2% for further use (with a STD of less than 0.1%). Today, the BOS slags have two main applications, namely: as road aggregates, and to produce Portland cement. Its use in the manufacturing of Portland cement, however, can be limited by high concentrations of MgO and FeO (American Iron and Steel Institute, 2001). Other applications include anti-skid material for icy roads.

Recovering the converter slurry, resulting from the cleaning of the BOSG, provides about 0.6-0.8% for further use (with a STD of less than 0.1%). There are ongoing trials to make use of the slurry on-site – mainly as an input to the sinter plant – but recovery options can be limited due to material chemistry. Difficulties in reusing slurry arise from its high Zinc content, which if recirculated round, can contaminate the steel.

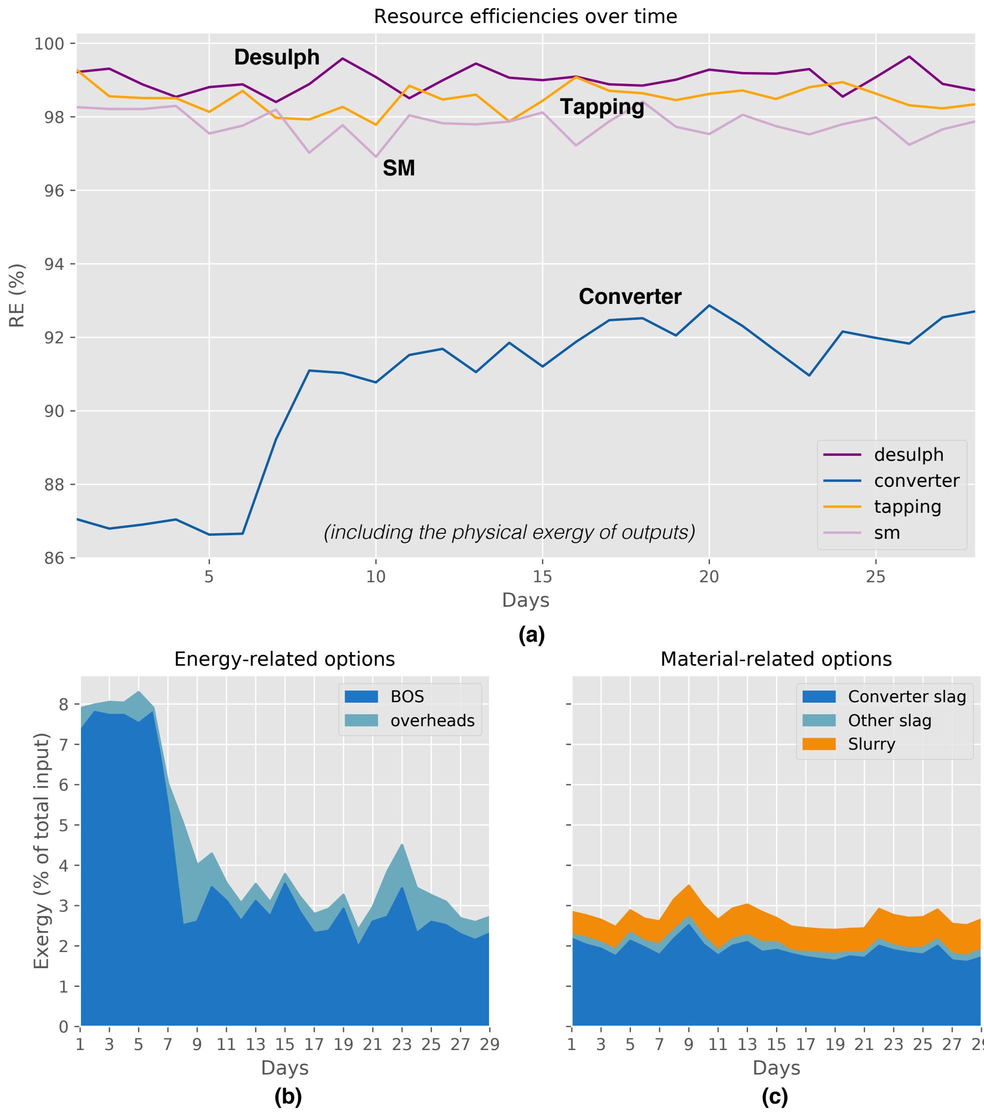

Figure 4.13: (a): RE variation across time; (b): improvements from EE; (c): improvements from ME

4.3.4 Comparing metrics: resource efficiency vs. energy intensity

To demonstrate the added value of measuring RE in units of exergy, this is compared to conventional EI metrics. Based on Equation 4.11 in Section 4.2.4, Equation 4.12 shows the converter's normalised energy intensity (EI_{norm}). E is energy, M is mass, and *prod* and *by-prod* are the main product and by-products. This is portrayed in Figure 4.14a for the 29 days.

$$EI_{\text{norm}} = \left(\frac{E_{\text{inputs}} - E_{\text{by-prod}}}{M_{\text{prod}}}\right) EI_{\text{max}}^{-1} = \left(\frac{E_{\text{gas}} + E_{\text{elec}} - E_{\text{steam}} - E_{\text{BOSG}}}{M_{\text{steel}}}\right) EI_{\text{max}}^{-1} \tag{4.12}$$

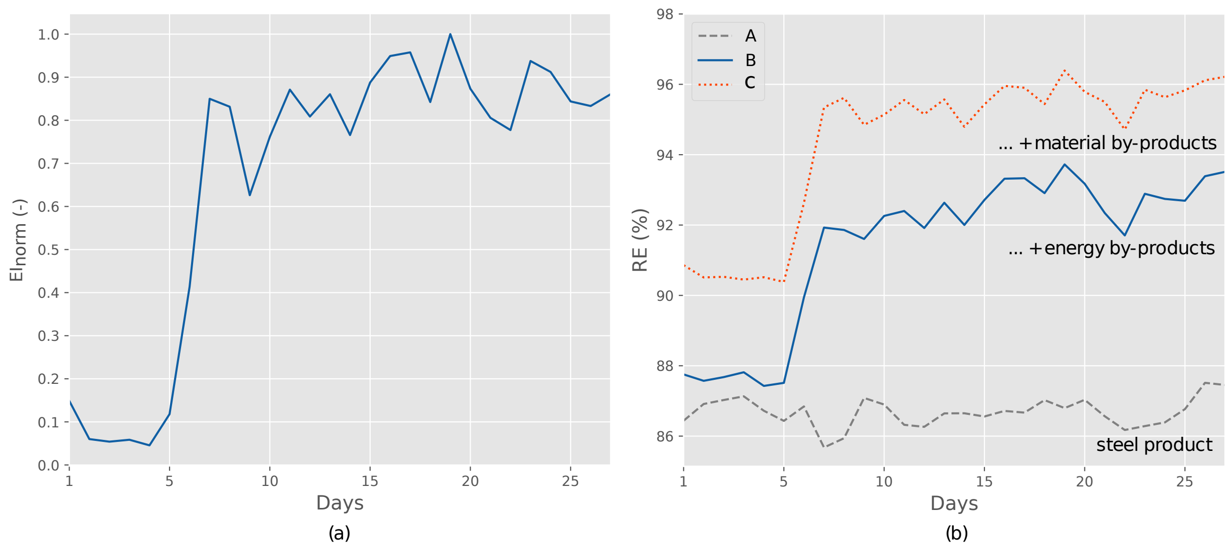

Figure 4.14: (a) Energy intensity (EI_{norm}) variations for the converter; for confidentiality reasons EI is normalised to its absolute maximum value (1.0 = lowest). (b) the converter's RE, where (A) considers the steel output as the only useful output, (B) includes the recovery of energy by-products and (C) includes material by-products.

The converter's EI_{norm} is compared to three definitions of the process's RE, each of which captures the recovery of different by-products. Figure 4.14b shows the converter's RE, described in Equation 4.13 (based on Equation 3.2, Section 4.2.4). Equation 4.13 – where *HM* is hot metal, and the superscript *mat* stands for materials – shows the overall expression for RE. Here, the appropriate elements for each RE definition are denoted with (B) and (C) superscripts. In Figure 4.14b, the RE is disaggregated into three parts: (A) where the steel is the only useful product; (B) where recovered energy by-products (e.g. BOSG and steam) are included; (C) where material by-products (i.e. slag and slurry) are also assumed to be recovered. RE (B), portrayed in blue in

Figure 4.14b matches the RE definition from Section 4.2.4 and Figures 4.11 and 4.13.

$$RE = \frac{B^M_{\text{prod}} + (B^E + B^M)_{\text{by-prod}}}{(B^E + B^M)_{\text{inputs}}} = \frac{B^{\text{steel (A,B,C)}}_{ch+ph} + B^{\text{BOSG (B)}}_{ch} + B^{\text{steam (B)}}_{ph} + B^{\text{slag (C)}}_{ch} + B^{\text{slurry (C)}}_{ch}}{B^{\text{gas}}_{ch} + B^{\text{elec}}_{ch} + B^{\text{HM}}_{ch+ph} + B^{\text{fluxes}}_{ch} + B^{\text{scrap}}_{ch}} \tag{4.13}$$

Figures 4.14a and 4.14b show that the expressions for the EI_{norm} (4.14a) and RE (4.14b) exhibit a similar trend when the energy by-products currently recovered (B) are included in the numerator. However, unlike the energy intensity, the RE captures the converter's raw material input variability, the heterogeneity in chemical composition (through the chemical exergy) and can additionally reveal improvements in the amount of both energy and material by-products recovered (version C). In contrast, the EI_{norm} metric can only be modified to credit improvements in the recovery of energy by-products (Equation 4.12), overlooking opportunities to make material-related improvements (the gap between RE(B) and RE(C)).

The use of an exergy-based RE changes the traditional definition of *best performer*, and places options such as reducing raw material inputs and recovering material by-products on the same level-playing field as energy-related ones. Additionally, this RE metric is dimensionless and can therefore be used to compare processes more widely across different industries.

4.4 Discussion

This study extracts energy and material data from the BOS plant's control system to analyse the resource use and efficiency of its processes during real operations – practice that is currently not implemented at the plant. For the first time, energy and materials were jointly visualised and measured under a single framework: exergy. Resource use for individual batches and days was monitored using Sankey diagrams (in units of both mass and exergy) over 29 days; this helped enhance the understanding of resource flows within the plant and facilitated communication with decision-makers at high management levels. In summary, this analysis reveals that:

- An integrated and transparent picture of the BOS plant's internal resource flows can be constructed using energy and material control data available. This, however, requires cleaning the data and matching up inconsistent spatial and temporal scales.
- Results show that there is still potential to improve resource use through both energy and material efficiency options (see Section 4.3.3). The sum of improvements in resource use

amounts to 7% of the total exergy input during the 29 days.

- The fraction of resource use improvements arising from ME strategies is about 40% – the remainder arises from recovering energy by-products (BOSG and steam) and from reducing overheads. This highlights the importance of tracking materials alongside process energy.

4.4.1 Comparison to previous studies

Previous studies analysing the exergy efficiency of BOS plants have revealed potential improvement options and given firms a means to compare their own performance. Costa et al. (2001) estimate that recovering all by-products and wastes could increase the plant's RE from 75 to 85%. More recently, in an analysis of a steelmaking network, Wu, Wang, Pu and Qi (2016) report an exergy efficiency of 95.8% – the steam, BOSG, sludge, dust, and slag produced are all fully recovered. Although comparing aggregated REs on a yearly basis can provide plants with guidance on potential interventions, this provides limited insight into the operational details behind these measures. Studies that do use more disaggregated plant-level data, however, either investigate simulations/models, e.g. Karali et al. (2017), Wang et al. (2013), or if using control data, are limited to the analysis of specific technologies (Porzio et al., 2013, Zhou et al., 2013); neither of these provide an integrated picture of the system's overall operational performance.

In practice, encouraging the implementation of EE and ME in industry requires a more detailed and holistic awareness of resource use variations (e.g. batches, hours, days) over entire systems. This study provides this, and in so doing improves conventional approaches used by industry practitioners to analyse resource efficiency in five ways:

1. Using control data creates a resource picture that is more representative of current operations than simulations or other top-down analyses. This is beneficial because it helps plant operators make real decisions about potential solutions, and because an improved physical balance facilitates a more accurate accounting of resources.

2. Through the collation of energy and material control data this study provides the prerequisites to better understand what variables influence RE. Capturing the effects of these variables gives plant managers insight into changes available during operation.

3. Currently, ME strategies, such as improving yields or recovering material by-products, are pursued to reduce costs and not recognised as energy-saving interventions. By incorporating

materials into the RE metric, it is possible to capture and therefore incentivise ME measures alongside those on EE (Section 4.3.4). This integrated approach has a direct impact on industry's interpretation of a 'best performer' and gives plant managers an alternative, more holistic metric which they can benchmark daily performance to.

4. Visualising materials and energy in a single diagram improves the visibility of the plant's resource flows and facilitates comparisons between energy and material-related improvements, as well as the communication of information to decision-makers (Section 4.3.2).

5. This study provides a decision-support tool that can bridge the gap between high-level indicators, which give little steer about how to improve processes, and extensive chemical engineering models, which are costly to run.

The long-term objective of this work is to develop and implement a decision-support software tool that can provide any industry firm with a detailed and holistic understanding of its RE, and to do so by directly extracting data from its control system. Developing methods through which to exploit the value of this control data makes sense given the advances made in sensoring technology and the current efforts invested in modernising the industry. The research presented in this chapter provides the backbone to such tool and could be a valuable contribution to the digital industrial platforms being developed by the European Commission. The methodology in Section 4.2 aligns with the practices and ideas that are being promoted through these platforms, namely a bottom-up approach that exploits the value residing in control data to improve the "traceability of industrial products" (EC, 2017*a*). The Commission believes that doing so "could make the Circular Economy a key market driver for the digitisation of industry" (EC, 2017*a*).

Before this approach can be fully implemented in industry, however, it must be further automated, and integrated into plants' hardware structures and decision-making practices. The further automation of this method will be enabled by performing more case studies of different industrial processes; this will also be needed to expand the applicability of this approach to other industry sectors. Doing so will enable us to improve the adaptability of: (1) the exergy method; (2) the data filtering process; (3) and the construction of the balancing model.

The application of the exergy method. Exergy has been widely used to assess the performance of industrial systems (Luis and Van der Bruggen, 2014, Sciubba and Wall, 2007). Despite the existence of different efficiency definitions for different processes, e.g. for the chemical industry

(Sorin and Paris, 1998), the (Gutowski et al., 2009) and steel sectors (Costa et al., 2001), several studies have attempted to standardise these (Lior and Zhang, 2007, Tanaka, 2008). With appropriate definitions, it is thus possible to apply the exergy-based RE metric to any industry sector. Having said this, differences in data quality can result in the greater uncertainty of exergy conversion factors – uncertainty which depends on the availability of composition data.

The filtering of the raw data. The filtering process (Section 4.2.2) was developed for the specific type of process considered (a BOS plant) and the given set of data available. Changes to these two aspects require adapting this method in order to make it more widely applicable to different types of control systems.

The construction of the model. Batch processes such as this one, differ from continuous processes common in other sectors, e.g. chemicals, or even within the steel industry (i.e. the BF). Analysing processes which involve continuous liquid flows is likely to be easier, as these have better data on material compositions and flows. Applying this method to multiple case studies will make it possible to develop a more generic approach to filter the raw data.

4.4.2 Research evaluation: has the research question been answered?

Chapter 2 reveals that previous academic studies investigating the energy and material efficiency of production systems have typically used either simulated or theoretical data. For RE improvements to be realised in practice, however, plant managers and operators must be able to track and analyse available RE opportunities on a continuous basis – this, at actionable time scales, i.e. every hour, every day or every week. To address this need, this chapter built on from the RE metric proposed in Chapter 3, and developed a more extensive approach to embed resource efficiency into daily operations. In doing so, this chapter explored the research question: *Can we gain a better understanding of resource efficiency using energy and material control data on a close-to-real time basis?* The analysis conducted in this chapter suggests that we can.

Metered data collected during a plant's operations provides the most detailed knowledge available on the consumption of resource flows. Even if access to better information and tools for visualising and quantifying RE during operations does not guarantee the execution of improvements, it is nevertheless the prerequisite to enable them. Unlike with annually, aggregated analysis or theoretical scenarios (e.g. through simulations), the use of control data makes it possible to:

- have a more accurate representation of process behaviour, and therefore of the inherent resource fluctuations and consumption dependencies associated with complex production processes. With the proposed approach we can observe the RE variability of processes across individual batches, days or weeks. This facilitates explorations into the causes behind the identified fluctuations and the levers available to reduce these.
- provide more realistic estimates of the available improvement potentials. By monitoring control data at detailed time-scales, it is possible to develop a more nuanced definition of a plant's "best practice" operation; we can use the plant's real operating conditions to define its best performance. This analysis now enables the calculation of improvement potentials for different product types, operation modes and resource inputs – among other variables.

The use of control data is key in providing plant managers with a better understanding of resource efficiency. This study has shown, however, that for this complex knowledge to be communicated effectively, control data should be depicted graphically. Sankey diagrams have proved to be a powerful way of offering this visual clarity. Ultimately, it is the coupling of control data with the concept of exergy and the tool of Sankey diagrams that makes the proposed approach so powerful. Feedback in support of the developed approach is presented in Chapter 6.

The specifications for this approach were outlined in Section 4.1. Having designed and tested this using data from the control system in a Tata Steel plant, it is now possible to evaluate how well the proposed approach has met these original requirements:

1. **improve the current understanding of the facility's integrated energy and material flows at the operational scale;**

   The new RE approach has improved the plant manager's understanding of the energy and material flows consumed and generated internally in the facility; a process-level picture of the resource flows in the BOS plant, based on the collected sensor data, was hitherto unavailable.

2. **provide a single metric to track the integrated RE of the production system;**

   This approach offers a single metric that consolidates energy and material flows by using the method of exergy. The characteristics and benefits of using such a metric have been discussed in detail in Chapter 3, Section 3.5.

3. **use available sensor data as much as feasibly possible;**

   At plant-level, values for resource flows were obtained entirely from available metered data. Mismatches between the inputs and outputs are labelled as 'imbalances' and constitute less than 5% of the total resource input (in exergy). At process-level, values for resource flows were largely obtained from the available control data. Only a small portion of the energy flows (electricity and nitrogen) had to be modelled and allocated to individual processes. These represent less than 3% of the total exergy input.

4. **ensure that plant managers, technicians and decision-makers have access to data granularities, which are appropriate for their management remit;**

   The analysis has been conducted at multiple system levels, from batch to daily scales, all which are of direct relevance to plant managers. These time-scales were chosen through discussions with on-site staff during the conducted interviews.

5. **be based on a transparent and repeatable method, that can be scaled up and across to other areas of the site.**

   So long as data is made available, this method has the advantage that it can be easily scaled up to cover the entire steelmaking site. Sankey diagrams have been developed and used as communication tools to enhance transparency.

4.5 Chapter Summary

This chapter presents the first attempt at extracting available control data to conduct an integrated exergy analysis of energy and materials at the operational scales of batches and days. This was exemplified through the study of a basic oxygen steelmaking plant during a period of 29 days and covering 900 batches. The value residing in control data was exploited by automatically constructing Sankey diagrams to depict the resource use of the plant and its processes. This improved the plant's understanding of the size and structure of its internal resource flows. For plants where the metered energy and material flows do not provide a balanced system, the data must be reconciled before the same method can be applied to quantify resource efficiency at operational scales.

Based on these constructed flows, RE improvements from recovering energy and material by-products, and reducing overheads were computed. In total, over 7% of the total exergy input to the plant over this period could be avoided. Most promising is the fact that about 40% of these direct savings arise from reductions in *material* use – the remaining 60% results from improvements in *energy* use. Energy savings available from reducing material use would, however, have been missed if a conventional energy study – that which is common practice – had been performed.

From discussions with industry practitioners, five future research avenues were identified: (1) expanding the scope of improvement measures to include, for example, the decrease in idle times and reductions in iron and steel yield losses; (2) expanding system boundaries – for steel, larger ME improvements arise by including downstream rolling and upstream sintering and iron-making processes; (3) quantifying result uncertainties to account for temporal and spatial misalignments in the data – some batches still have small negative imbalances; (4) standardising the method to other sectors; (5) understanding whether and how much batch-to-batch variations can be reduced. These research opportunities are discussed in more detail in Chapter 6.

"The phrase 'an idea whose time has come' captures the fundamental reality about an irresistible movement that sweeps over our politics and our society, pushing aside everything that might stand in its path."
(Kingdon, 2003)

5
Leveraging material efficiency as an EU energy and climate strategy

Q3: Why is material efficiency not integrated into the EU's energy and climate strategies for heavy industries?

Case study: European Union policies

This Chapter has been submitted to the journal *Energy Policy,* under the title: "Leveraging material efficiency as an energy and climate strategy in the EU". This was done in collaboration with Dr Simone Cooper-Searle and Dr Alexandra C.H. Skelton. They both reviewed drafts of this work and more specifically helped with the structuring and presentation of the results.

5.1 Introduction

Allwood et al. (2011) and IEA (2015*c*) provide evidence that suggests that the adoption of ME (material efficiency) is indispensable to achieving the global climate commitments pledged in the Paris Agreement.[1] Yet the use of ME as a measure for reducing energy use and CO_2 emissions is

[1]These ME initiatives could lead to rebound effects, but these are not considered in this thesis.

currently under-exploited in industry and under-incentivised in EU policy. The literature review in Chapter 2, Section 2.4 indicates that no previous study provides a comprehensive, empirical explanation of why this is the case.

In the EC (European Commission), policies that support ME belong in the environmental policy remit (EC, 2011*c*) – the Directorate General for Environment – rather than energy and climate. These environmental policies aim to guarantee resource availability, reduce price volatility and drive economic growth (EC, 2011*b*, EEA, 2010, 2016*a*), framing impacts on energy use and emissions as potential secondary outcomes. Those industrial policies that do target energy and emissions, however, have yet to leverage ME as a tool for achieving the region's binding energy and emissions objectives (Neuhoff et al., 2016, Skelton and Allwood, 2017).

The under-exploitation of ME in industry and the dearth of EU-level policy incentives suggests that widespread adoption of the integrated RE approach developed in Chapters 3 and 4 is likely to face opposition from industry firms. Before an effective strategy can be devised to facilitate its uptake, it is necessary to develop a comprehensive understanding of why ME, by itself, is yet to be incorporated into EU climate and energy policies. The purpose of this chapter is therefore twofold. First, it aims to investigate why ME is not a bigger part of the EU's energy and climate policy agenda, and second, to assess how ME could become a climate strategy and to recommend possible interventions. In doing so, this chapter builds on the studies performed by Skelton and Allwood (2017) and Cooper-Searle et al. (2017), and contribute to the discussion on how to facilitate the transition to a low-carbon heavy industry.

The chapter is structured as follows: Section 5.2 describes the method used; Sections 5.3, 5.4 and 5.5 present the analysis from the interviews and the review of the policy documents; Section 5.6 discusses and evaluates these results, from which suggestions for policy interventions are made.

5.2 Method

This section provides an overview of the method used to analyse the evidence, and outlines how a combination of frameworks are applied to this study, expanding on the literature described in Section 2.4.3 and the empirical data collected. Figure 5.1 portrays the schematic explaining the overall method, from the preparation of the interviews to the suggestion of policy solutions. This figure conveys the highly iterative nature of the data collection and processing mechanisms.

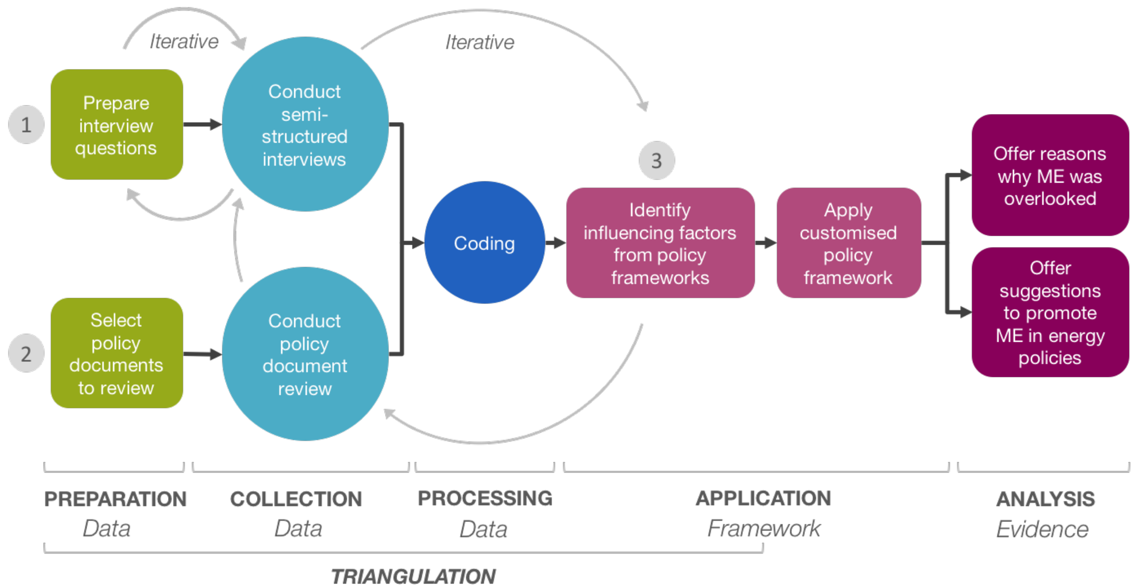

Figure 5.1: Overview of method used to analyse the setting of the EU policy agenda

A review of policy documents (Section 5.2.2) alongside semi-structured interviews with a range of policy stakeholders (Section 5.2.3) provide the evidence for the analysis. As with any qualitative analysis based on empirical data, the choice of conceptual framework(s) is primarily conditioned by the evidence collected. Rather than rigidly adhering to a particular policy lens, a structure is built based on the interview responses. Interview transcripts and policy documents are manually coded and structured by combining three conceptual frameworks reviewed in Section 2.4.3 – through their triangulation – and which focus on policy agenda-setting: multiple streams framework (MSF), historical institutionalism (HI) and rational choice institutionalism (RCI).

In Europe, political agendas exist at multiple levels. Within energy and environmental matters, the EU has had legislative authority since the 1987 European Single Act. The environment was made an official EU policy area in 1993 (Treaty of Maastricht) – mandate strengthened in 2009, when mitigating climate change became an official goal (Treaty of Lisbon) (Ohliger, 2017). It is therefore common for EU agenda-setting studies to be based around EU- rather than MS-level agendas. More specifically, EU policy experts consider the Commission as the main decision-maker (Herweg, 2016, Richardson, 2001, Zahariadis, 2008) – even if it represents just one of many relevant EU institutions. The following analysis accepts this assumption, and focuses on the EC.

5.2.1 Defining the conceptual framework

As part of the manual coding process, the interviews and policy documents were triangulated with the policy-theory literature to identify the variables influencing policymakers' decisions. These were structured into three sections (Figure 5.2): problem perception, institutional and political factors, and solution readiness. The following paragraphs describe each of these sections in turn. Table 5.1 provides additional information on why the specific variables in Figure 5.2 were included, and on how these influential factors were modified from their respective original frameworks.

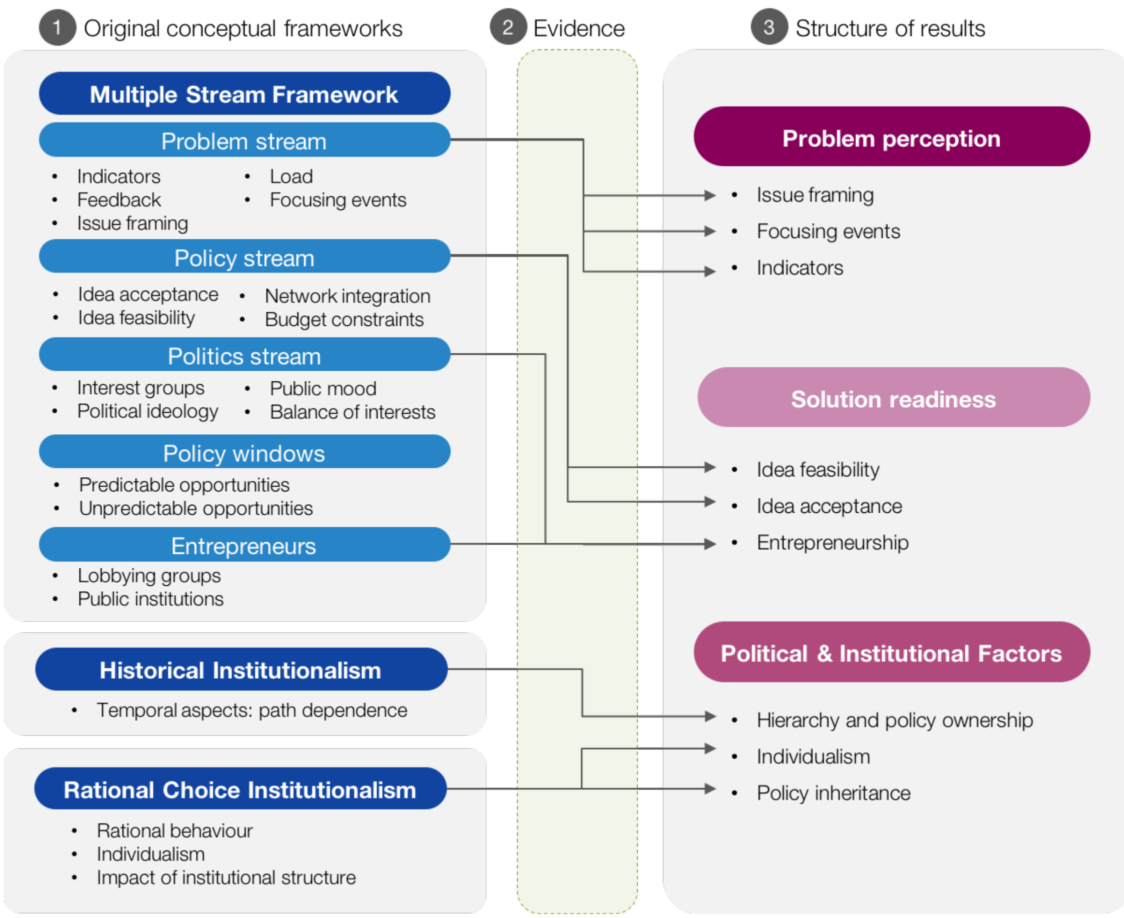

Figure 5.2: Conceptual framework used to structure the analysis of interviews and policy documents

Problem perception is assessed first. This, borrowing from Kingdon's problem stream (Kingdon, 1984, 2003), includes evaluating the evidence pertaining to: (1) how ME solutions are understood among the policy community; (2) the indicators used to track progress on EE, RE and emissions;

and (3) events that may have sparked the attention of policymakers in these areas.

Table 5.1: Influencing factors considered in this work, alongside explanations for their specific consideration

Influencing factor	Theory	Relevance to study	Explanation
Indicators	MSF (problems)	Yes	Explicitly mentioned in interviews (all DGs)
Load	MSF (problems)	No	Not mentioned in interviews
Focus events	MSF (problems)	Yes	Obtained through the review of policy documents (EC meetings), and briefly discussed in interviews
Feedback	MSF (problems)	No	Not mentioned in interviews
Interest groups	MSF (politics)	Yes	Explicitly mentioned in interviews; discussion is limited – data collection is challenging due to sheer volume of entrepreneurs
Balance of interests	MSF (politics)	No	Not mentioned in interviews
Political ideology	MSF (politics)	No	Not mentioned in interviews
Public mood	MSF (politics)	No	Discarded by EU policy experts (Herweg, 2016)
Budgetary constraints	MSF (policy)	No	Discarded by EU policy experts (Zahariadis, 2008)
Idea – value acceptance	MSF (policy)	Yes	Explicitly mentioned in interviews
Idea – technical feasibility	MSF (policy)	Yes	Discussed in interviews
Network integration	MSF (policy)	Yes	Explicitly mentioned in interviews (all DGs)
Policy windows	MSF (windows)	No	Limited understanding – Challenging to develop meaningful analysis of windows throughout the entire period considered
Policy entrepreneurs	MSF (entrepreneurs)	Yes	The Commission is treated as the main policy entrepreneur (Herweg, 2016, Maltby, 2013, Nowak, 2010, Zahariadis, 2008)
Path dependence	HI	Yes	Explicitly mentioned in interviews regarding DG Environment
Individualism	RCI	Yes	Explicitly mentioned in interviews regarding DG Environment and the EC
Institution structure	RCI	Yes	Explicitly mentioned in interviews regarding DG Environment and the EC

The influence of *institutional and political factors* is examined next. This section combines variables from Kingdon's political stream and the institutionalist approaches – both HI and RCI. Four variables are considered: (1) the impact of vertical hierarchy, i.e. the nature of the interactions between different management levels; (2) the influence of policy ownership, that is, which venues own what policies; (3) the effect of policy inheritance, or, in other words, policy lock-in; and (4) the role of individualism, i.e. rational behaviour. These four variables can encourage policymakers to uptake or disregard a particular solution; they also include the high- and low-level modes, described in Section 2.4.3, which explain the dynamics of institutional structures.

Last, the *readiness* of ME as a policy solution is explored. Three relevant points are covered based on interview discussions: the technical feasibility to implement ME; whether it aligns with the prevailing normative values of the policymakers (its value acceptance); and the role played by policy entrepreneurs, i.e. the actors pushing for specific policy solutions. These are described in Kingdon's policy and entrepreneurship streams (Kingdon, 1984), and also widely discussed in the literature (Bache, 2013, Herweg, 2016, Zahariadis, 2008).

5.2.2 Reviewing policy documents

The review of policy documents helps quantify the prominence of different public problems and policy solutions over time in each EC Directorate. Two separate analyses were conducted. First, individual policy documents were examined in search of relevant themes. These were chosen according to the variables in Figure 5.2 above. Over ten types of documents were researched, as summarised in Table 5.2; a total of over 30 were reviewed, as portrayed in Table 2.6. Particular focus is placed on the developments of the three most relevant Directorate Generals (DGs) within the Commission, as identified in Section 2.4.1: (1) DG Energy; (2) DG Environment; and (3) DG Clima. Parliamentary resolutions and other expert technical reports were also reviewed.

Table 5.2: List of policy documents reviewed

Type of document	Acronym	Institution	Time reviewed
Commission meetings minutes	PV	Commission	2012-2017
Draft meeting minutes Council	PV	Council	2014-2016
European Citizen Initiatives	-	Commission	2012-2017
Legislation proposals	COM	Commission	2014-2017
Action plans	COM	Commission	2011-2017
Roadmaps	COM	Commission	2011-2017
Flagship initiatives	COM	Commission	2011-2017
Documents relating to official instruments	C	Commission	2011-2017
Staff Working Documents (progress reports, impact assessments, etc.)	SWD	Commission	2014-2017
Public consultations	-	Commission	2000-2017
Own-initiative reports	INI	Parliament	2014-2017
Resolutions	TA	Parliament	2014-2017
Inter-institutional procedures	Eurlex	-	
National energy efficiency action plans	-	Commission	2012-2017
Annual reports	-	IEA	2014-2017
Annual reports	-	EEA	2010-2017
Resource efficiency report	-	International Resource Panel	2015-2017

Second, a systematic coding approach was taken to *quantitatively* assess the historical importance of energy, climate and environmental topics on the EC's political agenda. This was inspired by work from Baumgartner et al. (2002) and Princen (2009). To do this, the number of times a word is mentioned in the minutes of the weekly Commissioner meetings (over 230 documents) was quantified – from the 11th of January 2012 (EC, 2012*d*) to the 12th July of 2017 (EC, 2017*c*). The words searched include: "energy efficiency", "resource efficiency", "circular economy", "GhG emissions" and "CO_2 emissions". This serves as an indicator for evaluating the scope of the EU's environmental, climate and energy agendas, as well as the framing of ME across the EC. The database with all the Commissioner meeting minutes can be found in EC (2017*d*).

5.2.3 Conducting semi-structured interviews

Semi-structured interviews provide empirical evidence not available in the academic or grey literature. Interviews were conducted with 15 participants from a range of institutions involved in shaping policies that influence industrial materials, energy and emissions. These took place between April and October 2017, and lasted 40-60 minutes. Participants covered a wide range of profiles, including junior and senior civil servants, industry practitioners, consultants, researchers and sustainability officers. Table 5.3 lists the organisations covered in the interviews.

Table 5.3: Organisations covered in the semi-structured interviews

Organisation name	Type
worldsteel	Industrial steel association
Tata steel	Steel company
Arcelor Mittal	Steel company
International Energy Agency	International expert institution
DG Energy	European Commission Directorate General
DG Clima	European Commission Directorate General
DG Environment	European Commission Directorate General
DG Growth	European Commission Directorate General
Joint Research Center	European research center
Public policy consultancy	International expert institution

Interview protocols were prepared prior to the interviews. Table 5.4 portrays an example. Guidance on the preparation of interview structures and questions was obtained from Cloke et al. (2004), Longhurst (2010) and Cooper-Searle et al. (2017). The questions were designed to provide insights into the multiple variables identified from the literature (summarised in Section 5.2). The open-ended and semi-structured style of the interviews made it possible to collect and analyse

Table 5.4: Example of prepared questions for semi-structured interviews

Personal background	
1	What is your job? What does it consist of?
2	Are you involved in making/advising decisions on resource or energy efficiency?
3	Have you been involved in a project concerned with EE/RE in energy-intensive industries?
Questions relevant to the specific organisation	
4	How is your organisation involved in making or advising policies on EE/RE/emissions?
5	How were you involved in the EED review consultation?
6	Does your organisation incentivise the implementation of EE/RE/ME measures?
Understanding of link between energy and resource/material efficiency	
7	What potential does your organisation see for RE/ME to help reduce energy use?
8	How do you view energy efficiency in relation to other policy areas such as CE and RE?
Perception of problem	
9	Do you think there is a need to include material efficiency as a tool in energy/climate policies?
10	Hypothetically, how could your organisation support the integration of ME as a technical option to meet climate and energy targets?
Barriers to integrating resource/material and energy efficiency policies	
11	Thinking about industrial climate and energy policies as a whole, what do you think are the main barriers to link energy and resource efficiency policies?

data simultaneously, and to thereby refine the line of questioning.

Interviews were transcribed verbatim using the F5 software (F5 Networks, 2017). Transcripts were manually classified into themes according to the variables in Section 5.2.1. For example, if participants mention the Commission's 'structure' or 'hierarchy', these statements are categorised under 'institutional analysis'. Interviewees were asked to review their interview quotes to ensure correct interpretation. Although most interviews followed the general structure in Table 5.4, they were at times adapted to reflect interviewee's priorities and to ensure a natural conversation. The combination of policy documents and interviews made it possible to construct a methodical and thorough explanation of why ME has received little attention in energy/climate agendas.

5.3 Problem perception

The analysis of problem perception constitutes the first of the results sections. This is followed by Sections 5.4 and 5.5 where institutional factors and the solution readiness are investigated. Before taking action, policymakers must first be convinced that a problem exists. In agenda-setting, many factors affect the perception of a problem. The empirical evidence collected suggests that the main factors influencing this are: the rationale used to frame it (Section 5.3.1); the occurrence of specific predictable events (Section 5.3.2); and the indicators used to track it (Section 5.3.3).

5.3.1 Issue framing: the case of material efficiency

Figure 5.3 shows the frequency with which specific topics were discussed in the Commissioner weekly meetings between 2012 and 2017. The meeting minutes indicate that since the launch of the RE roadmap (in 2011), the Commission's interest on RE/CE has steadily increased. On closer examination though, it becomes clear that in meetings where CE is discussed, there is no mention of its energy or emissions impacts. In fact, in agreement with several policy documents (EC, 2011*b*, EEA, 2010, Eurostat, 2017*b*), RE and CE are only discussed in relation to resource scarcity, economic growth, price increases or security of supply. Conversely, EE and GHG emissions are debated in the context of energy security and climate change, with no mention of RE or CE (see Figure 5.3). This evidence reveals that RE/CE policies and energy and climate strategies are perceived as different problems, and as a result are never discussed in the same meetings.

This disconnect is important because resource-related policies from DG Environment are driven by different rationales than the energy and climate policies from DG Energy and Clima. Under the environmental remit, RE/CE is driven by rationales of scarcity, criticality, price increases and volatility – motivations which result in policies that under-leverage the energy-saving potential of ME. There are three reasons for this. Firstly, these rationales condition which specific materials and environmental impacts are prioritised. For example, if motivated by criticality (Valero et al., 2015), ME policies will focus on materials such as cobalt or neodynium, and neglect energy-intensive (yet widely available) ones, e.g. iron. Secondly, in the EU, institutional venue choice dictates the stringency with which measures are enforced, i.e. energy and climate targets are binding, whereas ME policies (except for waste legislation) remain non-binding. Thirdly, some ME measures are only incentivised by the need to reduce energy/emissions, e.g. wall insulation.

Evidence from the interviews suggests that DG Environment has attempted to re-frame ME as an energy and climate – rather an environmental – tool. One interviewee explained that the report by DG Environment on the energy-saving potential of RE (Mehlhart et al., 2016) was commissioned because *"environmental aspects have not really been at the forefront"*. This was supported by another interviewee, who stated that the report enabled DG Environment to highlight that

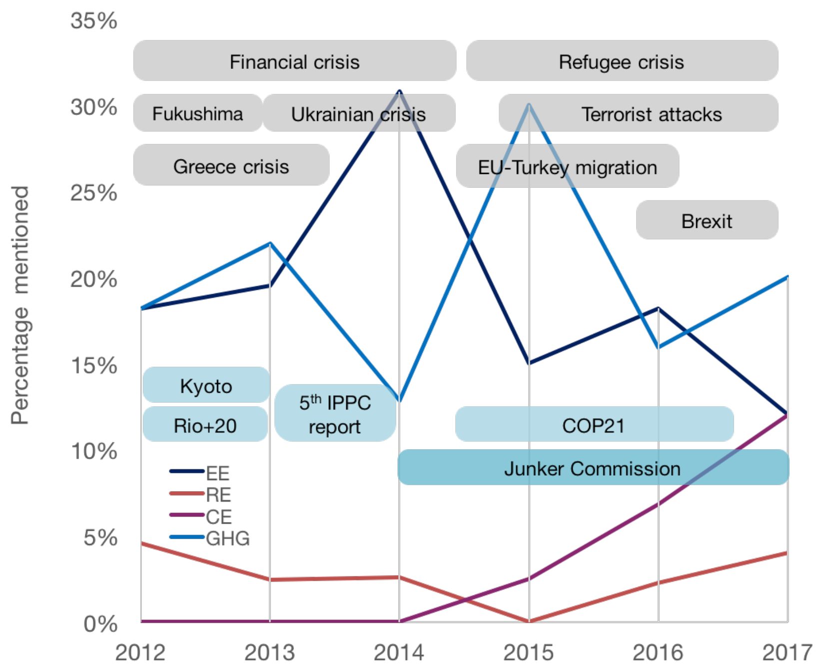

Figure 5.3: Topic analysis of weekly Commissioner meetings, covering energy efficiency (EE), resource efficiency (RE), circular economy (CE) and emissions (GHG), as reflected in the minutes; expressed in percentages. Blue and grey boxes indicate possible climate-related and unrelated triggering events respectively.

"there is also an energy dimension to [ME]". The authors of the report explicitly state that, *"while RE policies are worth pursuing in their own right for reducing environmental pressures, the induced energy savings provide a further rationale for their urgency"*.

Problem re-framing has occurred in other areas; EE is an example. Originally, EE policies were primarily motivated by energy security and economic growth, but in 2007, the EC launched its first combined energy and climate policy framework (EC, 2008*a*). Since then, the convergence between these two issues has continued to grow. For example, there is now a single Commissioner for Energy and Climate Change, and the Energy Union is due to combine energy and climate data collection mechanisms into a single governance system. EE's re-framing as a climate strategy was, however, strongly supported by academics and industry experts, something which ME currently lacks. In 2010, for example, the IEA (2010*a*) published an EE governance handbook outlining the barriers to EE, and detailing in-depth policy solutions to resolve this. In 2013, the IEA (2013) also begun a dedicated, yearly publication titled *Energy Efficiency Market Report*.

When framing efficiency policies as enablers of both economic growth and emissions reductions, a problem that arises is target-setting – in particular, whether these targets are relative (facilitating economic prosperity) or absolute (ensuring emissions reductions).[2] A position paper published by Business Europe (2016) exposes the importance of EE policy framing for industry firms: "industry should not be covered by an absolute reduction target of energy consumption, [as this] would give the wrong incentive to 'produce less' rather than 'being more efficient' ". This statement forewarns of industry's potential response to implementing ME as an energy-saving tool if framed incorrectly. To this end, it can be valuable to distinguish between ME options achieved by increasing productivity (e.g. improving yields or recovering by-products) and those that imply a reduction in demand (e.g. product life-extension) (Brown et al., 2012).[3]

5.3.2 Predictable events: influence of scheduled feedback opportunities

Specific events can turn policymakers' attention to certain public problems or solutions. These can be predictable e.g. the scheduled renewal of legislation, or unpredictable e.g. periods of crisis or disasters. Evidence from the interviews revealed two points. First, that although unpredictable events, such as those included in Figure 5.3, might have been windows of opportunity to build a more integrated ME/EE/climate policy agenda, this did not happen. Second, that policy entrepreneurs exploited the opportunity provided by predictable events, such as public consultations, to voice the need to integrate resource-related policies into energy and climate strategies.

A high-level Commission official explained that "*things can come on to the agenda through consultations*" and that the Commission "*use[s] the responses to the consultations [...] to come up with new ideas and to understand better the balance of opinions*". Yet this was not the case in the two EED consultations conducted in 2014 (EC, 2014*c*) and 2016 (DG for Energy, 2016), where industry stakeholders articulated the need to consolidate ME and EE as tools to achieve energy and climate goals: "*[EE goals] must be kept in balance with [RE] goals"*, and *"the conflict of aims between EE and RE [must be avoided]"*. This same high-level official explained that, *"it was*

[2]Absolute values are preferred for climate targets, as these take in account the impact of rebound effects – precisely the effect that economic targets want to encourage.

[3]The Ellen MacArthur Foundation's branding of existent ME measures as CE strategies is exemplary of effective *framing*. They accentuate the possibilities that CE can offer in terms of innovation, economic growth, and environmental and societal benefits, and its tenets are now endorsed by the EC (EC, 2015*a*) and hundreds of firms.

not the judgement of anyone in [DG Energy] that there was anything in the consultation that we should pick up on".

However, responses suggesting the need to integrate RE and EE/climate policies were few, did not suggest specific policy changes, and were overshadowed by responses alluding to other concerns such as the stringency of EE targets for 2030 or the regulatory and market changes required to improve investments in conventional EE measures already considered by the directive. From the responses to the EED consultations it can be concluded that there is no dedicated industry stakeholder group that advocates for the implementation of ME.

Specifically referring to energy and climate policies, one interviewee mentioned that policymakers tend to resist *"any suggested policy change... and if it is not suiting their agenda, they will probably allow you to write down the changes that they wanted to do anyway inside your policy measures"*. The participant concluded that this limits the extent to which these policies can be influenced through consultations, as these lead to *"a lot of inconsequential very small changes but no overarching support or impact"*. This finding agrees with incrementalist policy theories, as defended by Lindblom (1959), which state that unless a catastrophe occurs, policy developments are likely to happen "through a series of relatively small changes". This is discussed further in Section 5.4.3, where policy inheritance is explored.

5.3.3 Tracking material efficiency: multiple indicators

A change in an indicator can be another way of emphasising the relevance of a policy issue in a specific agenda. EE and ME policy areas are saturated with indicators, which means policymakers need to interpret their relative importance. Table 5.5 summarises some of these. Evidence suggests that ME metrics are inadequate, mainly because these often exclude the embodied energy reductions associated with reductions in the use of energy-intensive materials. However, even if embodied energy metrics (i.e. life-cycle-type measures) were to be included, policymakers show little trust in these. Interviewees highlighted three factors that can explain their relevance in highlighting, or otherwise, the potential for ME solutions.

First, environmental indicators are mostly consumer- rather than producer-centered. One of the interviewees admitted that the RE and upcoming CE monitoring frameworks *"are not targeted at producers"*, but rather at consumers. Similarly, LCA (life-cycle assessment) metrics focus on

Table 5.5: List of most relevant indicators from EC (2016*b*), EC et al. (2012), Humphris-Bach et al. (2016)

Indicator	Unit	Recent progress
Energy use		
Energy intensity	Gross inland consumption of energy divided by Gross Domestic Product	Decreasing since 2006
Energy intensity	Gigajoules per tonne output	Decreasing
Gross inland energy use	Million tonnes of oil equivalent (Mtoe)	Fluctuating (decrease between 2012-2014, increase in 2015)
Energy productivity	GDP (calculated in PPS) per gross inland consumption of energy	Increasing but too slow
Energy dependence	Net energy imports as % of total energy use	Increasing since 2001
Material use		
Resource productivity	GDP per Raw Material Consumption	Increasing since 2000
Resource use per capita	Domestic material consumption per population	Decreasing since 2008 but progress too slow
Material costs	Percentage of gross production value	High
Metal prices	Euros	13% increase between 2010-2020
Waste		
Generation of waste excluding major minerals	Waste generation (kg/capita/year)	Decreasing since 2004 but progress too slow
Landfill rate of waste excluding major minerals	Percentage of waste sent to landfill	Decreasing since 2010
End-of-life recycling input rates (EOL-RIR)	Percentage of end-of-life mass input versus total mass input	No trend available – but currently low
Environmental impacts		
Product footprint	Impact per function unit (e.g. kgCO2/ kg product output)	Progress over time not found
Organisation footprint	Impact per function unit	Progress over time not found

tracking the impact of products. Recent JRC reports, for example, analyse the durability, reusability and reparability of washing machines and dishwashers (Ardente and Talens Peiró, 2015). This suggests that embodied-energy-type indicators are more commonly used to inform end-user decisions and that there is less experience in using these indicators within climate and energy policies targeted at producers.

Second, the RE, CE and Raw Materials frameworks do not track the energy embodied in materials. One interviewee explained that introducing calculations on embodied energy would be challenging because *"market surveillance authorities [...] don't do life-cycle"*, meaning that they do not consider the energy consumed across the product's full life. Omitting upstream energy embodied in materials weakens the incentives to promote ME as a solution to reduce energy. This lack of embodied-energy indicators also besets EE policies and the ETS (EC, 2009, 2013*b*), in which only direct energy use and emissions are included.

Yet even if life-cycle type indicators capturing the embodied energy associated with material use were to be tracked, three interviewees signalled that the lack of clarity around LCA and resource productivity indicators makes them difficult to operationalise and interpret. One highlighted that the *"measurement of RE was considered very imperfect and there was a lot of controversy"*, but asserted that this *"was always acknowledged"*. This view was supported by another interviewee, who explained that *"one of the problems with the leading indicator [was that] it didn't mean anything to many industries"*. Regarding LCA metrics, one interviewee explained that *"embodied energy is a value judgement"*. Another said that: *"the more you start to compare at the small scale, the more you are confronted the need to do allocation [...] if you want to have a subset of a system and compare, then that's tricky"*.

These results indicate that the findings reported by Cooper-Searle et al. (2017) on the case of the UK's automotive climate agenda also apply for the heavy industry sector at the wider EU-level. The authors identified the lack of support for LCA metrics and posited that this results partly from the "lack of standardisation" and partly "from the uncertainty and complexity associated" with these (Cooper-Searle et al., 2017).

5.4 Political and institutional factors

Evidence gathered suggests that four institutional and political factors affect the EC's agenda-setting process, including: its *vertical hierarchy* and the structure of its *policy ownership* (Section 5.4.1), the behaviour of *individual actors* (Section 5.4.2), and *policy inheritance* (Section 5.4.3).

5.4.1 Vertical hierarchy and policy ownership: the impacts of institutions

The term *vertical hierarchy* refers to the interactions between management levels within the EC, while *policy ownership* refers to the parallel interactions across Directorates. Section 2.4.3 mentions the relevance of the mode of issue expansion, for which Princen and Rhinard (2006) proposed two alternatives: through high- or low-level politics. Interviews confirm the importance of high-level support in integrating ME into other areas, and stress the EC's hierarchical rigidity.

A Commission official explained that a policy agenda will depend on whether *"there is a very important top-down element; who is the Commissioner, who is the President; what priorities they set"*, adding that *"all of this is a bit beyond our control"*. Another suggested that, since 2011, there has been a lack of buy-in from political leaders. He argued that *"the Commissioner needs to be on board for this level of change to occur"*, and that without high-level support they *"couldn't really ever convince any of the other DGs to take [RE] seriously as an initiative, because there wasn't buy-in from the director general"*. This also meant that *"the rest of the DG [did] not really get RE or how it might work"*.

These statements stress the relevance of high-level politics within the EC and reveal that enacting policy changes is further complicated by the EC's *"pretty rigid hierarchy"*. To date, there is little evidence that ME is a priority issue for senior EC representatives in DG Energy and Clima; this could help to explain the lack of prominence it has relative to climate and energy strategies.

Interviews revealed that the cross-Directorate policy ownership of environmental, energy and climate matters can hinder the integration of ME in energy and climate policies. One interviewee explained that *"the Commission [has] silos which have their own agendas and instruments and even in the same DG there are different units with different objectives and [...] different instruments"*. Another argued that better cross-directorate coordination is required if the interdisciplinary solution of ME is to be appropriately incentivised:

"the director generals need to talk to other director generals and sell them the benefits of mutual cooperation, then these would tell the directors who would tell the head of units, who would tell the staff to work together with the staff in the other DGs. But without that everyone is busy doing their own thing".

Discussing the RE strategy developed in 2011 (EC, 2011*b*), another interviewee recalled the poor relationship between different Directorates: *"there was a huge amount of frustration between the Cabinet and DG environment with the Director general in the middle"*. Discussing DG Energy's involvement in DG Environment's report on the "Energy Saving Potential of Increasing Resource Efficiency" (Mehlhart et al., 2016), one interviewee from DG Environment mentioned that although they were involved internally, they were *"not tremendously engaged"*. On the interactions between these three DGs, a third interviewee explained:

"Everyone wants to control their own policy [...] It's a big hassle if anyone else tries to change it. Firstly, because they don't control it. Secondly, because it makes it more complicated. Thirdly, because they don't have the time. Fourthly, because changing policies sometimes opens up policies to debate [...] which can lead to unforeseen, unwanted changes in the policy which people are already working on".

The segregation of energy, climate and environmental matters across multiple Directorates is not unique to the Commission, but affects national governments and industry firms also. One interviewee explained that, in national governments: *"an energy, economic or industry department might deal with [...] energy, and then issues [on] resource efficiency and waste will probably be with an environmental department".*

Civil servants are in a unique position to forge relationships with interest groups, thereby establishing the flow of information required for policy proposals. Central to the Commission is civil servants' expertise and dedication to the "principles embodied in their programmes" (Kingdon, 2003). It was civil servants (through the *low-level* politics route), who steered the launch of the RE roadmap in 2011. And yet the evidence collected indicates that high-level political support is key when dealing with multi-disciplinary issues such as ME, for which fundamental changes across multiple policy areas are required.

5.4.2 Individualism in decision-making: the relevance of rational theories

Interviews reflect that the motivations for paying attention to given policy solutions can be affected by the specific people involved in the decision-making process. Five interviewees mentioned the importance of the personality and skills of specific individuals in the development of both environmental and climate policies.

In reference to the environmental agenda, one interviewee explained that RE *"was Potočnik's thing at the time, and now we have a new Commission and a new Commissioner and the new big thing is the CE"*. While discussing the overlap between EE and the ETS, another argued that *"[Dimas] had his big idea, and didn't want to jeopardise it"* by incorporating EE improvements. A third interviewee mentioned that in understanding why a specific issue does not receive attention it is important to consider the *"dynamics of the posts and people…who is in what post and how these people connect with other people in other DGs"*.

The skills and previous experience of specific actors were revealed to play a relevant role in determining the success of an issue in reaching the political agenda. One interviewee highlighted that *"[Commissioner Potočnik] came from innovation so he knew a lot about innovation and about economics [...] and was interested in win-wins between economics and the environment"*. He also explained that the fundamentals behind the RE strategy were *"very much Potočnik's perspective on how things could move forward"*.

Section 5.4.1 revealed that a cross-Directorate issue such as ME, is more likely to become an energy/emissions instrument if this is promoted from above (i.e. through the *high politics* route). The relevance of people's individual interests highlighted in the interviews suggests that for ME to be appropriately integrated in energy and climate policies, a high-level policymaker needs to be personally committed to engineering this. As the Commission's priorities have been long set (in 2014) and its current term is coming to an end (in 2019), it seems improbable that any change will take place before a new Commission is elected in.

5.4.3 Policy inheritance: the dependence on historical developments

Aside from the need for high-profile and Commission-wide support, incorporating ME measures to energy and climate agendas will require overcoming the resistance imposed by previous policy developments. As proffered by historical institutionalists, a high degree of policy continuity is to be expected from any long-standing political institution (Hudson and Lowe, 2009). In this study, interviews confirm that the hostility faced can be largely attributed to the policy lock-in created by the ETS – the crux of the EU's climate policy.

During interview discussions, four interviewees agreed that the most feasible solution is to improve the ETS to make this the main energy/climate policy for heavy industry. Yet there is disagreement about how to modify this. One interviewee stated that *"we should improve [the ETS] by turning it into a global emissions trading system, with a very limited cap that evolves in line with the Paris agreement"*. Other suggestions included appropriately capturing the effect of EE improvements, and adjusting the carbon price. One interviewee suggested that *"getting the price right is the right thing to do"*. Another added that *"there is the psychological effect of high* *prices, you see an effect in industry of extended periods of high prices".*

Other participants were more critical about the effectiveness of changing the ETS. One contended that *"there is evidence that changing the prices might not alter the uptake of EE"* and that they are unlikely to trigger structural changes in firms. Academic experts support this statement and relate the ineffectiveness of carbon prices to four factors: the adoption of carbon-leakage prevention mechanisms[4]; the sequential nature of decision-making along supply chains (i.e. cost effects downstream depend on mitigation decisions made upstream); imperfect competition; imperfect cost pass-through (Skelton and Allwood, 2017).

Modifying the ETS will also require overcoming resistance from industry stakeholders, who are anxious to avoid conflicts with other policy areas and concerned about the scheme's effect on competitiveness. Business Europe (2016) (an industry representative body) argues that the overlap between the ETS and complementary measures – such as the EED or the Integrated Pollution Prevention and Control (IPPC) Directive – reduces the effectiveness of the scheme. In fact, to prevent the extent of this overlap, both the EED and the IPPC policies have already been modified to explicitly exclude ETS industries and CO_2 emissions respectively, "amid fears that it could lead to energy efficiency improvements, reducing demand for emissions allowances and in so doing weaken carbon prices" (Corporate Europe Observatory, 2015). In response to this, several researchers have separately confirmed that given the surplus of allowances – which is likely to continue unabated for another decade – there is no reason to believe that complementary measures are detrimental (Sandbag, 2017).[5]

Business competitiveness is at the centre of most ETS debates. This is reflected in an impact assessment from EC (2015*b*), where it was stated that: "as regards the issue of cost-pass through, many stakeholders claim it is difficult especially since the products are traded on global markets, while others underline that determining concrete cost-pass through rates may be challenging as many factors are at play". In opposition to this, researchers believe there is reason for encouragement. Firstly, little evidence of leakage exists (Erbach, 2015). Secondly, viable options are available to mitigate this; for example, Neuhoff et al. (2016)'s proposal for a consumption charge.

[4]In the UK, at least 95% of ETS allowances are allocated for free to the steel sector (Allwood and Skelton, 2017).

[5]Sandbag (2017) states that: "additional emissions reductions from complementary measures add to the surplus of allowances, are absorbed into the [Market Stability Reserve] over time, and then cancelled". The think-tank also provides other reasons to support the need for complementary measures.

Even if new evidence of leakage were to be provided, the introduction of other trading schemes, particularly that of China, may bode favourably for its prevention.

The historical developments of climate policy, and more specifically of the ETS, are key to understanding the options available for bringing ME into the energy and climate agendas. Indeed, the 'increasing returns' dynamic behind the ETS is likely to be detrimental to both the *technical feasibility* and the *idea acceptance* of integrating ME in energy/climate agendas – aspects which are discussed further in the next section.

5.5 Solution readiness

Even when policymakers perceive an issue as a problem to which they must respond, this, on its own, is not always enough for it to be incorporated into a political agenda. Another relevant factor that demands investigation is the readiness of the proposed solution. In this study, *readiness* is defined in terms of whether an idea is technically feasible, and whether it aligns with the values of the EC and the wider policy community. These two requirements are discussed in Sections 5.5.1 and 5.5.2. Previous analysts have also emphasised the importance of policy entrepreneurs (e.g. industry stakeholders) when policymakers are deliberating on highly technical issues. This argument, which was confirmed through our interviews, is discussed in Section 5.5.3.

5.5.1 Technical feasibility: the mechanics of policy implementation

A multitude of ideas available to curb industrial CO_2 emissions regularly compete for consideration and adoption in the EC. For a specific idea to not only stand out, but to "survive to the point of serious consideration" (Kingdon, 1984), that idea must be technically feasible. Here, *technical feasibility* relates to the practicalities of implementing a given solution. Policymakers must believe that the specific mechanisms by which such solutions would be enacted are attainable. Our interviews indicate that EC policymakers perceive the integration of ME into energy/climate agendas to be taxing because of institutional, political and operational factors. Other than this, the technical feasibility of implementing ME in energy/climate policies is only partially understood.

One interviewee explained that the EU has *"a very rich set of legislative instruments of different types and [...] also more potential... there are all sorts of things we could do."* The wide-ranging implications and drivers for reducing material use, however, make it challenging to develop policies that fully capture all of its nuances. And as revealed in the interviews, this can make it hard to find appropriate solutions to leverage the energy- and emissions-saving potential of ME.

Incentivising ME, according to one of the interviewees, requires *"systemic change…going beyond individual policies to creating the right framework"*, i.e. it must reflect the interdependencies between industrial energy use and emissions across an entire value chain, sector or facility. Another suggested that *"until we know more it is difficult to know what the right instrument would be"*. With relation to DG Environment's report on the energy-saving potential of ME (Mehlhart et al., 2016), a third interviewee mentioned that they *"found it very difficult to come to concrete policy suggestions"* and that *"in terms of policy conclusions that could be taken up at the EU-level, [the report] didn't really serve that purpose"*.

This could be associated with the fact that, as suggested by two interviewees, ME is prohibitively technical, which could make it challenging for policymakers to operationalise. One believed that there is still *"a learning curve that governments and industry need to work through and it would be quite steep"* and *"[the EC] need[s] even more concrete examples of the energy saving potential of RE"*. Another explained that *"the thing with RE is that the concepts are, I think, understandable mainly to a technical audience [...] but translating that into policy is obviously more difficult"*.

In spite of this complexity, a number of interviewees offered ideas of how to integrate incentives for ME into current and forthcoming EU policies. One suggested that *"the area where you are going to see most discussion about the relationship between RE and EE is going to be in Eco-design in the next couple of years"*. Developing minimum standards for the material efficiency of new EU appliances and devices, e.g. for durability or recyclability, can be appealing because Eco-design is a product policy that has low levels of subsidiarity. As explained by this same interviewee, this means that if *"a MS wants to see efficiency grow [this can] rely on better products coming into the market without doing anything other than voting for it in the [EU's] decision-making process"*.

Another interviewee proposed modifying environmental policies: *"there are other policies that are important, water and waste legislation…anything that improves processes, so the IED has some impact on resource use"*. The IED (Industrial Emissions Directive) develops the so-called BREFs – or best practice reference documents – which provide guidance on EE options for energy-intensive facilities to reduce emissions. Albeit not covering CO_2 emissions, BREFs could provide technical support if the given ME measures proposed also reduce other emissions (e.g. particulate matter).

For these ideas to materialise into policies, they would need to get active commitment and support from multiple Directorates and policy areas. Yet in practice this may prove challenging. One interviewee reflected on the current lack of integration between energy and climate policy in the EU, *"it is really frustrating that they didn't want to factor in EE into the ETS [...] this has been extremely harmful to energy and climate policies over the past 10 years"*. This could result from organisational and political factors. As one interviewee speculated *"[DG Clima] didn't want to have anything to do with EE. [Policymakers in charge of] the ETS never really wanted industrial EE regulation to happen"*. Challenges faced in integrating energy and climate policies could act as frictional barriers towards incorporating a third policy area.

Interviewees also mentioned operational factors that may affect the feasibility of implementing ME as an energy and climate solution. One mentioned the fact that policymakers *"are dealing in some cases with data issues"*, specially in policies on secondary material use, where *"sharing data across the system is necessary to ensure the quality of recycled material"*. Another reckoned that there is a lack of methods to ensure that Member States (MSs) *"are accounting properly for what happens in their territory or in other people's territory"*.

While technical impracticality can by itself prevent a policy solution from becoming part of a political agenda, other factors can act to overcome it. This was the case with the implementation of the ETS in 2003. Despite the technical difficulties in enacting this policy, there were many other reinforcing aspects and events that contributed to its final adoption.[6]

5.5.2 Idea acceptance: agreement across the policy community

For policymakers to accept an idea, everyone in the policy community would need to have a similar understanding of what the idea is. If these ideas are to be taken seriously, they must also be compatible with the policy community's values (Kingdon, 1984). The interview discussions suggest this is not the case for ME. Bringing ME into energy and climate agendas will face opposition by policymakers, not least because there is a perception that ME can undermine efforts from other policy areas (e.g. in EE) and no agreed-upon understanding of the full gamut of ME options.

[6] Convery (2009) summarises these as follows: (1) the adoption of the Single European Act facilitated a single market environment (1986); (2) the opposition to a carbon energy tax (sole alternative to the ETS), in 1992, which caused the withdrawal of its proposal (3) the failure of COP Buenos Aires to define trading rules for Kyoto in 1999; (4) the support from the European Council and MSs; (5) Bush's rejection of the Kyoto protocol in 2001; (6) the realisation, in 2002, that emission reductions were not on track to meet Kyoto targets.

While participants were all familiar with the term ‘material efficiency’, its exact interpretation varied. Most participants were only familiar with a selection of ME measures, but none acknowledged that they encompass an umbrella of different strategies (nine according to Allwood et al. (2011)). Two recognised material by-product use as a ME strategy. One gave the example of *“the use of slags of course [...] the slag you can valorise for cement use”*. Another mentioned industrial symbiosis, *“...[in] a steel plant that produces some gases in the blast furnace, we have CO and so this can be a feedstock in the chemical industry [...] that’s a way of looking at the materials, not just the energy”*. Two others gave recycling as the main example. Some were disparaging about its value. In fact, one interviewee voiced concern over the lack of a widely-accepted definition: *“[RE] is just a buzzword, it means many different things to many people”*.

Beyond the lack of common understanding, the interviews revealed two other factors that might impact on idea acceptance: confusion over the link between energy and material use, and the potential trade-offs and conflicts with other policy goals. When asked about the link between material and energy use, three interviewees initially interpreted this as the resource use associated with EE actions, as opposed to the energy impact of reducing material use. For example, one mentioned the *“need to know more about the resource impact of our policies”*. Another argued that *“if you improve processes to save emissions you might have some resource savings at the margins, but I don’t think the resource impact is currently quantified”*. While discussing the EE targets for buildings, one participant explained that *“when you insulate a building, you save energy but your resource use might go up, so you need to be clever about it”*. Only one interviewee mentioned that *“it’s important to acknowledge that there is obviously embedded energy and embedded energy cost that are in materials that is potentially wasted as part of industrial processes”*.

Some interviewees believed that leveraging ME’s energy-saving potential may be challenged by the need to simultaneously support other drivers. For example, one interviewee explained that if ME is merely driven by its energy- or emissions-saving implications this would *“help on some resources but not on others”*. One interviewee said that *“there are situations where they might work against each other. Some measures can conflict or contradict, like with water irrigation measures that can be energy-intensive”*. Another believed that *“EE doesn’t help in the circularity argument”* and that *“EE policies are not in sync with the transition to a circular economy”*. Three participants mentioned contradictions in the buildings sector. One explained that *“EE policies are only linked to use-phase consumption”* and that they *“are not looking at the whole system, so* *they are coming up with bad measures"*. Although there was no mention of heavy industries, perceived conflicts in other sectors, i.e. buildings, can influence policymakers' disposition to intervene.

The interview quotes presented in Section 5.4.1 (on vertical hierarchy) imply that adopting ME as an energy/emissions tool will require high-level political support and cross-Directorate efforts (from DG Energy, DG Clima and DG Environment). Perceived conflicts and contradictions between Directorates, they suggest, will make it more challenging to gain this support. Without the support of Commissioners and Director Generals, it is unlikely that the EC will decide to bring this issue into a wider discussion with the European Parliament and other relevant stakeholders.

This section analyses the opinions of EC officials, but these actors only comprise one of the many policy communities involved in the EU's agenda-setting process. If an idea is not widely accepted within the EC it will likely generate greater debate once Member States, the EU Parliament and industry stakeholders are involved. Despite the fact that the EC is the main initiator of legislation – and as such is highly influential – it is unlikely to defend policy modifications that are opposed by these other stakeholders. This obstacle is further discussed in Section 5.5.3.

5.5.3 Entrepreneurship: the influence of interest groups

In his theory, Kingdon (1984) posits that policy solutions gain prominence through multiple channels, including concerted activities by policy entrepreneurs inside and outside the responsible public institutions. In this context, policy entrepreneurs are advocates who promote specific policy solutions in the hope for future gains "in the form of material, purposive or solidary benefits" (Kingdon, 1984). In this study, *entrepreneurship* is understood to be important in raising the profile of ME solutions in the Commission, as suggested by the empirical data collected.

Interviews unveil the relevance of expert institutions. For example, one interviewee mentioned specific researchers that promote certain ME measures: *"in the working group the European Energy Research Alliance also have their word in defining priorities"*. Another revealed that the European association of SPIRE (2017) (Sustainable Process Industry through Resource and Energy Efficiency) is particularly influential. Yet, despite the existence of some support, some interviewees suggested the need for more. One stated: *"I think the fact that the IEA hasn't covered [ME] that much means that in some cases policymakers haven't seen it either"*. The IEA's limited promotion of ME to date may have a definite effect on EU policymakers, as there is evidence suggesting that EU institutions treat the agency's reports as trustworthy sources of expertise.[7]

Less prominent is the support provided by industry stakeholders. While EC officials did mention the relevance of industry in the development of industrial policies in general, none of the interviewees referenced a lobby group that specifically promotes ME as an energy/climate solution in industry. One interviewee recalled industry's involvement in previous policy decisions, and gave the voluntary Strategic Energy Technology plans of the Energy Union as an example: *"it is certain that in our case industry is the main contributor"*. The interviewee further explained that issue papers *"were submitted to Member States and then the stakeholders, [i.e.] the representatives of the industry"*. Another claimed that the EC *"would not want to undermine the position of industry"*, and that for an idea to become part of the industrial policy agenda, this would at least require buy-in from industry itself: *"ideas have to come from industrial stakeholders"*.

This agrees with Klüver (2013), who contends that for highly technical issues, the Commission is forced to rely more heavily on lobbying groups as these possess economic power and expert information. The author believes that the general population is likely to be less engaged on technical aspects of ME policies. In fact, Smith (2017) explores the reasons behind the lack of media attention given to ME, and more specifically the historical role of "broadcasting [...] in shaping how societies talk, think about and act on issues surrounding material demand". The author concludes that the media coverage of ME consists of negative "sparse rehearsals" that critique consumption and that "the relationship between environmental change, material consumption and everyday life" must be re-framed and made more positive and tangible (Smith, 2017).

Interviewees did not reference a lobby group that specifically promotes ME as an energy/climate solution. This suggests that either there are insufficient proponents of ME for industry or that their initiatives have had little success in reaching influential decision-makers. The latter may be due to the fact that support for ME is relatively recent. However, measuring the role played by entrepreneurs and the impact these have on policymakers decisions is an extremely taxing endeavour; it is difficult to capture the effort going in to promote an idea and the involvement of specific entrepreneurs is rarely mentioned – unless referenced/acknowledged in policy documents.

[7] In the Parliament's resolution report of 15 December 2015 on Towards a European Energy Union (2015/2113(INI)), reference is made to work by the IEA: "according to the IEA, energy efficiency is the 'first fuel' and represents the best return on investment of any energy resource". This argument was used as support for the Parliament's call to apply 'energy efficiency first' directed both at the Commission and at MSs.

5.6 Discussion: leveraging material efficiency to reduce energy use

The above sections have sought to answer the question posed at the start of this chapter: *"Why is material efficiency not integrated into the EU's energy and climate strategies for heavy industries?"*. In other words, we evaluated the factors preventing ME from becoming part of the EU's energy and climate agendas. Our evidence revealed that despite the proved need for ME to achieve energy and emissions targets (Allwood et al., 2010), its demonstrated potential for improvement (Cullen and Allwood, 2013, Cullen et al., 2012), DG Environment's willingness to promote this (Mehlhart et al., 2016), and some industry support (DG for Energy, 2016, EC, 2014*c*), several factors prevent ME from becoming part of the energy and climate agendas. The most prominent factors highlighted in interviews and observed from the literature are summarised below. Based on this, suggestions for future policy interventions are made.

In relation to the **problem perception**,

- None of the indicators monitored by the EC captures the energy savings available from reductions in material use, and the sheer volume of these indicators decreases the political appetite to add new ones. Yet embodied-energy metrics are not trusted among policymakers.
- The existence of other rationales to pursue ME in DG Environment – for example, reducing resource inputs, trade reliance, criticality of materials – makes it increasingly challenging to re-frame this as an energy/emissions issue. The current Commission, however, is focusing more on energy and climate issues than on environmental ones; this may facilitate the integration of ME in energy/emissions policies.
- A number of industry stakeholders made suggestions to integrate ME and EE policies in public consultations (DG for Energy, 2016, EC, 2014*c*). Yet these lacked detail and were not supported by a dedicated group advocating for ME. The limited time between consultations and final revisions could prevent the EC from implementing substantial policy changes.

In relation to **institutional factors**,

- The rigidity of the institutional structures in the Commission, alongside the lack of high-level political support for ME in the DG Energy and DG Clima, can all hinder the integration of ME in the energy and climate agendas.

- Cross-Directorate ownership of energy, climate and environmental issues further complicates their integration. This suggests that collaborations between Directorates must be improved, and high-level political buy-in is key to achieve this.
- Difficulties experienced in the ongoing integration of energy and climate policies – now under a single Commissioner and soon managed under a single governance framework – may discourage the Commission from integrating additional aspects onto this, i.e. ME.
- The lock-in imposed from policy inheritance, primarily the ETS, is also perceived as a barrier – that is, the transaction costs involved in changing existing policies.

In relation to the **solution readiness**,

- All interviewees were aware of the meaning of ME. Yet its interpretation varied among them. This interpretative flexibility leads to confusion around the concept and can make it more challenging to get high-level political buy-in.
- The link between energy and material use is another source of confusion, which suggests there is still a steep learning hurdle to be overcome before ME is leveraged as an energy and climate solution.
- The perception of potential conflicts between ME and EE highlights the need for policy-makers to be better informed about the interactions between the two measures.
- The lack of data in the areas of waste and industrial symbiosis were reported by interviewees as potential barriers to implementing ME-related policies.
- There is no dedicated interest group currently advocating for the inclusion of ME in energy policies. The need for technical expertise in the area of ME, suggests that the creation of a powerful industry stakeholder group is indispensable to catalyse policymakers' attention.

These findings show that many factors can influence whether a policy problem becomes part of a policy agenda. All of these factors must be considered if material efficiency is to become a larger part of the EU's energy and climate policy portfolio. The identification of the barriers preventing the inclusion of ME in the EU's energy and climate policy agendas should equip policymakers with the necessary knowledge to drive the resource efficiency agenda forward. The next section explores the levers available to do this.

5.6.1 Proposal of policy interventions: looking forward

The factors preventing the integration of ME in energy and climate agendas described above require foundational – rather than superficial – legislative, executive and cultural changes. Proposed solutions must come with a high-level political buy-in and support from industrial stakeholders, and are more likely to succeed if they only demand incremental modifications to existing binding policies. The policy analysis conducted in this section is an ex-ante exercise, which makes it impossible to know how events will actually unravel. However, the knowledge gathered places us in a good position to make future suggestions. Table 5.6 (spread over three pages) summarises the multiple avenues that could be explored to incentivise the adoption of industrial ME as an energy and climate tool. This table compiles an extensive list of interventions that are based on suggestions made by interviewees and on solutions recommended in the literature.

Interventions are classified according to the degree (whether a minor, intermediate o major change) and type of change that is required (whether informational, technical, financial, legislative, executive, or administrative). Minor changes often represent informational interventions that do not require a big shift in current, mainstream thinking, whereas major changes involve legislative, financial or executive modifications that are likely to occur only after 2030. Intermediate changes cover those that either go beyond the provision of information but can be enacted before 2030, or that are informational but require a shift in accepted lines of thought. The years of 2020 and 2030 are used as distinguishing features, as these are the years to which energy and emissions targets are specified, and for which independent policy frameworks have been established. This also largely coincides with the fourth trading period of the ETS (2021-2028). Table 5.6 also indicates which stakeholder is better equipped to lead a given intervention (whether Member States, Experts or the EC), and gives a detailed example of how the intervention could be enacted.

Among the interventions available, the most efficient (and perhaps the most likely to receive political and industrial support) is to ensure that the ETS – the cornerstone of current industrial energy and climate policies in the EU – successfully incentivises the adoption of ME. This is because the abolition of the EU ETS is likely to be strongly resisted, mainly for two reasons. First, in developing the premiere carbon pricing system (the ETS), the EU took on a leading role in global climate change policy. Seeing the system fail would send a negative signal to the rest of the world (Convery, 2009). Second, industries and MSs have a vested interest in the ETS – a result of its long-standing operation. Policy experts refer to this as the 'increasing returns'

Table 5.6: Potential interventions to leverage energy-saving potential of ME in EU energy and climate policies. interm. is intermediate, *MS* is Member State and *EC* is the European Commission; *Experts* refer to both industry practitioners and academics.

Degree	Type	Description	Leader	Example
Before 2020				
Minor	Informational	Incentivise the adoption of ME by providing information on the energy-saving potential of ME	MS, EC	Include ME actions within the "indicative list of examples of eligible EE improvement measures", as portrayed in Annex III of the 2006/32/ec procedure.
Minor	Technical/ informational	Improve trust on embodied-energy metrics	Experts	Develop more transparent methods through which to allocate resources or emissions to specific products/activities. Sankey diagrams, for example, could improve visibility of scale and structure of data.
Interm.	Informational	Clarify conflicts between energy and material use	MS, EC, Experts	Engage with academics or external consultants to conduct a report on this for industry and other sectors
Interm.	Technical/ informational	Incentivise the development of industry standards for ME	MS, EC	These are currently being jointly developed by Environmental Citizens Organisation for Standardisation and European Environmental Bureau.
Interm.	Informational	Introduce ME into public agenda	MS, Experts	Smith (2017) suggested that creative and entrepreneurial partnerships between researchers and media professionals could raise public awareness about ME – which would increase pressure on governments/ the EU, and help re-frame "the relationship between environmental change, material consumption and everyday life".
Before 2030				
Minor	Informational	Provide standard definition for embodied energy in the EED's guidance documents	MS, EC, Experts	For example in the accompanying document 'Commission implementing decision establishing a template for NEEAPs under Directive 2012/27/EU of European Parliament and Council COM(2013) 2882 final'
Minor	Informational	Include appropriate indicators to incentivise the energy-saving potential of ME	MS, EC	Include producer-oriented metrics in the publication of the next RE and CE monitoring frameworks, using guidance from previously-developed LCA-type indicators.
Interm.	Informational/ technical	Collaborate with industry/MSs to develop digital platforms that encourage ME	MS, Experts	Get involved in large-scale projects to investigate ME; e.g. SPIRE is working on a project titled: "Process Decision Making: integration of life-cycle assessment and costing tools for process decision making" as part of the Digital Single Market initiative (EC, 2017*a*).

Degree	Type	Description	Leader	Example
Before 2030				
Interm.	Informational	Incentivise MS-level and industry-led initiatives	MS, EC	For example, the German government has encouraged the development of "sector-specific aids, methodologies and information such as RE checks and process systematisation tools to assist manufacturing [firms]" with RE projects – currently led by Centre for Resource Efficiency
Interm.	Technical	Develop more examples of specific options to reduce energy use by reducing material use	Experts	Fund research projects that investigate energy-saving potential for ME in industry, e.g. through the Horizon 2020 programme or through projects like SPIRE (2017).
Interm.	Administrative / informational	Incentivise the training on the resource efficiency management of production	MS, Experts	Germany is a good example: VDI (2016) has developed information material (e.g. resource checks, process chains, a best-practice data base and a cost calculator), as well as tailored qualification seminars on resource efficiency.
Interm.	Informational	Commission a resource efficiency governance handbook	MS, EC	The IEA's EE Governance Handbook provided key suggestions on how to adapt and coordinate legal and institutional arrangements to scale-up EE. (IEA, 2010*a*)
Interm.	Informational	Incentivise communication between actors along supply chains	MS, EC	Such as the support provided in the UK, France and Germany on industrial symbiosis (OECD, 2016)
Interm.	Informational	Push for consideration of wider ME options/implications internationally	MS, EC	G7 Resource Efficiency Alliance is a good venue to push for wider range of RE measures; expanding focus from waste management (G7 Resource Efficiency Alliance, 2016). Develop support for ME within global initiatives such as the Clean Energy Mission Innovation.
Interm.	Administrative/ financial	Boost investment through Digital Single Market	MS, EC	Develop dedicated funding for projects specifically targeting energy savings through ME measures, e.g. in the form of Public Private Partnerships (PPPs) and pilot studies (EC, 2016*a*).
Interm.	Administrative	Create a unified ME stakeholder group	Industry	Industry firms should unite to promote the adoption of ME as an energy-and emissions-saving tool.
Major	Administrative/ executive	Incentivise the creation of body that collects industry material flow data	MS, EC, Experts	Create a forum such as the International Energy Agency which is responsible for collecting material flow data.

Degree	Type	Description	Leader	Example
After 2030				
Major	Legislative	Allow the inclusion of embodied as well as direct energy savings	MS, EC	Change the definition of 'energy savings' in Article 7 of the EED to include 'embodied' as well as 'direct' energy savings.
Major	Legislative	Enforce collection of material flow data from industries	MS, EC	Enforce resource rather than energy audits in Article 8 (EED). Large enterprises should also report material flows and ME.
Major	Legislative/ executive	Develop MS- or EU-level plans for supply chains rather than sectors	MS, EC	The new Industrial Strategy in the EU or in the UK may be an appropriate policy framework in which to do this
Major	Legislative/ financial	Implement fiscal measures to encourage ME	MS, EC	Literature examples: compensation charge to reinstate the carbon price downstream; compensating for carbon leakage independent of embodied carbon, e.g. corporate tax relief independent of energy use; or other strategic tax exemptions (Neuhoff et al., 2016, Skelton and Allwood, 2017).
Major	Legislative/ financial	Modify the design of the ETS emissions cap	EC	For example, by aligning the ETS cap with stringency of Paris agreement and capturing EE and ME improvements in the calculation of its annual reduction rate. Other options include: "dynamically managing caps either through auction release or a changing cap" (Scott et al., 2017).
Major	Legislative/ financial	Modify the design of the ETS allowance benchmarks	EC	Improving the quality of the production data used in allocations and updating the benchmarks to include ME interventions by including indirect as well as direct emissions within the benchmark boundaries can be a first step. Another option is to include ME measures in the BREFs that are then used to define the benchmarks.
Major	Legislative/ financial	Increase the scope and stringency of energy regulations	MS, EC	Another option to modify the ETS is to restrict the impact of this and to instead widen the scope and increase the stringency of the energy regulations (end the EED's exemption on ETS industries)

dynamics: many apparatuses and mechanisms have already been put in place to ensure that the system functions well and the money generated from it is used to fund research projects.

Kingdon (1984) contends that opportunities for change – or policy windows – arise in various ways, including through the occurrence of sudden events, changes in the public mood or measured indicators, and government turnovers. If the ETS remains the province of industrial climate policies and the evidence presented above proves accurate, sudden events and institutional turnovers are most likely to trigger the policy changes required to integrate ME in climate/energy agendas. Potential outside events that could initiate a policy shift include: (1) the unexpected shortage of a given resource; (2) unforeseen trade tariffs on energy-intensive materials, e.g. America's new tariffs on steel; (3) the need for new climate deals as a result of Brexit.

In the upcoming decade, one predictable window during which discussion on the integration of ME might be initiated, is the next revision of the ETS. But even if policymakers, industry stakeholders and Member States were to agree to make pertinent modifications to the ETS, this window is subject to the slow pace of change in EU-level policymaking: ETS revisions made at this time are not expected to come into effect until after 2030. The entrance of the new Commission in 2019 presents another opportunity for such discussion; though, again, even if the new Commission makes the integration of ME a firm objective, required policy interventions are unlikely to be enacted within their five-year term.[8]

A third potential catalyst for change is in the revisions of complementary measures, for example, Articles 7 or 8 in the EED. If ETS modifications prove challenging and lengthy, increasing the stringency and scope of EU-level energy and/or environmental policies becomes an effective alternative. Although this is likely to face opposition by industry stakeholders, there are groups of researchers and policymakers who argue that the modification of complementary options may be the more realistic option – given the resistance experienced in changing any specific provisions of the ETS. A UK-based think-thank, Sandbag, aptly argues that "the appropriate question is thus not whether complementary measures are needed, but how the EU ETS can be designed to better accommodate necessary, appropriate and efficient complementary measures" (Sandbag, 2017). The main drawback to making intermediate or major modifications to other EU energy and environmental policies is, again, that they are likely to be enacted in the post-2030 period.

[8] It is possible that Brexit negotiations trigger an unforeseen revision of the ETS in 2019. It is, however, uncertain whether these negotiations will open up the opportunity to revise other provisions.

There are multiple reasons why EU-level action is preferred for pursuing the integration of ME in energy/climate policies: the international nature of supply-chains; the ability of EU-backed initiatives to pool public resources and attract the required quantity of private investment; the fact the EU is responsible for the governance of a large number of environmental and energy issues. However, given the barriers just discussed, it appears that major, short-term policy interventions at the EU-level are limited. The policy shift required to leverage ME as an instrument to reach energy/climate targets will therefore require action from Member States, industry and academics.

Successful cases where MSs have taken charge in driving policy change are plentiful. Germany's early support for solar photovoltaic systems is just but one example (Sandbag, 2017). In the areas of ME, Germany has, again, become the European leader (BMUB, 2016, G7 Resource Efficiency Alliance, 2016). By 2013, Germany had already adopted the *German Resource Efficiency Programme (ProgRess)* and created the *National Resource Efficiency Platform* (BMUB, 2016). Three years later, in 2016, a revised version of ProgRess was launched (ProgRess II), and alongside it the first RE industry standards (VDI, 2016). ProgRess was developed through intensive consultations with stakeholders, and as a result, the Federal Government now counts with the broad-based support of 16 German Länder, 40 sectoral associations and other institutions.

These developments are key for the EU as a whole, and other MSs should be encouraged to capitalise on Germany's progress. The drafting of Britain's new Industrial Strategy as a consequence of Brexit could provide a unique opportunity to do this (HM Government, 2017). In doing so, the resulting industrial policies would be able to more effectively address the limited adoption of ME measures, and would help modernise the heavy industries that remain operative.

5.6.2 Evaluation of research method used

The literature in Chapter 2 confirmed that no single policy theory can capture all the factors influencing the formation of policy agendas. Many experts have in fact advised that, in practice, employing a combination of theories can be more insightful. Abiding by the pragmatic approach governing the overarching research methodology of this thesis, this chapter integrated three policy theories, namely: MSF (multiple stream framework), HI (historical institutionalism) and RCI (rational choice institutionalism). The specific combination of these three theories was chosen according to the interview responses and the available policy documents (e.g. meeting minutes).

Kingdon's MSF can explain a plethora of exogenous factors affecting the policy agenda. This theory strives to offer a more nuanced perspective on agenda-formation by adopting more realistic assumptions about both the collective behaviour of policymakers and the decision-making process. Although the concept of *timing* is core to MSF, i.e. *when* a specific issue is brought up to policymakers' attention, fewer insights are offered on the impact of policy legacy. The inclusion of HI complemented Kingdon's theory and made it possible to consider the effect of previous policy developments on current political decisions – an issue that continued to appear in the interviews. To provide an understanding of the analysed issue, which reflected the aspects discussed in the interviews, it was necessary to incorporate aspects of RCI. Unlike MSF and HI, RCI focuses on the behaviour and motivations of individuals and the impact that institutional structures can have on their decisions. It was only through the combination of these three theories that it was possible to offer a holistic answer to the research question posed at the beginning of this chapter.

The selection of a representative interviewee sample is always challenging. Despite making efforts to include individuals from all three policy areas, with different responsibilities and varying levels of expertise and seniority, it is still possible that interview results are not exhaustive. In the future, it would be beneficial to expand the interviewee sample size, and to ensure that people responsible for agenda-setting at the national level are included.

5.7 Chapter summary

This chapter has analysed the factors which prevent ME from becoming part of the EU's energy and climate agendas. By conducting interviews, reviewing policy documents, and expanding upon three policy theories – namely rational choice institutionalism, historical institutionalism (Hindess, 1984, Sabatier et al., 1999) and multiple streams framework (Kingdon, 1984) – this chapter evaluates why this is the case. Combining institutionalist frameworks with Kingdon's MSF provides a richer understanding of the factors influencing the agenda-setting process in the Commission, more so than either framework would give in isolation.

This study suggests that the leading option for ensuring the uptake of ME as an energy-saving tool in heavy industries is to modify the ETS, not least given its imposed policy lock-in (i.e. the time, money and efforts already committed by Member States, industry and policymakers). At the same time, the vested interest in the ETS could undermine efforts to make it more effective.

To this end, a raft of other energy and environmental policy options exist, namely to expand the stringency and scope of DG Energy's Energy Efficiency Directive or DG Environment's CE Package. Nevertheless, all viable options hinge on achieving multiple prerequisites: high-level political buy-in, improved cross-Directorate collaborations, the creation of a dedicated industry lobby group, improved metrics, as well as improvements in the collection of material data and in the transparency of embodied emissions/energy calculations.

The mandatory revisions of the ETS and the EED for the period 2020-2030 have already taken place, and the Commission turnover is not due to happen until 2019. This, in conjunction with Kingdon's theory – which contends that opportunities for agenda change arise only when multiple factors converge at the right moment in time (Kingdon, 1984) – suggests that, in the absence of any major triggering event (e.g. a climate disaster, an unexpected resource shortage, or the need for unforeseen Brexit deals), there is limited opportunity for any radical policy interventions to take place before 2030. For this reason, this study recommends that individual Member States and industry companies take action in incentivising the uptake of ME in order for the transition to a low-carbon heavy industry in Europe to take place.

6

Conclusions and research opportunities

This final chapter now consolidates the results from Chapters 3-5 and describes this thesis's contributions to knowledge (Section 6.1). Section 6.2 discusses the wider implications of the results obtained, and Sections 6.3 and 6.4 outline the potential research opportunities and future developments outside of academia. To conclude, Section 6.5 summarises the overarching conclusions.

6.1 What new contributions to knowledge have been achieved?

This thesis set out to answer the overarching question (Q0): *How can we help industrial firms become more resource-efficient?* In this section we assess to what extent this question has been answered. The overarching question was divided into three research questions (Chapter 2.5.1), with each question addressed as a chapter of the thesis. The focus was to develop: meaningful RE metrics (Chapter 3); analysis tools for firms to leverage RE improvements at operational scales (Chapter 4); an understanding of current policy barriers and opportunities for leveraging RE as an energy-saving measure in industry (Chapter 5). Together, the analyses of these three chapters provide a partial answer to this thesis' overarching research question. The individual contributions made by each chapter are discussed in turn.

Q1: How can energy-intensive industries measure and benchmark their energy and

material efficiency in a unified manner? (Chapter 3)

Historically, efforts to reduce industrial carbon emissions (and energy use) have been limited to EE (energy efficiency) options, i.e. reducing the direct use of fuels and recovering waste heat. Material production, however, involves myriad processes, which combined constitute a complex network of interacting resources, including energy, materials and water. Overall energy savings are hence not only possible through reductions in fuel inputs and wasted heat, but can also be achieved through reductions in material use. What is more, neglecting the impact of material use in emission mitigation efforts provides only partial insight into the energy savings available and overlooks unavoidable trade-offs – reducing energy use in one part of the production may increase material use elsewhere and vice versa. Energy-intensive industries must therefore be equipped with actionable metrics that allow them to leverage the full gamut of RE options; this is indispensable for creating transparency about RE, improving its traceability and providing accountability.

In response to this need, a meaningful RE metric was proposed in Chapter 3. The range of capabilities of this RE metric was tested through a case study: the global steel sector, for which the most recent and comprehensive data was used (provided by worldsteel). This new metric offers improved features when compared to existing indicators:

- Energy and material flows are consolidated into a single metric. This reduces the number of variables to be tracked, while at the same time providing a more complete and nuanced picture of a system's resource efficiency.
- The reduction of material inputs and improvements in the recovery of material by-products can now be quantified and thus encouraged alongside more conventional EE measures. This opens up hitherto neglected opportunities to reduce overall energy use.
- The quality of this data delivers improvements in the accuracy of the steel industry's RE calculations. For the first time, representative resource efficiency distributions are presented for plants and production routes across the sector.

This integrated RE metric offers a suitable alternative for benchmarking energy-intensive industries, and that it can be key for comparing energy and material efficiency options on an equal footing. Having recognised this, and as a result of this study, *worldsteel* is now using exergy to benchmark the RE of its members – a welcome development given the absence of internationally-agreed methods for comparing steelmaking plants and routes (IEA, 2008). The analysis of Chapter

3 was published in the Journal *Resources, Conservation and Recycling* (Gonzalez Hernandez, Paoli and Cullen, 2018). The data used can be found in: (Gonzalez Hernandez et al., 2017).

During the interviews conducted for Chapter 4 and 5, most interviewees agreed that it is either necessary or beneficial to integrate the analyses of energy and materials into a single metric. One explained: *"I'm totally bought into the idea that [...] you need a balance understanding of what's the energy and material implications or consequence of a decision that's made, and only make one which is the best outcome, in overall terms"*. Another explained that it is necessary to *"broaden out the understanding that energy is just one resource input that goes into the broader industrial production process; that there are other materials and inputs that are associated with that and there the efficiency which with they use and through which the waste of those resources is reduced is also very important"*.

This new RE metric can be used to track performance and establish RE objectives at multiple levels. In fact, in Chapter 3, the RE metric was used to set targets at the sector level. To ensure the identified measures are adopted in practice, however, these sectoral objectives need to be translated into concrete practical actions. This is precisely the motivation behind Chapter 4, where the integrated RE metric was developed into an engineering tool for plant managers and operators.

Q2: Can we gain a better understanding of resource efficiency using energy and material control data on a close-to-real time basis? (Chapter 4)

The novelty in this chapter stems from the unique combination of three well-established techniques: data analytic methods to extract available control data, the thermodynamics-based RE metric proposed in Chapter 3, and the visual tool of Sankey diagrams. As industry is currently undergoing a digital transformation – companies are striving to extract as much information from their metered data as possible – it is only logical to develop tools that align with this vision. The use of control data is therefore a crucial feature of this work. To test the functionality of the RE method, this was tested through a case study: the resource use and efficiency of a steel production plant were tracked during real operations for a month. Evaluating operational-level resource efficiency in this way can prove valuable because:

- It incentivises material efficiency as a complementary way of reducing energy use in industry, and enables better-informed decisions on how and where to improve RE (EE and ME combined) at actionable scales.

- It makes RE more visible at detailed operational levels, where decisions about resource-use improvements are ultimately made.
- It provides a middle ground between sophisticated chemical engineering models and simplified performance indicators. It offers greater insights than single indicators, requires less time and expertise than complex engineering models, and lays the groundwork for prediction exercises to be carried out.
- It offers plant managers and operators a powerful framework with which to communicate RE improvement options to higher management levels. Well-designed Sankey diagrams often facilitate the communication of complex information.
- It can reduce the time, cost and expertise required in traditional energy audits. Ultimately, as stated by Business Europe (2016), companies that are permitted to devise their own methods for achieving imposed environmental obligations, become more proactively involved in policy development.

Two interviewees provided positive feedback on the developed approach by articulating its potential value. One described this as follows: *"It's really interesting [...] It gives that kind of consistency, kind of a something...that would be comparable across different scales of operation...yes. Definitely has a potential to work...and solve some of the problems that we found in our, naive thinking about resource efficiency metrics"*. Another emphasised the advantage of visually illustrating our results in the form of Sankey diagrams: *"The visual display of the breakdown of the exergy is extremely powerful because it can be understood by anybody. You can show it to an operator, a manager, the CEO and they would all understand immediately from the visual display where everything is going and you can communicate this to people very easily [...] it's a very effective way of communicating"*.

This case study is the fundamental proof-of-concept from which a decision-support tool will be developed – a tool to be elaborated further in pilot projects with industrial partners. What resulted from Chapter 4 is a credible substitute for current EE and ME monitoring and auditing exercises – an approach that goes beyond conventional, myopic views of resource use, and which can accelerate the auditing process. The analysis of Chapter 4 was published in a Special Issue of the journal of *Applied Energy* (Gonzalez Hernandez, Lupton, Williams and Cullen, 2018). The code used to process the control data can be found in: (Lupton and Gonzalez Hernandez, 2018).

Q3: Why is material efficiency not integrated into the EU's energy and climate strategies for heavy industries? (Chapter 5)

Lastly, Chapter 5 constitutes an important contribution to the wider debate on the decarbonisation of energy-intensive industries in the EU. For the first time, empirical evidence is provided to explain why ME has not been integrated into the EU's energy and climate policy agendas. Evidence collated from policy documents and semi-structured interviews was triangulated with relevant literature and three policy theory frameworks: rational choice institutionalism, historical institutionalism and Kingdon's multiple stream framework (Kingdon, 1984). Unlike in previous studies, this work considers the entire policy landscape, including energy, climate and environmental DGs (Directorate Generals).

The results show that ME is primarily considered an environmental and economic strategy. This is problematic for two reasons. First, ME policies in the environmental policy remit are non-binding. Second, these policies do not necessarily focus on energy-intensive materials – for which embodied energy savings are greatest – but rather focus on scarce and critical materials instead. The energy savings available from reductions in industrial material use are currently neglected. In fact, the carbon emissions of energy-intensive sectors are solely legislated through the Emissions Trading Scheme (ETS), which has been reported to be ineffective in promoting both EE and ME strategies (Neuhoff et al., 2016, Skelton and Allwood, 2017).

The analysis suggests that the lack of integration of ME in energy and climate policies stems from a combination of contributing factors. These include institutional, political and informational barriers such as: the difficulties in reframing the prevailing rationale to pursue ME; the inadequacy of monitored indicators; the lack of high-level political buy-in from DG Energy and Clima; the ETS policy lock-in; the uncoordinated policy management across Directorates; and the lack of a designated industry lobby.

A number of policy interventions are proposed to address the identified barriers. From within these, the leading option is to improve current ETS policies. If this proves challenging, a raft of other options exist, namely within DG Energy's Energy Efficiency Directive or DG Environment's CE Package. The limited agency of EU institutions to adequately modify current energy/climate legislation before 2030 reveals the need for Member States and industry stakeholders to drive the move to a low-carbon heavy industry.

The conclusions drawn from Chapter 5 are particularly insightful for policymakers and high-level managers from industry firms – the decision-makers who, in practice, have the power to encourage and execute resource efficiency improvements. The content of Chapter 5 was published in the journal *Energy Policy* (Gonzalez Hernandez, Cooper-Searle, Skelton and Cullen, 2018).

Q0: How can we help industrial firms become more resource-efficient? (Chapter 1)

This thesis has explored three specific concepts which will assist industrial firms to become more efficient. First, an engineering metric was proposed to more meaningfully quantify the resource efficiency of production systems. In doing so, it has made the complex concept of exergy more accessible to industry practitioners. Effectively, having access to this new metric is a prerequisite for making decisions on the implementation of RE improvements; it enables energy-intensive firms to start tracking the RE of their operations and allows them to quantify the technical opportunities available to improve this.

The adoption of metrics, however, must be complemented with more advanced analytical tools that enable plant managers and operators to investigate these RE opportunities in more detail. The second concept explored is the development of such tools. At this stage, the proposed RE analytical tool provides a prototype from which more automated solutions can be developed. Today, the deployment of these analytical tools necessitates the enforcement of environmental and climate policies – they are the principal mechanism persuading reductions in industrial energy use and emissions. The third research area in this thesis investigated the policy barriers and drivers for resource efficiency in the EU. Identifying the policy levers available to drive industry's interest on RE is therefore a crucial step in making industry more resource-efficient.

Although Chapters 3, 4 and 5 only provide partial answers to the overarching research question posed in Chapter 1, they constitute the fundamental knowledge from which more advanced, commercial solutions can be developed. Overall, this thesis offers a unique interdisciplinary perspective on how resource efficiency should be measured, analysed in industry and incentivised in policy. Following this research, industry now has several new methods and tools to help asses resource efficiency in their processes, and policy makers are in a better position to drive the RE agenda forward.

As this is the first thesis in our research group that endeavours to develop practical tools to help industry improve its integrated RE, many ideas for future research have been identified; these are discussed in-depth in Section 6.3. Before detailing the research developments required to provide a more complete answer to this thesis' overarching research question, the next section discusses the wider implications of the methods used and the results obtained.

6.2 What are the wider implications?

Most analyses of RE are top-down. They analyse aggregated data over long periods of time (often years and at the country or global scale), examples of which include work by Cullen and Allwood (2013), Cullen et al. (2012), Eisenmenger et al. (2017) and Ayres et al. (2011). These studies provide meaningful estimations of the potential resource savings available across entire supply chains. Improving the accuracy of these estimates and capturing the nuances of RE measures (i.e. potential operational limitations or temporal variations) involves bolstering these top-down methods with bottom-up analyses.

Having access to more and higher-quality, bottom-up data has the potential to help companies and governments make better-informed decisions about how to reduce industrial resource use. This is the claim made by Internet-of-Things enthusiasts, who trust that collecting a greater volume of increasingly granular data from machines will revolutionise the way production is currently done and managed. The potential of this digital transformation is unquestionable, but there is still a great deal to learn about what can be done with all the data that is collected. This problem, which requires making sense of the 'big data' collected, is key to improving the sustainability of current industrial processes. The thesis, therefore, has focused on finding ways to provide a meaningful RE analysis from the vast amounts of data already collected by industry.

There are, of course, several methods available to analyse RE in industry. Competing alternatives to the chosen integrated ExFA method include: LCAs, IOAs and MEFAs. LCAs serve as instruments to assign responsibility for the use of resources and as a result are particularly relevant to compare the environmental impact of two similar products. Typically, LCAs are opaque and rely on averaged plant data, which is never representative of a single plant. IOAs are often conducted at high-levels of aggregation (e.g. countries or regions) and are constructed using economic rather than physical data, and so can only at best give a top-down picture of resource use. MEFAs, which trace the flows of resources and depict these in the form of Sankey diagrams, can resolve many of these issues; the allocation of resource use is not required, the analysis is based on physical data and can be applied at any system level. MEFAs, however, treat energy and materials separately, and therefore neglect the interactions between the two. To overcome the drawbacks of these methods, this thesis integrates MEFA and ExFA methods.

In doing so, other limitations must be accepted. Exergy analyses: can be challenging for non-technical audiences; can be time-consuming; do not necessarily capture the functionality of specialised materials; lack formalised industry standards that support it. Furthermore, almost everyone has a basic understanding of energy and materials, yet, even within the engineering profession, very few understand exergy.

Despite these shortcomings, this thesis contends that the use of exergy as a RE metric is worthwhile for three reasons. Firstly, an exergy-based RE metric is able to capture improvements in the use of materials alongside those in energy. This is not possible in energy-only intensity metrics currently used as benchmarks, where raw material inputs and material by-products are excluded. A common analytical framework is the first step towards a unified resource efficiency narrative. Secondly, exergy analyses are based on the performance of processes rather than products, thereby providing more valuable guidance to upstream producers on where to reduce resource use. Thirdly, exergy can be made accessible to non-expert audiences, for example through the use of Sankey diagrams. Once a metric has been mainstreamed, people are comfortable using it even if they do not understand the intricacies behind it – the metrics of gross domestic product (GDP) or internal rate of return (IRR) are just two examples where a metric has been widely adopted despite little understanding of how it is calculated.

When applied manually to bottom-up data, the already complex exergy method has the potential to become overly taxing. This is why this thesis has explored tools to address this. Automation of the data collection and analysis processes could make integrated exergy analyses a feasible practice for industry firms. The possibility of collecting actual resource use data from the control systems in individual plants was therefore investigated. The case study in Chapter 4 reveals that it is possible to measure RE and to construct resource-flow Sankey diagrams by extracting available control data. This work not only proves that the automated extraction and processing of control data was possible. It also forms the proof-of-concept behind this approach and is a fundamental step in achieving the long-term goal of this thesis: for this data to be automatically aggregated up to the level of countries or sectors.

While Cullen and Allwood (2010, 2013) and Cullen et al. (2012) found greater efficiency improvement potentials in downstream production and in end uses, there is still both a need and an opportunity to improve the RE of upstream material producers, and to encourage coordinated supply-chain efforts. This for three reasons. First, gaining industrial, political and public support to reduce overall production demand downstream is likely to be challenging and protracted. Second, in the EU alone, over 4500 industrial plants operate under ETS regulation – about 500 of which are chemical plants and just 280 of which are iron/steel/coke producers (EEA, 2017); these plants must significantly reduce their CO_2 emissions by 2030. Third, the deployment of disruptive technologies such as carbon capture and storage continues to be slower than anticipated (IEA, 2017), which only increases the need for short-to-medium term improvements in industrial RE.

Providing industry firms with the necessary instruments to measure and improve RE is crucial. This is clear from the results obtained in Chapter 5, which show that weak political support and policy incentives for implementing RE to reduce industrial energy use and emissions will hinder the widespread adoption of Chapter 4's RE approach. The triangulation of empirical evidence, policy theory frameworks and reviewed literature conducted in this thesis suggest that EU-level action to promote the adoption of RE in industry before 2030 is limited. This increases the extent to which individual Member States and firms will need to drive the transition to a low-carbon, resource-efficient industry. Without pressure from governments and the need to comply with legislation, however, it will be challenging to convince industry to invest in RE improvements that are not *profitable* under current business models.

In Chapter 5, the relevance of metrics in bringing an issue to the attention of policymakers was highlighted. The literature for this chapter revealed that among the resource-related indicators currently tracked by the Commission, there exists no combined measure for the efficiency of energy and material use in industry. Within the relevant scoreboards (EC, 2016*b*, Humphris-Bach et al., 2016), the Commission focuses on product- rather than process-oriented metrics, which are less insightful for upstream material producers. This thesis therefore also provides a timely contribution to the ongoing debate on how to appropriately measure industrial RE.

Implications for industry practitioners

For industry to become resource-efficient and low-carbon, individual firms must develop an integrated understanding of resource use that includes both energy and materials. In most cases, this transition will require the restructuring of company silos, as energy and materials are currently analysed by separate departments. Firms should be open to engage with academics and governments in the development of pilot projects to investigate the resource savings available from ME measures. Developing more examples of ME interventions in industry could also facilitate the creation of a dedicated ME lobby group for industry. The absence of such a group is currently limiting the extent to which RE measures are considered as solutions to reduce energy and emissions.

This thesis has received high-level industry support from *worldsteel* (global industry association), who has decided to start a pilot project to benchmark the RE of its member companies. This exergy-based benchmarking method will be an important new addition to their current online energy-based approach and will similarly be used to analyse yearly resource flows for a set of plants. Worldsteel's support is only the beginning
wider cross-sectoral acceptance is required to ensure its widespread adoption across all industries.

More widely, beyond providing a more integrated alternative for industry benchmarks, the holistic approach developed in this thesis can:

1. help industry comply with environmental regulation by revealing greater opportunities than are visible from energy-only analysis.
2. provide industry with the systems-wide perspective it needs to analyse the energy-saving potential of ME options and to capture other trade-offs.
3. facilitate communication across management levels – between technical staff and high-level managers – through the use of Sankey diagrams.

As part of this research, there have been extensive interactions with industry practitioners. By collaborating with TataSteel it has been possible to interview operators, plant managers and sustainability officers within the company. The insights offered by these conversations confirmed the validity of the approach outlined in this thesis.

Implications for policymakers

Continuous communication with stakeholders has been essential in the development of this thesis. This work has been presented to key decision-makers, such as the current Commissioner of Energy and Climate Change in the EU, policy experts in the OECD, the IEA and the German Ministry for Economic Affairs and Energy, among others.

Policymakers at the EU-level have limited scope to incentivise ME as an energy and climate tool. In the short-to-medium term (i.e. before 2030) EU-level support is likely to be restricted to informational measures. This thesis provides the technical support required to realise many of these interventions, including for example: the development of industry RE standards; the collection of material data across entire supply chains; and the publication of a Resource Efficiency Governance Handbook. EU policymakers could additionally help by promoting the entire gamut of ME measures (beyond waste management) within the forum of the G7 Resource Efficiency Alliance, or, by mainstreaming ME in the public agenda.

Still more relevant are future developments in Member States. Above all, the evolution of the UK's post-Brexit industrial strategy is noteworthy, as this could provide an opportunity to promote some of the ideas developed in this thesis. In the recent *Industrial Strategy White Paper*, the government articulated its commitment to ME. "[W]e are committed to moving towards a more circular economy – to raising productivity by using resources more efficiently", it stated, and to "raising the resource productivity of businesses, including [...] the promotion of recycling and strong secondary materials markets where products are designed, with efficiency and recyclability in mind" (HM Government, 2017). That this strategy is only in its infancy opens up the opportunity to make suggestions on how to measure and realise ME interventions.

Despite the limited specificity of the Industrial Strategy, the government continues to focus on ME's productivity benefits, and not on its potential to reduce energy use and emissions: "we will publish a new resources and waste strategy to support businesses in maximising the economic benefits from greater resource productivity". While it is obvious that productivity is important, promoters of the energy-saving potential of ME should capitalise on the results obtained here in Chapter 5, highlighting their potential as an additional rationale for pursuing ME – the energy embodied in materials is large in the case of energy-intensive materials like steel or chemicals.

The Sector Deals proposed in this white paper could provide individual industry firms with the financial and technical support required to further develop an approach such as that presented in this thesis. This support is now particularly important, as the business environment in which UK energy-intensive industries currently operate has been criticised for not being “conducive to large-scale demonstration projects as there is limited capital available, and companies are currently focusing on business continuity and cost savings” (WSP Parson Brinkerhoff; and DNV GL, 2015). These sector-wide schemes, however, should be complemented with initiatives that cover broader boundaries, i.e. that involve an entire supply chain (such as light-weighting) or that cross between two chains (such as industrial symbiosis).

Alongside the Sector Deals, the Industrial Strategy proposes other schemes specifically designed “to support investment in industrial energy efficiency”, and which consequently do not incentivise ME. Instead, these schemes should allow for the inclusion of ME strategies as methods to reduce energy use, more so because the coverage of ME in recent Decarbonisation Action Plans (WSP Parson Brinkerhoff; and DNV GL, 2015) has been limited.

Implications for academics

Chapter 5 reveals that more research is needed to convince companies that energy savings from ME interventions are available in real applications. Follow-on research projects are proposed, including the development of more transparent energy allocation approaches, and the improvement of material data collection. The most relevant proposals are further discussed in Section 6.3.

Academic engagement with relevant stakeholders, such as industry practitioners and policymakers, is key for promoting the adoption of ME in industry for two main reasons. Firstly, industrial and political support for ME as an energy-saving measure continues to be weak. Secondly, for highly technical issues such as industrial ME, the development of policies relies heavily on external expert knowledge (as discussed in Chapter 5, Section 5.5.3). There are a number of ways in which academics can interact with industry firms or policymakers:

- By responding to public consultations conducted by the Commission (EC, 2018). Academic participation in technical industrial issues is often low (see EC (2014*c*) or DG for Energy (2016)). Consultations are often conducted on specific policy issues over a period of 12 weeks, and provide an opportunity for people to voice and document their concerns.
- By becoming part of research associations that engage with institutions such as the EC,

the European Council, the OECD or the UN. One example uncovered during the interviews conducted in Chapter 5 was the EERA (European Educational Research Association), which is made up of over 35 national and regional research associations from across Europe.

- For academics interested in having a closer collaboration with industry, another option is to join SPIRE (2017) (Sustainable Process Industry through Resource and Energy Efficiency) – a European Public-Private Partnership which brings together academic researchers, representatives from many heavy industry associations (e.g. European Steel Association) and industry companies. In total this includes over 130 industrial and research stakeholders.

6.3 Future research opportunities

This thesis has marked the beginning of a long-term relationship with Emerson, the sponsor of this PhD. As a result of this work, Emerson will continue to support this research: this year a new PhD student will continue to expand upon the ideas developed here. Beyond academia, this work has had a tangible impact on the company's view of RE. Emerson is currently in the process of incorporating RE as one of its operational certainty consulting services worldwide. In doing so, the industrial collaborations developed throughout this PhD will be key – mainly in the steel and the chemicals and petrochemicals sectors. A number of ideas for further investigation were identified from the findings described in Chapters 3-5. These are outlined below in Sections 6.3.1-6.3.5. These further developments will help facilitate the practical implementation of RE as a measure to reduce energy and emissions in energy-intensive sectors.

6.3.1 Expanding the scope and applications of the resource efficiency analysis

The approach in Chapter 4 facilitates the monitoring of resource use at close-to-real-time, and in doing so highlights opportunities available for improvement. Beyond computing the savings available in the recovery of by-products or the reduction of fuel inputs, the value of this work could be expanded by exploring other improvement options, such as Fe yield improvements or operational differences across batches, to name but a couple. Because differences in resource use result from the interaction of multiple variables, a model that describes these relationships must be built to expand on this analysis. If the objective is to be able to estimate specific parameters (e.g. energy/material use or scrap input ratios) and to predict different scenarios, mathematical models validated with empirical data are likely to be most appropriate: these tend to be more economical and less time-consuming.

Chapter 4's analysis currently covers a single facility over a period of a month. This limited temporal sample neglects the resource use variations that occur across months. At the same time, the study scope delimits the available improvement options that can be investigated. Future work therefore involves applying the RE approach to entire sites over several months. This would make it possible to have a more accurate picture of the RE savings available across time, and to fully exploit the benefits of combining EE and ME analyses; for steel, larger ME improvements arise in downstream rolling, and upstream sintering and iron-making processes.

The case study examines batch production within a single facility and therefore applies a method that is applicable to this boundary and process type. The filtering and balancing of the raw data would need to be modified to make them applicable to continuous processes. Less conflicting and missing data is to be expected, but other new features could complicate the analysis, such as internal recycling loops. Covering a wider range of processes and sectors, each of which have different characteristics and data collection systems, will also be valuable for automating the analysis of different process control software in the long run. In fact, discussions are currently underway between Emerson, governments and other industry firms to develop larger-scale pilot studies to facilitate the expansion of this research.

6.3.2 Linking resource efficiency to cost and CO_2 emission reductions

Tracking the flows of resources – be it individually or jointly using exergy – is a pre-requisite to identify *which* processes are most resource-inefficient and *where* the largest resource savings lie. Yet, not all RE improvements are equally cost-effective nor have the same effect on a process' CO_2 emissions – the link between RE and emissions is dependent on the carbon contained in the specific resource flows. In general, having an understanding of the physical flows underpinning production is also important because resource prices can fail to capture environmental impacts (e.g. CO_2 emissions) (Cleveland et al., 2000). Further analysis is therefore required to assess the impact that resource use reductions have on the costs and CO_2 emissions of operations.

One option to explore the cost implications of RE is to use the approach developed by Tsatsaronis (1993) and Lozano and Valero (1993). Here the authors combine the thermodynamic exergy method and conventional economic analyses (denoted as exergo-economic or thermo-economic analysis) to evaluate the economic performance of energy systems. This makes it possible to identify not only the process inefficiencies "but also the costs associated with these inefficiencies and the investment expenditures required to reduce them" (Abusoglu and Kanoglu, 2009). Exergoeconomic analyses found in the literature are mainly applied to power plants and heating systems; no example was found of the application of this method to material production plants.

Calculating the CO_2 emission reductions associated with reductions in resource use only requires an additional step: the conversion of energy (joules) and materials (tonnes) into carbon (tonnes of C) or CO_2 emission flows (tonnes of CO_2). With access to default carbon contents or CO_2 emission conversion factors for most industries (from national GHG inventory guidelines (IPCC, 2006)), these calculations are now straightforward.[1] In fact, several studies have recently begun to trace carbon and CO_2 emission flows using SDs, examples of which include papers by Wu, Wang, Pu and Qi (2016), Wu, Qi and Wang (2016) or by Bajzelj et al. (2014).

A first attempt at mapping the carbon, CO_2 and iron flows for global ore-based steelmaking is depicted in Figure 6.1. The data provided by worldsteel for Chapter 3 was used. Figure 6.1 only covers one of the three production routes mapped in Chapter 3. To quantify and visualise the CO_2 emissions of the global steel sector, this would need to be expanded to include the DRI-EAF and scrap-EAF routes. Performing these calculations using the data in Chapter 3 and mapping these onto an element-level SD presents a new research opportunity, as no such map currently exists. This could also be performed for the plant-level resource maps in Chapter 4; this would allow plant managers to toggle between mass, exergy and CO_2 emission maps.

While mapping the above carbon flows, it became obvious that appropriately accounting for the CO_2 emission reductions of ME measures would require the allocation of upstream (or embodied) emissions – to equitably compare the savings from ME measures to those from EE options. This idea led to the identification of the research opportunity presented in Section 6.3.3.

6.3.3 Calculating and visualising embodied energy and emissions

Exergy efficiencies are suitable for consolidating energy and materials into a single metric and for encouraging EE and ME within the analysed boundaries – in the case of Chapter 4 within a single facility. However, to fairly estimate the resource savings available from ME measures, it is necessary to quantify the embodied energy/emissions associated with materials. While this

[1] As part of the ETS, most energy-intensive facilities operating in the EU will even have specific conversion factors readily available.

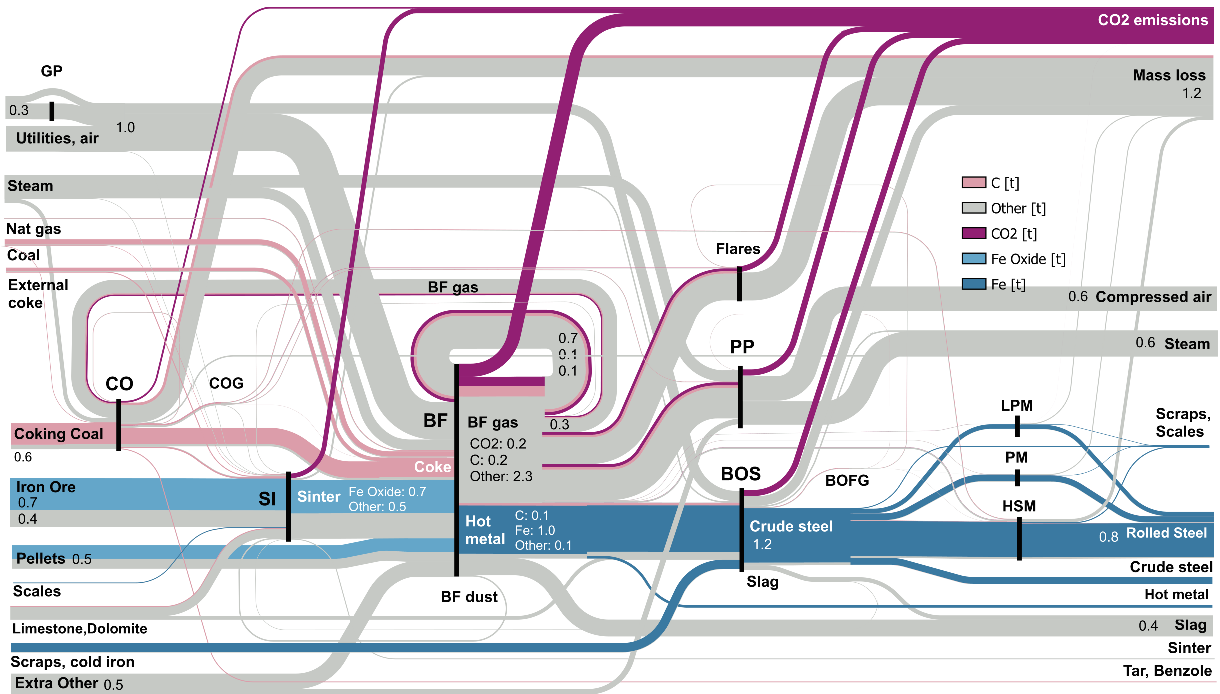

Figure 6.1: Element-level flows for global ore-based steel production using the worldsteel data provided for Chapter 3; measured in tonnes. Of particular interest are the coloured flows, which portray the sources of carbon and the location at which these are converted into CO_2 emissions. Light and dark blue flows show the Fe fraction of resources (as oxides and pure Fe flows respectively). GP – Gas Plant; CO – coke oven; SI – sinter; BF – blast furnace; BOS – basic oxygen steelmaking; HSM – hot strip mill; LPM – long product mill; PM – plate mill; PP – power plant.

may be more relevant when looking at entire supply chains, including embodied energy/emissions within the boundaries of a site is also meaningful.

Chapter 5 revealed that energy, emissions and resource-related indicators tracked by the Commission only measure direct energy or material use, ignoring that embodied. There is good reason for this: CO_2 emission intensities – a well-known metric of LCA-type analyses – are interpretations of how responsibility (or blame) can be attributed amongst processes and assigned to given materials/products. They are not physically-accurate representations of process emissions; emissions are always generated at a given point source and only carried as CO_2 in specific off-gases or as carbon in solid products. The subjective nature of environmental allocations has actually been long recognised as a methodological problem in LCAs (see Chapter 2, Section 2.2.2).

To address the mistrust of embodied-energy calculations, the results of embodied-energy analyses could be depicted in Sankey diagrams. Such maps would reveal both *where* emissions are generated and *how* these are allocated from upstream to downstream processes or products. Figure 6.2 depicts such an example for the element-level flows of a TataSteel steelmaking site. Generated emissions are portrayed as vertical, purple lines at the point at which they are actually emitted. These are then allocated down onto the main material flows (in orange) and carried across to the final product. Figure 6.2, however, is only a first attempt to visualise both carbon flows and allocated CO_2 flows, and other options should be explored. The final design of the visual should be directly informed by the opinions of relevant stakeholders in industry, policy and academia.

These visualisations could also be useful for exploring alternative allocation methods. Particularly relevant would be to investigate the options available to value the energy embodied in waste materials. Using exergy as the basis for this allocation may be interesting. Attributing the process exergy losses to material by-products and losses could help to both incentivise their recovery and emphasise the fact that downstream ME actions are likely to offer larger energy savings than those upstream. The implications of the allocation methods on the sector's incentives to reduce emissions would need to be further investigated.

6.3.4 Quantifying the uncertainty of resource use and efficiency

In Chapter 4 it was shown that even after filtering out the more obvious errors in the control data, some batches remained imbalanced. These imbalances are caused from the uncertainty in both the data inputs and the exergy calculations. Uncertainties can arise from three main sources: errors in the techniques used to measure the flows of these inputs; discrepancies between the temporal and spatial granularities of the data inputs and the RE analysis; and uncertainties in the conversions from materials and energy flows to exergy units.

One option to evaluate the uncertainty of the results in Chapter 4 is to use the Bayesian analysis described in Lupton and Allwood (2017*a*), where each data input and exergy conversion factor would be assigned an uncertainty. Figure 6.3 shows the results obtained from the Bayesian analysis conducted by Lupton and Allwood (2017*a*) to estimate the uncertainty associated with the mass flows of the global steel industry, as calculated by Cullen et al. (2012). These have been visualised as SDs where darker colours illustrate more certain flows. This approach to visualising uncertainty could be used at the plant-level to portray the uncertainties described above.

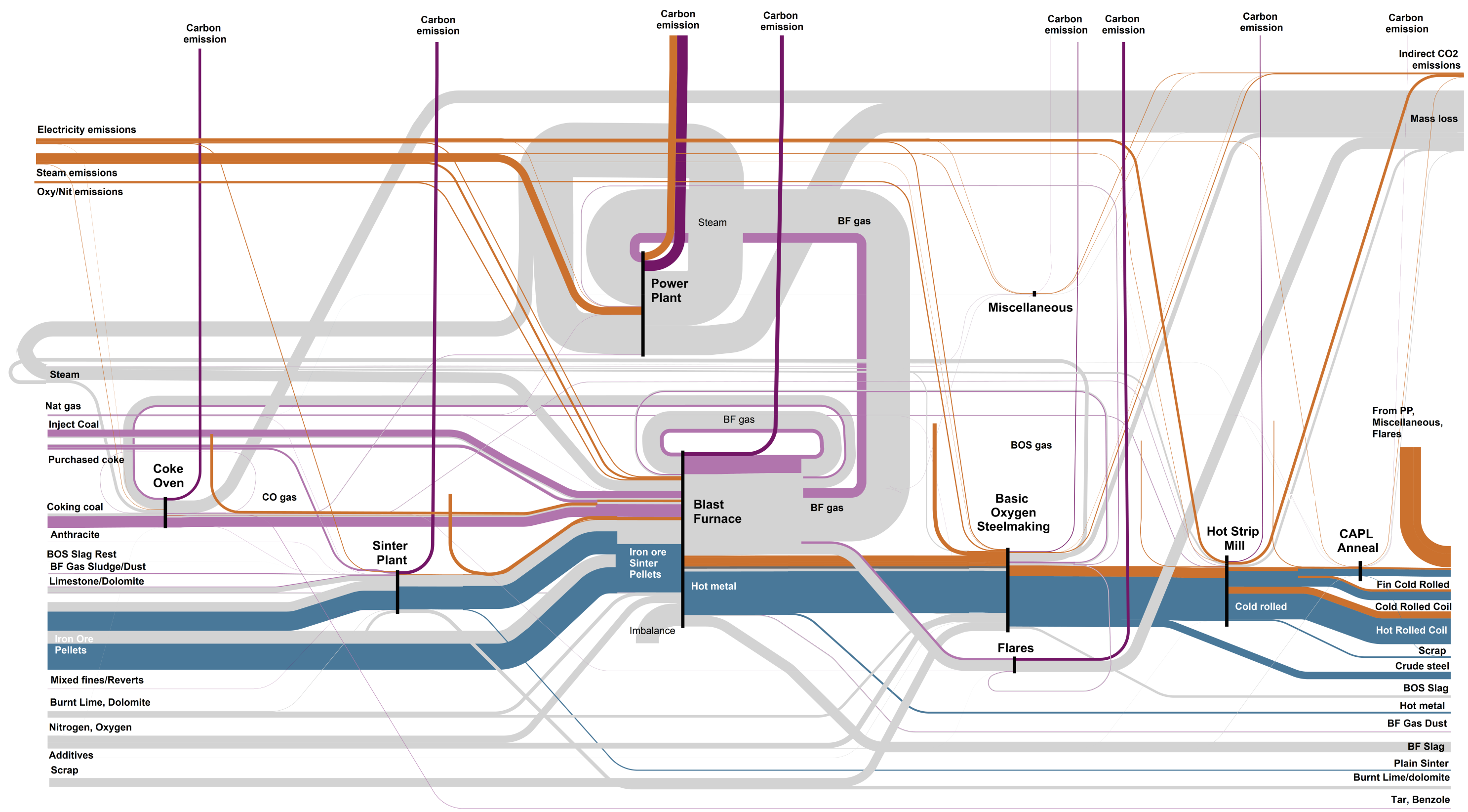

Figure 6.2: Element-level flows for the entire TataSteel site. Of particular interest are the coloured flows, which portray the sources of carbon and the location at which these are converted into CO_2 emissions. This diagram shows both virtual flows (embodied energy from upstream processes) and real flows (resources actually being consumed and produced where shown). The Sankey diagram was constructed using CO_2 data collected through Tata's internal carbon monitoring system. Pink is used for carbon flows, purple for generated CO_2 emissions, orange for allocated emissions, blue for iron (Fe) flows, grey for all others.

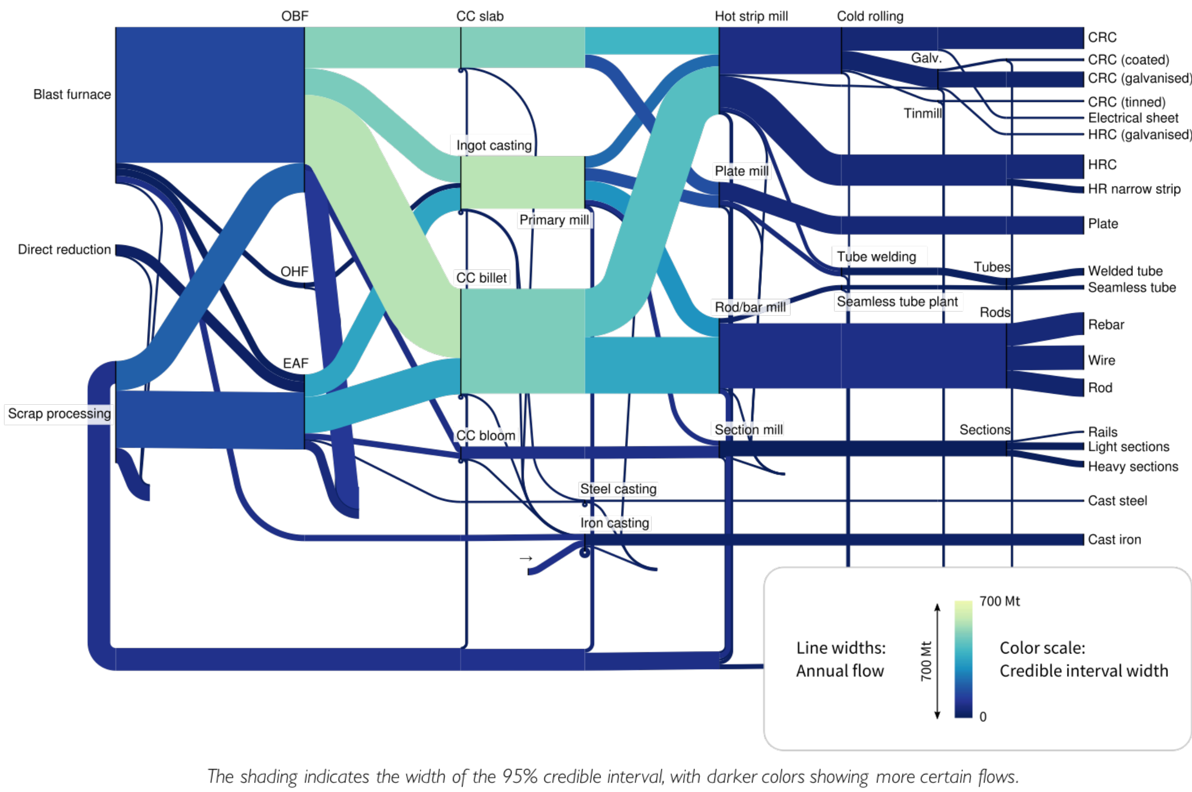

Figure 6.3: Results obtained in an uncertainty analysis performed by Lupton and Allwood (2017*a*), based on work by Cullen et al. (2012) on the global steel industry. Colours depict levels of uncertainty for each stream. Image obtained from Lupton and Allwood (2017*a*).

Quantifying this uncertainty can help identify the sources of imbalances and therefore the flows in which measurement improvements are most needed. Appropriately communicating this uncertainty is relevant because it enables managers to make better-informed decisions on the potential investments for improving resource use. As energy and mass imbalances imply financial imbalances, this too could help companies ensure that their financial data adds up.

Expanding upon this idea, it would be interesting to investigate the minimum number of sensor measurements required to balance resource flow data (with a given level of uncertainty). *Soft-sensing* approaches, which can predict states and parameters that are not physically measured by hardware (Martinez Prata et al., 2010) could be used to do this. Data-driven methods for soft sensing include: Principal Component Analysis, Partial Least Squares, Neuro-Fuzzy Systems, Support Vector Machines and Artificial Neural Networks (Kadlec et al., 2009).

6.3.5 In-depth policy analysis of Member States and industry firm attitudes

Chapter 5 focused on understanding the Commission's standpoint towards including ME in energy and climate agendas. This was an appropriate starting point, as the Commission is both the principal initiator of legislation in the EU and the body currently responsible for the EU's CO_2 emission, energy and resource-related regulations. The analysis in Chapter 5, however, revealed the Commission's limited agency and in doing so stressed the need for Member States and industry firms to play a key role in the transition to a low-carbon era – this if the EU is to comply with the commitments made in the Paris Agreement. From this conclusion, it seems logical to expand the analysis remit to investigate the attitudes, expectations and ambitions of both individual Member States and industry stakeholders. Future analytical effort should focus on collecting and analysing empirical data at national and firm levels.

Conducting an in-depth policy analysis for all 28 Member States and for the myriad European industry firms would be a futile exercise. Instead, future research should focus on key stakeholders. Three Member States are of particular interest in 2018: (1) Germany, (2) Poland, (3) the United Kingdom. Key energy-intensive industry firms in these three MSs are most relevant.

Germany and Poland have in common that industry provides the single largest economic contribution to their total gross value added, above 25% (Eurostat, 2017*a*). Ensuring that RE is leveraged as a climate and energy strategy in these countries is therefore crucial for the EU as a whole. What makes these MSs even more interesting is the fact that German and Polish attitudes to climate change, and in turn resource efficiency, are diametrically opposite.

On the one hand, Germany is the Member State with the most developed and widely supported Resource Efficiency programmes and policies. German citizens are also the most worried about climate change. A recent study by the National Centre for Social Research (NatCen) reported that out of 18 European countries, "Germans are the most concerned, with 44% *very* or *extremely* worried about climate change" (Barasi and Harding, 2017). On the other hand, Poland is struggling to develop solid decarbonisation strategies for its heavy industries. The same NatCen study placed Polish citizens "at the other end of the spectrum, [with] just 15% of Poles [reporting] they are *very* or *extremely* worried (Barasi and Harding, 2017)" about climate change.

The case of the UK is particularly interesting because of its current political situation. As a result of Brexit, the UK has the opportunity to redefine its industrial decarbonisation strategies and national policies; the Industrial Strategy has already been launched with such intent (HM Government, 2017). This new policy developments and debates have opened up a policy window during which the indispensable role of resource efficiency could potentially be leveraged.

6.4 Other future developments

This thesis has also inspired other ideas or projects outside of the academic realm. These largely follow from the suggestions for policy interventions made in Chapter 5.

6.4.1 Integrated resource efficiency standards

In supporting the dissemination of RE practices across European industries it is crucial to reduce the effort and expense involved in introducing environmental management systems and conducting environmental or energy audits. This also involves expanding RE consulting and improving the infrastructure for training of engineering consultants.

Current energy-management (ISO 50001) and MFCA standards (ISO 14051) overlook the relevance of ME options in reducing energy use and emissions. This may be captured by LCAs (ISO 14040), but these produce aggregated, product-oriented metrics that provide no insight into the improvement measures available within a firm. As mentioned above, Germany has begun to develop Resource Efficiency Standards (VDI-4801) (VDI, 2016), and there is much experience to be gained from these initial developments. However, there is an opportunity to expand these standards beyond the separate analysis of energy and materials, and to bring these together using the concept of *exergy*. This would facilitate the German government's aim to "address energy and material flows together to a greater extent in order to exploit synergies between them".

6.4.2 Integrated resource efficiency guide book

The general approach taken in this thesis to jointly analyse the efficiency of energy and material use appears to have broad appeal among engineers, scientists, economists, policymakers and even the general public. It is therefore proposed to use this thesis material to write a guide book for industrial resource efficiency. Given the success of MacKay's book 'Sustainable energy - without the hot air' (MacKay, 2009), Cullen and Allwood's sequel 'Sustainable materials - with both eyes open' (Allwood et al., 2012) and other multiple popular engineering books written by Ashby (Ashby, 2013, Johnson and Ashby, 2014), a book written in this same style could be both well received and useful to a diverse range of audiences.

6.4.3 Exergy calculator

One of the main difficulties in implementing the exergy method in practice is the calculation of the specific chemical and physical exergies. This step could be simplified with the development of an online calculator, which would automatically perform these calculations. Valero and Valero (2018) developed the "Easy exergy calculator", but this is limited to *chemical* exergies and does not calculate the chemical exergy of metal alloys. Another option would be to develop a similar concept to the conventional steam tables that have been used by engineers for decades. Chemical and physical standard tables covering a wider range of compositions and physical conditions would speed-up the conversion process from mass and energy flows into exergy units.[2]

6.4.4 Improved resource-flows visualisations

Advances in Sankey-drawing software facilitated the construction of the time-series SDs in Chapter 4. The *floWeaver* Python package developed by (Lupton and Allwood, 2017*a*) made it possible to map the resource flows for 900 batches and 29 days, avoiding the need to manually draw each of these (the code can be found at Lupton and Paoli (2017)). A single template was constructed to establish the general layout of the SD and this was used to depict flows for all other iterations. Lupton and Allwood (2017*a*) made significant progress in improving the flexibility of *floWeaver*, and it is now possible to: automatically switch between multiple aggregation levels or units of measurement; designate data hierarchies; or specifically define the diagram's structure and appearance.[3] Yet, to fully integrate SDs in the practices of plants, it is necessary to expand their capabilities to incorporate additional attributes (i.e. impacts such as CO_2 emissions) – or control variables – such as material quality or process efficiency.

To expand the capabilities of SDs and to ensure they are effective at conveying the relevant information, a formalised design procedure must be established. Until now, however, the rules governing the graphic design of SDs have been largely disregarded in industry and academia,

[2]This is being explored as a fourth year project in CUED, by Jeremy Fouillou.

[3]Other online, interactive and time-series Sankey diagrams have also been developed for large international institutions such as IEA and Eurostat, for example.

often leading to poor executions (some of which are summarised in Subramanyam et al. (2015) and Soundararajan et al. (2014)).

One approach to resolve this is to devise a method that combines the guidelines proposed by Tufte (2006) with the framework outlined by Cleveland and McGill (1984). Tufte (2006) summarises five design principles that must be considered when constructing visuals to encourage analytical thinking, including: comparisons; causality, structure and explanation; multi-variate analysis; integration of evidence; and documentation. Cleveland and McGill (1984) developed a framework to organise the retinal variables proposed by (Bertin, 1983) – which represent six graphical characteristics including colour, shape, orientation, size, texture and value – according to the accuracy with which people perceive each of them. For example, colour hues and saturation lie at the bottom of the accuracy scale as these are best at showing qualitative differences whereas simple 2D lines, which are based on the retinal variable of size, lie at the top of the ranking.

Sankey diagrams designed under the above formalised procedure would, for example, use colour only to depict inaccurate or qualitative information. To communicate accurate, quantitative aspects, the variable of size would be chosen instead. According to these guidelines, other visualisation options must be explored to complement SDs. For example, incorporating simple line graphs to track specific variables or flows could be more effective, even if these are not capable of tracking more than a couple of variables simultaneously.

6.5 Conclusion

This thesis constitutes an important step towards facilitating a holistic analysis of the resource efficiency of energy-intensive industries – a development that is key to preparing the sector for the forthcoming resource-efficient and low-carbon era. The resulting framework is *holistic* because it covers entire systems; it is *flexible* because it can be applied at any system level; it is *integrated* because exergy consolidates energy and materials into a single framework, capturing the interactions between these; it is *transparent* because Sankey diagrams are used to visualise the results and to shed light on the underlying method.

The *exergy* metric provides a firm basis for incentivising the reduction of raw-material inputs and the recovery of material by-products, neither of which is captured in conventional energy metrics. Alongside this, visually portraying resources in Sankey diagrams provides a meaningful contribution because it can facilitate communication across the many stakeholders involved in material supply chains. By applying this approach (developed in Chapter 3) to a case study with real plant data – a basic oxygen steelmaking plant – in Chapter 4, this research provides key practical guidance for plant managers, industry associations and policymakers. The long-term vision is that the proposed approach can serve as a springboard for extracting the value residing in a plant's control data. Aggregating this data from individual plants can then help construct more accurate and detailed bottom-up analyses of industrial activity in entire countries or sectors.

The energy- and emissions-saving potential of material efficiency interventions has to date been under-exploited in industry and under-incentivised in EU policies. Based on the time-frames of existing policies and the barriers preventing EU policymakers from enacting change, Chapter 5 demonstrates the pressing need for Member States and industry firms to take charge in incentivising ME as a low-carbon industry strategy. National developments made in Germany through the Resource Efficiency Programmes and Resource Efficiency platform are an exemplar of the policy shift required across Europe. The UK's post-Brexit Industrial Strategy offers a unique opportunity to capitalise on Germany's progress.

This research has resulted in the publication of three journal papers, three conference papers and five conference presentations. This work has also resulted in real impact in industry, through the implementation of the RE benchmarking method in worldsteel and Emerson's ambition to translate the research into a viable resource efficiency consulting solution.

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