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Extending European energy efficiency standards to include material use: an analysis

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ABSTRACT
Existing international emissions reduction policies are not sufficient to meet the internationally agreed objective of limiting average global temperature rise to 'well below' two degrees, resulting in an emissions gap. Materials – such as aluminium, cement, paper, plastics and steel – act as a carrier of industrial energy that allows, through trade, the transfer of embodied emissions between sectors and countries. However, the use of materials has been overshadowed by policies focusing on energy efficiency improvements and deployment of a low carbon energy supply. This article argues that policies based on material and product demand can support domestic climate change mitigation and reduce the emissions gap, yet there is little obvious integration between climate and material efficiency policies. The article investigates current 'emissions flows' through the EU economy and how much of these are captured and excluded from existing EU climate policies. We analyse the potential increase in emissions coverage that would be achieved by extending EU directives that currently target the energy use of products (cars, buildings and appliances) in operation, to include the emissions required to produce the goods (i.e. embodied emissions). The analysis shows that a greater integration of material efficiency strategies within climate change mitigation policy could significantly increase the emissions coverage of existing product policies.

Key policy insights

- Consumption is a key driver of emissions and demand reduction is an important policy option in reducing emissions, at least in the short-term, to reduce the risks of a longer-term reliance on technology breakthroughs and while the EU carbon price remains low.
- Emissions embodied in material-intensive manufactured products consumed in the EU represent the equivalent of over 40% of EU production emissions, offering significant scope for emissions reductions along product supply chains.
- Consumption measures that target the use of materials and products offer complementary mitigation options to low carbon energy supply technologies alongside costs savings.
- Existing EU policies addressing the energy efficiency of products can be used to scale up material efficiency measures.

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KEYWORDS
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1. Introduction

Current climate commitments included in the Paris Agreement fall short in meeting the global carbon budget to limit average global temperature rise to 'well below' two degrees (Rogelj et al., 2016). Climate policies focus on

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deploying a low carbon and efficient energy supply. However, focusing on GHGs emitted from the point source of where energy is physically combusted ignores opportunities to reduce emissions from the consumption activities that drive energy use and process-based emissions, which can be up to 50% of emissions in certain materials such as steel and cement (Bednar-Friedl, Schinko, & Steininger, 2012).

Around a fifth of global carbon emissions can be attributed to the production of five key materials: steel, cement, plastic, paper and aluminium (Allwood, Cullen, & Milford, 2010), which form the backbone of modern economies (Müller et al., 2013; Müller, Wang, & Duval, 2011; Pauliuk & Müller, 2014; Steinberger, Krausmann, & Eisenmenger, 2010). Demand for materials has surged in the last few decades (Pothen & Schymura, 2015; Schaffartzik et al., 2014). The emissions associated with materials as they are transformed into products are referred to as embodied emissions and consider the GHGs emitted directly and indirectly at each stage of the production process (Peters & Hertwich, 2008). Many studies now explore how to reduce the embodied emissions through greater material efficiency (Allwood, Ashby, Gutowski, & Worrell, 2011; Barrett & Scott, 2012; Carruth, Allwood, & Moynihan, 2011; Liu, Bangs, & Muller, 2013; Milford, Pauliuk, Allwood, & Müller, 2013; Müller et al., 2013; Pauliuk & Müller, 2014). By material efficiency we focus on making products with less material inputs or substituting for less carbon intensive material inputs.

However, there is a lack of information on the policies which can support the scaling up of material efficiency strategies to achieve emissions reductions at scale. We explore extending existing policies covering the energy efficiency of products (use phase emissions) to include the emissions of their production (embodied emissions). Our analysis focuses on the EU, because the EU has the most advanced climate and product policies. The EU's Ecodesign directive, which has been used to regulate the energy efficiency of electrical products, already has a mechanism in place to regulate non-energy product inputs such as materials, yet it is underutilized. Although a wealth of research exists on calculating embodied emissions, this is one of the few articles, to the best of our knowledge, which explicitly and systematically links such research to environmental policy. Although we cannot provide policy makers with a definitive policy solution, we highlight the importance of an entirely underrepresented area of climate policy. The relevance of this research for policy-making is one of the strengths of this analysis.

The rest of Section 1 is dedicated to a review describing current EU climate policies; the climate impact of materials along geographically separated product supply chains; and the incentives for reducing supply chain emissions. The research questions are presented in Section 1.4. Section 2 describes the method. The results are presented in Section 3 and the implementation of the policy extension is discussed in Section 4.

1.1. EU climate policies

The EU plans to reduce emissions produced within its territory by 80–95% by 2050 from 1990 levels. The EU Emissions Trading Scheme (EU ETS) is the primary mechanism for addressing EU industrial and power emissions (Branger, Lecuyer, & Quirion, 2015; Drummond & Ekins, 2017). It places a cap on emissions produced by selected energy-intensive industries above a certain size, creating a market for carbon allowances that these industries can buy or sell when they have a carbon shortage or surplus. However, around 60% of the carbon allowances under the EU ETS were allocated for free due to competitiveness concerns that have yet to materialize (Bassi & Zenghelis, 2014; Branger et al., 2015), and many producers in the scheme have enough allowances to satisfy their production for several years, keeping the carbon price too low to incentivize low carbon investments (Drummond & Ekins, 2017). Although the third EU ETS phase revised benchmarking allocation scheme recently put into action has reduced free allocations, Stenqvist and Åhman (2016) suggest it remains unlikely to incentivize investments in low carbon production at the desired scale of change needed in some sectors. Arguably the EU ETS is failing to incentivize low carbon production (Sato, Neuhoff, Graichen, Schumacher, & Matthes, 2015), including the reduction of material use (Spash, 2010), to levels required for a two degree, or lower, future, contributing to an emissions gap.

Commercial, residential and the remaining industrial emissions outside the EU ETS rely on regulations and standards to improve their energy efficiency in operation, which has brought down emissions in the operation of buildings, cars and electrical appliances (European Commission, 2015). This means that, inevitably, embodied emissions are becoming an increasingly significant source of emissions related to energy-using products (Chen & Thomas NG, 2016; Product Sustainability Forum, 2012; WRAP, 2014b). This trend is likely to continue as sectors strive to achieve net zero or low operational emissions (Chastas, Theodosiou, & Bikas, 2016; Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013). Focusing solely on the operational performance of energy-using products, however, is likely to be insufficient to meet 80% or higher reduction targets (Giesekam, Barrett, Taylor, & Owen, 2014) and in their recent assessment of the suitability of EU climate policies Drummond and Ekins (2017) find the current suite of EU climate policies insufficient to meet EU climate commitments.

Without economy-wide emissions pricing, which is currently limited to a subset of subsidized industries and not generating a carbon price that incentivizes investments in radical low carbon innovations, further policy options are needed to address these market failures. In this article, we explore options to upscale material efficiency using existing energy efficiency measures.

1.2. Emissions embodied in products

Emissions become embodied in products as raw materials (e.g. fossil fuels and minerals) are processed into useful materials (e.g. glass and metals) and manufactured into products (e.g. buildings, cars and electronics) which in turn are used as inputs to all intermediate sectors (e.g. agriculture, construction, transport and financial services) or sold to final consumers (e.g. households and government). Environmentally extended input-output analysis methods have been developed since the 1970s to model the environmental impacts associated with inputs and outputs of production processes to final consumers (Miller & Blair, 2009; Nishimura, Hondo, & Uchiyama, 1997). As 'carriers' of industrial energy, the trade of materials and products results in the transfer of embodied emissions between sectors, countries and consumers. These so-called consumption-based emissions accounts differ to the international production-based emissions accounting approach. Production emissions are those produced by all institutional units within a country/region's territory that contribute to the country/regions' gross domestic product (GDP) (Peters, 2008). Consumption-based emissions are those embodied in the final consumption of a country/region (Kanemoto, Lenzen, Peters, Moran, & Geschke, 2012).

A growing body of literature uses input-output methods to analyse the material use (Giljum, Bruckner, & Martinez, 2015; Pothen & Schymura, 2015; Schaffartzik et al., 2014; Wiedmann et al., 2015) and emissions (Davis & Caldeira, 2010; Hertwich & Peters, 2009; Kanemoto, Moran, Lenzen, & Geschke, 2014; Peters, Minx, Weber, & Edenhofer, 2011; Scott & Barrett, 2015; Xu & Dietzenbacher, 2014) embodied in the final demand for products (includes goods and services). Due to globalization there is an increasing geographical separation of consumers and the pollution emitted in the production of consumable items (Peters & Hertwich, 2008; Wiedmann, 2009). Studies have focused on emissions embodied in traded products finding that much of the apparent success in decreasing emissions produced within the EU's territory in the last ten or so years have been more than offset by an increase in emissions embodied in imports to the EU (Kanemoto et al., 2014; Peters et al., 2011). For example, China's production emissions have rapidly risen, with net exported products accounting for around a fifth of its emissions (Qi, Winchester, Karplus, & Zhang, 2014), destined mainly for consumption in developed countries (Kanemoto et al., 2014).

The share of traded emissions embodied in energy-intensive materials (e.g. cement, steel and paper) has remained at around 40% and the share of manufactured goods (e.g. clothing, electronics and vehicles) accounts for a growing 30% share (Peters et al., 2011). These trade patterns are representative of the structure of the global economy and the movement of energy intensive manufacturing to lower cost, less industrialized countries (Timmer, Erumban, Los, Stehrer, & De Vries, 2014).

Measuring only emissions released from producing entities neglects the full embodied impacts of products. Evidence shows there is significant potential in emissions reduction through material and product measures. In analysing the 'reach' of EU-wide collective corporate action, Skelton (2013) identifies that the EU has influence over additional (non-traded) emissions in the region of 1 Gt CO_2, amounting to nearly a third of EU industry production emissions, by addressing company supply chains. Barrett and Scott (2012), Girod, Van Vuuren, and Hertwich (2014), Pauliuk and Müller (2014) and Allwood et al. (2011) show the potential for material efficiency and product consumption measures to contribute to meeting climate targets. Strategies include material substitution (Giesekam et al., 2014), product longevity (Bakker, Wang, Huisman, & Den Hollander, 2014), lightweight design (Müller et al., 2013), urban planning (Müller et al., 2013) and product-service systems (Reim, Parida, & Örtqvist, 2015; Roelich et al., 2015).

1.3. Incentives to reduce embodied emissions

The EU has published a Circular Economy Package with the aim of 'closing the loop' of product lifecycles through production systems which are not dependent on the extraction of virgin material. The package is intended to address all aspects of product supply chains (EC, 2015). The international imbalance of traded emissions raises important policy issues as to whether high consuming countries should take on higher mitigation targets to reflect emissions embodied in their final consumption (Springmann, 2014; Steininger et al., 2014), and the political and practical feasibility (Afionis, Sakai, Scott, Barrett, & Gouldson, 2017). Afionis et al. (2017) demonstrate how consumption accounting could be adjusted to fit with current political realities and identify policy mechanisms that could potentially be utilized to address consumption-based emissions. They conclude that such an approach could unlock new opportunities for climate policy innovation and for climate mitigation. We show in the context of this analysis that there are a number of advantages and co-benefits for businesses to monitor and manage their embodied emissions.

Material efficiency options have become increasingly important due to the limited opportunities for improving energy efficiency in material production (Liu et al., 2013; Milford et al., 2013; Pauliuk & Müller, 2014), which tends to be very efficient already, due to energy being a major cost factor in the production process (Müller et al., 2013). Additional savings can be sought further down supply chains by the users of materials. A number of success stories have been reported for example in the UK where construction companies have reported up to 40% reductions in embodied carbon combined with a 25% cost saving in just a few years (The Green Construction Board, 2014). These companies now have a reputation for good environmental management which is being transferred to other organizations across the sector, and are more resilient to volatile and rising resource and commodity prices (WRAP, 2014a).

Another benefit is the anticipation of future climate legislation (WRAP, 2014a). To meet climate targets, energy-intensive material industries such as cement are starting to explore high abatement measures such as carbon capture and storage (CCS) which would increase producer costs to levels much higher than the carbon price anticipated in the EU ETS (which reinforces the weak price signal of the EU ETS) (Rootzén & Johnsson, 2016). Inevitably, the cost would be passed onto the users of cement, albeit the cost would diminish with each stage of transformation as cement becomes an increasingly small share of the total production costs. Managing embodied carbon can limit future costs and circumvent uncertainty and high risks involved in CCS technologies (Smith et al., 2016).

Monitoring embodied emissions will enable the most material intensive products to be eliminated from the market and encourage innovation and competition by promoting the better environmental performance of products throughout regulatory standards, at least in more stable markets (Blind, Petersen, & Riillo, 2017). Crippa, Janssens-Maenhout, Guizzardi, and Galmarini (2016) found the implementation of regulatory standards for emissions and engine efficiencies in cars in Europe and America had a 'trading up effect' through economic integration where suppliers, who want to reach the widest possible market, use improved standards in their home country, driving similar standards to be implemented due to the benefits from greater economies of scale. This had the co-benefit of reducing localized air pollution and related health issues.

1.4. Research questions

While EU climate policy remains somewhat detached from its Circular Economy Agenda, climate policy will fail to capture the mitigation benefits of material and product use. We analyse the opportunities for integrating circular economy within climate change mitigation policies by extending existing energy efficiency standards on energy-using products (vehicles, buildings and electronics) to include non-energy material use in their production. Non-energy material use is applied more broadly to all physical supply chain inputs that are associated with a transaction cost which includes energy, material and processed goods and services. Raw materials which have no recorded purchasing cost are not included in this analysis. Our research questions are:

- What are the emissions associated with material and product flows in and out of the EU?
- What proportion of EU embodied emissions are currently excluded from its domestic climate policies?

- What could be the additional emissions coverage of extending EU product-specific energy efficiency policies to include material and product use?

The discussion centres on policy interactions, the effectiveness of regulatory standards and practical issues to implementation.

2. Method

We provide an ex-post analysis of the emissions embodied in the production and use of products purchased in the EU market. The former is calculated using environmentally-extended multi-region input-output analysis (EE-IOA) and the latter using data from EU emissions inventories. We distinguish between emissions produced directly by sectors/ products in operation to those embodied in production. Our static analysis explores the potential increase in emissions coverage to capture the associated climate impacts of material and product demand without anticipating future impacts on the economy and trade, which are highly uncertain.

EE-IOA has been used to analyse the emissions scope of international climate policies such as the Kyoto Protocol (Kanemoto et al., 2014; Peters et al., 2011), demonstrating that emissions reductions from countries participating in the Kyoto Protocol were completely offset by an increase in emissions imported to participating countries from those outside the protocol. We follow a similar methodological approach to identify emissions included and excluded from EU climate policies at the product level. We focus on policies that address the energy performance of products to identify the value in looking across product supply chains as a means to deliver both gains in material efficiency and climate mitigation. We focus on three EU directives that match these criteria:

- EcoDesign Directive: sets minimum mandatory requirements for the energy efficiency of products, such as household appliances and information and communication technologies (Directive 2009/125/EC).
- Energy Performance of Buildings Directive: sets minimum energy performance requirements for new buildings, for the major renovation of buildings and for the replacement or retrofit of building elements (e.g. heating and cooling systems, roofs, walls, etc.) (Directive 2002/91/EC).
- Vehicle Emissions Performance Standards: sets emissions standards for fuel combustion in passenger cars and light commercial vehicles (Directive 98/69/EC).

Using EE-IOA we identify the embodied emissions associated with the energy-using products addressed by the three EU directives. Each product group is assigned to a representative sector(s) in Exiobase (the EE-IOA model), shown in Table 1. The embodied GHGs associated with both intermediate use and final demand are calculated.

2.1. Input-output analysis

EE-IOA is a well-established method for calculating consumption-based emissions (Wiedmann, 2009). A series of linear equations describe how producing a single unit of final demand requires inputs from all sectors of the global economy (Miller & Blair, 2009). Different sectors of an economy not only require material and product

Table 1. Product mapping from the IOA to EU energy efficiency directives.

Energy-using products captured by EU directives	Production sector(s) from the IOA
Vehicles	Manufacture of motor vehicles, trailers and semi-trailers
Buildings	Construction
Appliances	Manufacture of office machinery and computers; Manufacture of electrical machinery and apparatus n.e.c.; Manufacture of radio, television and communication equipment and apparatus

Note: n.e.c., not elsewhere classified.

inputs, but they also generate by-products (e.g. pollution and waste) during production. Using an inter-industry trade matrix and environmental extension, the equations can determine how pollution originating from producing sectors become embodied in goods and services for final consumption. We are only interested in trade for final consumption in the EU. The EE-IOA attributes the proportion of emissions embodied in imports that are for final consumption in the EU and excludes the emissions originating in the EU that are exported for final consumption elsewhere (Kanemoto et al., 2012) (i.e. in this case we do not account for emissions embodied in imports that are re-exported). Refer to Supplementary Section 2.1 for further methodological detail.

2.2. Data sources

We use a geographically aggregated version of the EXIOBASE input-output (IO) table (Tukker et al., 2013; Wood et al., 2015) which represents the production and consumption activities within 163 product groups across three regions: the EU, non-EU Annex I countries, and non-Annex I countries (Supplementary Section 2.2.). We use the GHG emissions extension in Mt CO_2 equivalent (Mt CO_2e). Compared to other IO models, EXIOBASE has the greatest disaggregation of material and manufacturing sectors, the focus of our study. See Supplementary Section 2.3. for a comparison of the structure and results of EXIOBASE compared to other available models. For the purpose of display, sectors are aggregated into seven high-level groupings (Supplementary Table 1). EXIOBASE v2 is the only version of the database which is currently available (December 2016) and this version contains data for the year 2007. We would cautiously argue that although the scale of the results presented may be overestimated as they refer to production activities before the recession, the contribution of products, such as construction, remains as important as in 2007 (see supplementary Section 2.3.). There is a planned update, EXIOBASE v3, which includes a time series from 1997–2011, but this is not publicly available yet.

Our regional groupings are somewhat out-of-date as the Annex I and non-Annex I separation no longer exists in the Paris Agreement. However, we feel they still represent industrialized countries which have pledged higher reduction targets compared to emerging and developing economies that have generally lower per capita emissions and less stringent climate targets.

The operational emissions for residential buildings and private car travel are sourced separately from the EU's GHG inventory (European Environment Agency, 2014a) as they are not measured within the IO table. However, for electrical appliances, e.g. TVs and fridges, the emissions are not released directly at the source (i.e. in the home), but instead at the power plant where fossil fuels are combusted and then distributed as electricity to homes to operate appliances. Data on how much of the power sector's emissions are attributed to the use of appliances is not available therefore we only account for the embodied emissions of appliances. Electricity used to operate appliances would be assigned to purchases of electricity in the EE-IOA. Isolating how much of the electricity is for appliances compared to lighting, cooking etc. is not possible.

2.3. Analysing EU product policies

We calculate the emissions embodied in the intermediate and final use of vehicles, buildings and appliances. Using vehicles as an example, supply chain emissions can take different forms: (1) emissions associated with any industry that ends up embodied in a vehicle purchased by an EU final consumer, e.g. emissions from the steel industry that make a car bought by a household; (2) emissions associated with the vehicle industry that ends up in a final demand product, e.g. the on-site emissions from a car making factory and the car is then bought by a delivery service which is used by a household; (3) emissions associated with any supply chain that involves the vehicle sector, e.g. the emissions associated with the steel industry that go into a car used for delivery services bought by a household; and (4) emissions associated with an industry that makes a product that goes directly to final demand without being part of any intermediate stages, e.g. emissions associated with a vehicle factory making cars bought by households. We assert that EU material efficiency policy on vehicles could reduce the emissions in any of these four. The same logic applies for buildings and appliances. See Supplementary Section 2.4. for a further explanation on how to use IOA to identify the sum of the emissions flows that are associated with these products supply chains. Based on this scope, emissions associated with vehicles used in construction for example are reported within all three sectors at some point along their supply chains. Summing embodied emissions for vehicles, construction and appliances would therefore result in some double counting. All three product groups need to be included in one calculation to calculate the emissions reach of extending all three directives (Supplementary Section 2.4.).

Some of the embodied emissions will originate in sectors regulated by the EU ETS and therefore are captured by existing EU climate policy. IOA shows in which sectors and countries embodied emissions originate. For each product group, we distinguish the emissions produced in sectors which we identify as being included in the EU ETS (see Supplementary Section 2.5 for the sector allocation).

Finally, policies addressing material and product use do not just apply to energy using products. Therefore, we calculate the embodied emissions associated with all material-intensive manufactured products (e.g. furniture, textiles, glass products and fabricated metal products) to estimate the total emissions scope of standards on the carbon content of goods consumed in the EU (Supplementary Section 2.4.).

3. Results

Operational and embodied emissions are presented first at the economy-wide level and then for the three product groups (buildings, cars and electrical appliances). The third sub-section calculates emissions embodied in all manufactured goods purchased in the EU market.

3.1. Emissions embodied in EU products

Figure 1 shows supply chain emissions flows from global production, through supply chains, to the final consumption of products in the EU, including imports in and exports out of the EU. Production emissions in the EU

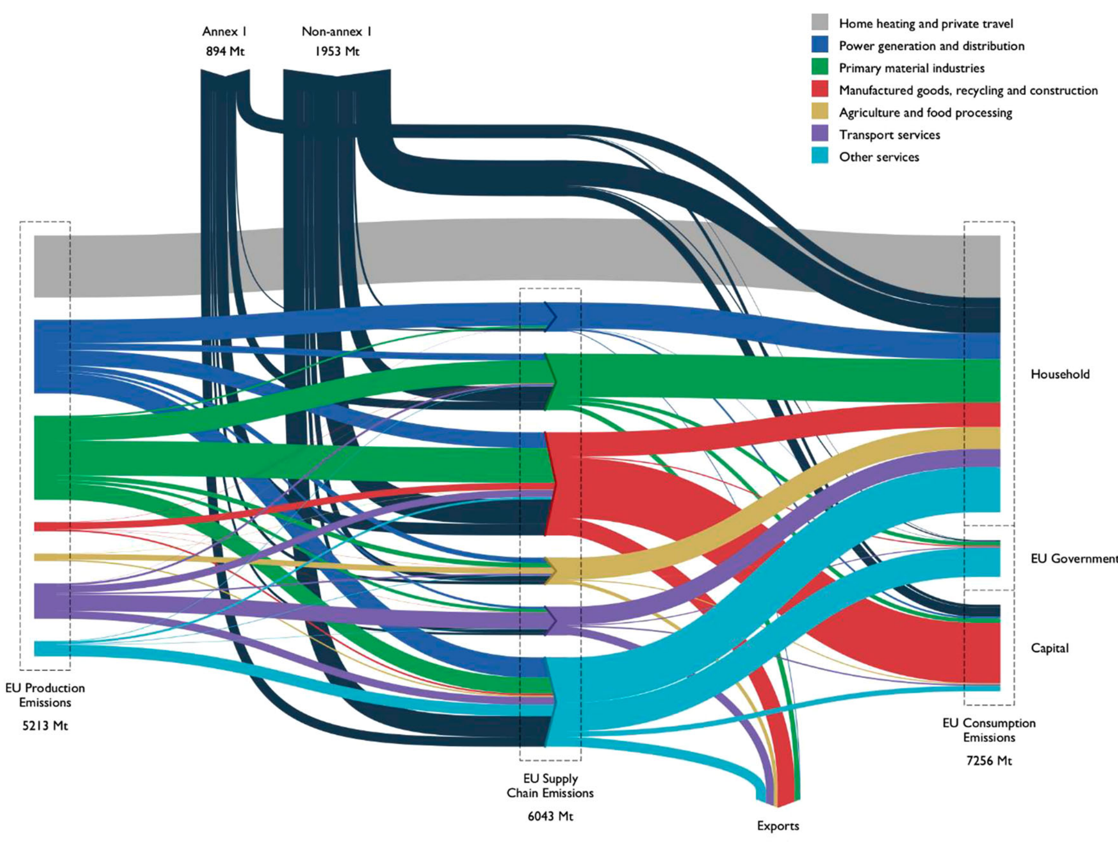

Figure 1. The supply chain emissions associated with global product flows of the EU.

in 2007 were 5213 $MtCO_2e$, with the width of each flow on the left-hand side of Figure 1 representing production emissions by sector, the conventional accounting approach. In the same year, the EU's consumption-based emissions, the right-hand side of Figure 1, were 39% higher, at 7,256 Mt due to the EU's trade balance. Emissions embodied in EU imports were 2847 Mt and emissions embodied in their exports were 804 Mt, meaning that the EU is a net importer of 2043 $MtCO_2e$ (imports–exports). Around two thirds of imported emissions are from countries previously classified as non-Annex I countries, whose emissions are expected to continue to rise till at least to 2030 based on their nationally determined contributions submitted to meet the Paris Agreement.

The middle section in Figure 1 shows the emissions embodied in products with some part of the supply chain occurring in Europe. Comparing the production emissions (left) with the supply chain emissions, some sectors emit more GHGs in their production than those embodied in their supply chains, and vice versa. The former holds true for the power sector and primary material sectors, which are very energy intensive to produce, and tend to be used as inputs towards the start of supply chains (i.e. to be further processed into products). The latter holds true for manufacturing and services, who are significant procurers of products and which tend to be towards the end of supply chains and sell more directly to final consumers.

Services and manufacturing sectors combined directly produced 447 Mt (9%) of EU production emissions. However, the emissions embodied in these sectors across their respective supply chains account for 1619 Mt (22%) and 1869 Mt (26%) of EU consumption emissions. Around a third of emissions embodied in both product groups are generated outside EU territory. Of the emissions embodied in services, 38% (622 Mt) is attributable to the primary material sectors and 32% (517 Mt) to electricity. Figure 2 shows that around 40% of the emissions resulting from primary materials used by services are related to the mining and processing of energy sources; however, the remaining 60% are related to non-energy materials (e.g. metals, chemicals, plastics and wood). Material efficiency measures are therefore a key leverage point where emissions can be reduced.

3.2. Emissions excluded from EU climate policies

Around 45% of EU production emissions are generated in industries capped in the EU ETS. This includes emissions from the power sector (72% of ETS emissions), energy-intensive industries such as oil refineries and steel works (22% of ETS emissions), and commercial aviation (separated into its own cap). To address the remaining

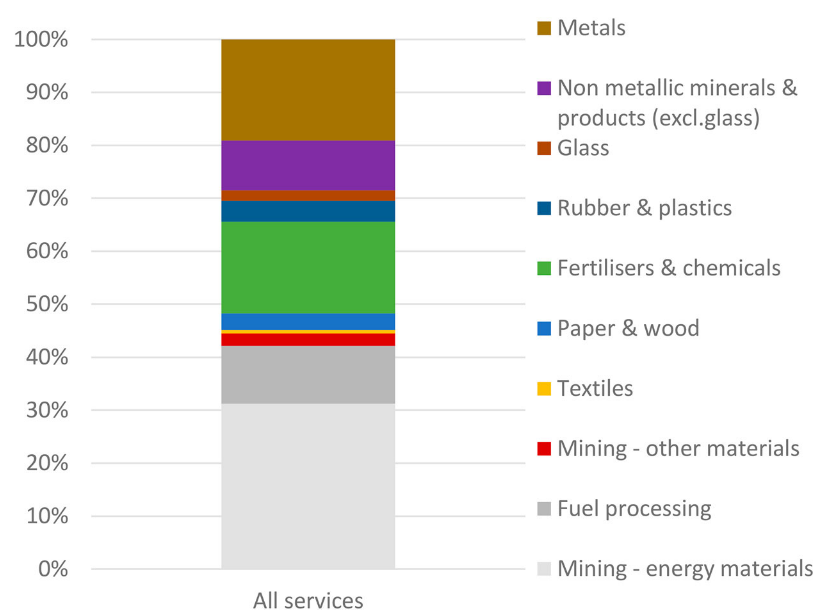

Figure 2. Share of embodied emissions of EU services attributed to materials and manufactured goods.

55% of emissions outside the EU ETS, there a number of EU directives focusing on energy efficiency. Many studies have explored the options for reducing operational energy use in buildings and cars, but most neglect the materials necessary to manufacture and construct these (Müller et al., 2013) and the volume demanded. We identified three directives that apply energy efficiency performance standards to appliances, buildings and vehicles, and therefore have the framework in place to extend these standards to cover embodied carbon:

- EcoDesign Directive
- Energy Performance of Buildings Directive
- Vehicle Emissions Performance Standards

Figure 3 compares in use (the conventional accounting approach) to embodied emissions related to the products addressed by the EU directives. The values include emissions embodied in products sold to both intermediate (industries) and final (households, government and large capital investments) consumers. We have separated embodied emissions that originate in sectors already capped under the EU ETS. Absolute emissions results should be reviewed with some caution as the data is from before the global financial crisis when production activities in some European countries were at a peak. However, we do not have evidence to show that this changed the share of material inputs to production processes and the economy has recovered to pre-recession levels on aggregate, albeit unevenly across countries.

In 2007 in the manufacture of electronics and electrical appliances (a sector which has been growing in physical terms), 230 Mt was emitted . Operational emissions, which are regulated by the EcoDesign directive, are allocated to the power sector and not directly to electrical appliances, as they are emitted where the fuel sources are combusted. From 1996 to 2012, EU consumption of telephone equipment rose tenfold; demand for other electronics such as computers, tablets and televisions rose fivefold; and purchases of household appliances such as fridges and freezers remained stable (European Environment Agency, 2014b). Of the 230 Mt CO_2e embodied in appliances purchased in the EU, 60 Mt (26%) sit within EU ETS sectors, leaving 170 Mt unaddressed potential (2.4% of EU consumption emissions).

The building performance directive tackles the energy use of buildings, which continues to increase at approximately 1% a year, despite implementation of the directive in 2002. In addition to the 594 Mt CO_2e released directly from commercial, institutional and residential buildings (European Environment Agency, 2014a), 773 Mt were embodied in construction materials themselves. An equivalent of 5.7% (406 Mt) of EU consumption emissions were outside the reach of the building directive and ETS.

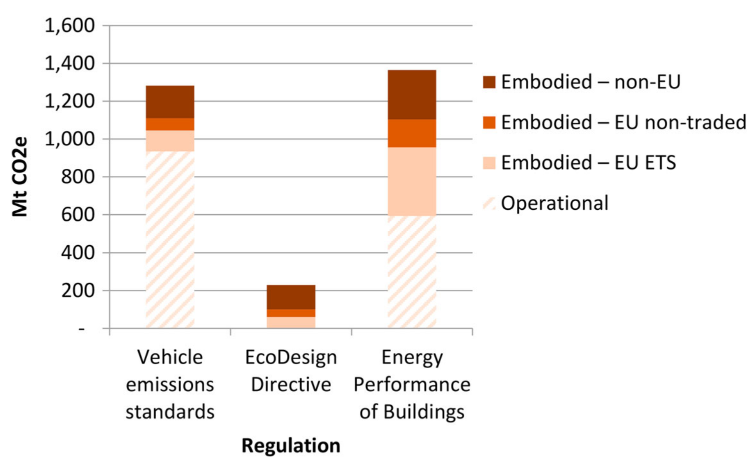

Figure 3. Operational and embodied emissions of selected products in 2007, Mt CO_2e (*operational emissions of electrical appliances are allocated to the power sector where the fuel sources are combusted*).

Road transport in 2007 emitted 934 Mt CO_2e (European Environment Agency, 2014a), representing 18% of EU production emissions. These are regulated by European vehicle emissions standards. An additional 346 Mt were embodied in the manufacturing of the vehicles purchased in the EU. A third of these are captured in industries capped by the EU ETS, leaving two thirds of the embodied emissions outside the scope of EU climate policy (3.3% of EU consumption emissions). Using the same logic, regulations on embodied emissions can be applied to all non-energy using products, currently not addressed specifically by EU climate policies.

3.3. Emissions scope of extended product policies

We calculated the total emissions range across all manufactured goods, not just energy using ones. This includes furniture, textiles, glass products and fabricated metal products. We estimate that 2061 MtCO_2e, equivalent to 40% of EU production emissions, are related to material-intensive manufactured products' supply chains, both for use by intermediate and final consumers. Some 789 Mt (38%) of these greenhouse gases are emitted within EU ETS sectors; however, the suggested policy extension would increase the coverage of emissions beyond the EU ETS to include both domestic non-traded and imported emissions. These figures represent the potential reach of policies, but not the emissions reduction potential as we don't know how politically feasible they are, how economic and trade variables would be impacted (e.g. prices and trade patterns) or the reaction of consumers to such policy changes.

4. Discussion on policy interactions and implementation

Our results show that emissions embodied in imports for final consumption in the EU are 2847 MtCO_2e, whereas emissions embodied in EU exports destined for consumption elsewhere are only 804 MtCO_2e. These net-imported emissions mean EU consumption drives 39% more emissions than those emitted in its production activities. Nearly half of the consumption emissions are embodied in manufacturing and service sectors, which use a lot of energy, material and product inputs along their supply chains. It was found that 18 and 30% of emissions associated with cars and buildings were excluded from EU performance standards and the EU ETS. We were unable to calculate the operational emissions for appliances; however, 74% of the embodied emissions are outside the EU ETS. The equivalent of 40% of EU production emissions are embodied in manufactured goods bought by EU residents, and 38% of these are captured within the EU ETS. We now discuss the advantages of product standards as a policy option to include material use, whether interactions with the EU ETS could undermine its effectiveness, and practical issues of implementation.

Businesses are generally risk averse. Standards can create useful market stability, as well as incentives to support eco-design principles (Dalhammar, 2016). Standards do not determine how businesses meet the targets, giving more control to companies, which Dalhammar (2016) finds is favourable to manufacturers. In terms of international markets the literature seems inconclusive as to whether an imposition of such regulations is in breach of trade laws, although this has not been the case for European energy efficiency product standards. In an analysis of nearly 6,000 European firms (Chan, Li, & Zhang, 2013) suggest that concerns over industry competitiveness in the EU ETS are so far unsubstantiated and in fact innovations in energy-using products is reported as a way to increase market competitiveness (European Commission, 2016). Crippa et al. (2016) found that standards for road transport in Europe and North America has led to a global increase of emissions-regulated vehicles and a reduction in localised air pollution. The standards provided a stimulus for innovation in catalytic converters and filter systems. Car markets have meant that production in non-regulated countries have met the European standards to be able to export there, and as a result there has been in the region of a 60% reduction in particulate matter, which impacts negatively on health, since 1990. This however, has limits for emerging economies with increasing market power such as China, whose domestic market is getting stronger, making them less dependent on export production (Holzer & Cottier, 2015).

Some policies can undermine the effectiveness of others. Energy efficiency lowers production costs and creates financial savings which are freed up to spend on additional consumption and its associated impacts, known as rebound effects (Sorrell, 2009). Reduced demand for energy and materials within EU ETS sectors can also free up allowances enabling trading participants to emit at a lower cost if the equivalent volume of allowances is not retired from the scheme (De Perthuis & Trotignon, 2014; Koch, Fuss, Grosjean, & Edenhofer, 2014). The changing structure of the economy which results in the expansion and contraction of sectors is an ongoing challenge for allocating carbon permits in the EU ETS (Stenqvist & Åhman, 2016). Therefore, there needs to be some way of dynamically managing caps either through auction release or a changing cap (De Perthuis & Trotignon, 2014). This would avoid rebound effects as it would maintain the carbon price and carbon would actually be removed from the system.

Regulatory standards capture carbon at the product level and as such target inefficiencies across the supply chain, unlike the EU ETS. Standards incorporate losses up to the point of consumption and even disposal (if recycled content was part of the regulation for example) and can incentivize the redesign of products. This impacts the economy-wide demand for energy, other materials and products, not just a share of the production emissions. Because emissions are captured at the product level this overcomes issues of carbon leakage. Demand for products cannot simply be met by carbon-intensive imports.

The nature of policy instruments has implications for how easy they are to extend, and how they interact to deliver emissions reductions. The EU ETS could be extended to include additional sectors but, in its current form, would still only capture a proportion of production emissions. Regulations and standards can more readily be extended to include embodied emissions, either within their current scope or with the addition of new requirements (Table 2). The Energy Performance of Buildings directive and the emissions performance standards for light-duty vehicles do not include embodied emissions (European Union, 2009b; Szalay, 2007); however, the EcoDesign directive was designed to take a more holistic approach. The EcoDesign directive requires that a preparatory study is carried out to determine whether a product group necessitates requirements to be set, and for which stages of the product lifecycle these should be implemented (European Union, 2009a). However, many product groups were assessed before recent advances in energy efficiency and when embodied emissions data were sparse and of poor quality (Huulgaard, Dalgaard, & Merciai, 2013). Therefore, all EcoDesign directive requirements have been related to operational energy and no products have had requirements set for embodied emissions to date (Maxwell et al., 2011). Our research indicates that these measures can, however, enhance the policy package for climate mitigation.

In terms of practical implementation, there are widely documented barriers to the implementation of ecodesign principles in business operations and product manufacture, such as time and resource constraints; lack of interpretation of life-cycle findings to designing solutions; collaboration challenges across complex global supply chains; a lack of integration within product development; and limited knowledge. However, frameworks are being developed to overcome these barriers (Brones, Carvalho, & Zancul, 2017; Dekoninck et al., 2016; Rossi, Germani, & Zamagni, 2016). There are often tensions and trade-offs in designing less material intensive products and practices, for example the availability of recycled content and the balance between durability and the quality of recycled materials (Brones et al., 2017). Regardless of how the Circular Economy agenda is implemented, these types of issues will need to be resolved.

Table 2. Potential to extend selected policies to include embodied emissions.

Current regulation	Possible addition	Additional requirements /next steps
EcoDesign Directive	Within current scope to set requirements to address some aspects of embodied emissions, including minimum guaranteed product lifetimes and promoting modularity, upgrading and repair (European Union, 2009a).	More appropriate methods to be used for preparatory studies in the EcoDesign directive, which used more recent data, accounted for technology development and took into account product lifetimes.
Energy Performance of Buildings Directive	Extend current requirements to include embodied energy in the integrated energy performance of buildings (Szalay, 2007).	Standardization of the calculation of embodied energy for building elements and processes.
Vehicle Emissions Performance Standard	Extend standards to include whole-lifetime emissions (Correia, Batista, Marques, & Silva, 2014).	Standardization for the calculation of embodied emissions for vehicle elements and processes.

It should also be noted that methods used in product-level assessments underpinning these directives are process life cycle assessments (LCA) and are not based on the same methods and data described in this article. The two methods are individually robust but use different data and undertake analysis at different scales. Process-LCA operates at the product level (Suh & Huppes, 2005; Suh et al., 2004). The IOA approach taken in this study operates at the economy-wide level and incorporates industry interactions which enables us to evaluate cross-sector overlap, and allows us to investigate both the inputs of product manufacture and their use in other areas of the economy. For example, we can look at the materials used to manufacture a car (to think about ways to design a lighter weight version) and also who uses cars downstream of their production (to think about how to reduce the number of cars on the road and where to focus policy interventions). This enables us to quantify the potential economy-wide impacts of eco-design principles when applied to both producers and a range of users of manufactured products.

5. Conclusions

EU consumption embodies 39% more emissions than it produces, a trend common across industrialized countries. We calculate that just under a quarter of EU consumption emissions are capped under the EU ETS and that emissions from material-intensive sectors are not easy to reduce from energy efficiency policy alone. The emissions flow chart in Figure 1 presents a framework which identifies different leverage points in the economy, where policy can intervene to reduce material and product use, and thereby GHGs. Through resource reduction measures, industrialized countries can target emissions sitting outside their current climate policies, including imported emissions, and is likely to result in a cost saving,

Opportunities to increase the scope of climate policy are not restricted to those in this article, but we have attempted to show the additional value of integrating efficient material and product use into existing climate mitigation policy. Policies which consider product supply chains have the potential to influence emissions beyond those from production. When analysing material-intensive manufactured products, we calculated their embodied emissions to be the equivalent of over 40% of EU production emissions, offering significant scope for emissions reductions. Further quantification on the actual emissions reductions achievable by different material and product use strategies need to be measured to show economy-wide savings possible across alternative strategies.

There is work to be done with intermediate and final consumers on designing the right policies to exploit these opportunities and this needs to be underpinned by a mainstreaming of knowledge of embodied emissions flows into policy, as well as research. Further consideration needs to be given to the impact of this new perspective on policy-making. Specific attention should be paid to the practical implementation of polices addressing embodied emissions, including the accounting procedures and administrative requirements for measuring and monitoring supply chain emissions crossing international borders. The exact mechanisms to ensure any overlap between policies are complementary in bringing about an absolute reduction in emissions, and do not undermine existing policies, need to be identified. This is a strength of IOA in informing product policy design.

A limiting factor of this study is that we calculated emissions associated with material and product flows by the magnitude of economic transactions between sectors, and not the physical quantity of traded goods, which is not available in such detail at a global scale. For example, emissions from steel production are attributed to procurers of steel based on the price each consumer pays for that steel. Therefore, the data do not reflect the fact that different consumers pay different prices for the same commodities. Global commodities are aggregated into 163 product groups, and reflect an average emissions flow for the combined group, whereas the emission intensity within groups can vary considerably. Publications on the integration of physical data with global economic trade flows are increasing, with such developments hopefully able to contribute to similar policy assessments in the very near future.

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