Towards zero carbon emissions – climate policy instruments for energy intensive industries, materials and products

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Abstract

Energy intensive industries (EIIs), producing the basic materials and products needed in society, contribute significantly to global emissions of greenhouse gases (GHGs). Motivated by the fear of carbon leakage, climate policy has so far treated the EIIs leniently with e.g. low carbon prices and/or free allocation of emission allowances. This has not resulted in more than marginal emission abatement. However, the emissions from EIIs have to approach zero by 2050 to 2070, following the overall target of the Paris Agreement. It is therefore urgent to develop policy strategies for a deep decarbonisation of EIIs.

In this study, we explore the role of various policy instruments in the transformation of EIIs to zero emissions and how they can be combined. In our analysis, we acknowledge the specificities of the various EII sectors with regard to mitigation options (e.g. available technologies and potential for recycling), market situation, and feedstock substitutability. The feasibility of specific policy instruments depends on these specificities and might therefore differ between subsectors of the EII.

The analysis of instruments is structured through an extended typology that takes its starting point in the economic impact the instruments have on the actors. The types of instruments include the commonly used sticks, carrots and sermons, as well as an additional type that we call "cushions" (Sticks, carrots and sermons are often assumed to be equal to regulation, economic instruments and information but we have slightly adapted the concepts to fit our "resource" perspective). These cushions can be flanking policies, that soften the negative effects on competitiveness that follow from implementing policy instruments, while climate policies between countries are not in pace. We also differentiate between instruments according to where along the value chain they are applied. How different instruments affect the competitiveness of industry is a key consideration.

We conclude that both energy and material efficiency, emissions-free processes and clean energy are needed to transform the EIIs. For this purpose, a range of instruments can be used in different parts of the value chain and the mix can change over time as technologies, markets and institutions change. New approaches to policy evaluation are needed to assess the combined and long term effects of such policy strategies.

Introduction

Energy intensive industries (EIIs) contribute significantly (20–25 %) to global emissions of greenhouse gases (GHGs) (Edenhofer et al., 2014). Climate policy has, however, so far only addressed EIIs to a small extent. This has to change in the longer run, if the agreed target of the Paris Agreement, keeping the global temperature increase well below 2 °C, is to be met. For this, emissions have to approach zero during the second half of this century. This in turn means that all sectors, including EIIs, have to be decarbonised. The transition process has to start now and the development of policy strategies is therefore urgent.

Much of the literature on GHG mitigation in EIIs has dealt with efficiency improvements which are expected to have potentials to reduce emissions by 15–30 %, see e.g. (Edenhofer et al., 2014). When more radical emission reductions have been discussed the focus has mostly been on carbon capture and storage (CCS) (IEA, 2012). Other more innovative options have not yet been explored. Recently, there has been an interest for analysing more radical changes to the industry, including process changes that allows for an electrification of the whole process (using electricity from renewable energy sources) and extensive use of biomass for replacing natural gas or oil/coal, see e.g. (Fischedick et al., 2014, Lechtenböhmer et al., 2017, Bataille et al., 2018).

Climate mitigation studies based on energy-economic modelling usually take its starting point in carbon pricing as being the main policy instrument driving mitigation, complemented by R&D efforts for enabling long-term low carbon options. Assuming carbon pricing as the main policy rests upon the idea that efforts should be globally cost-efficient and result in a uniform marginal abatement cost. The political economy of climate policy tells, however, a different story where policy makers constantly prefer a host of more tailored policy instruments that take into account the specific situation and requirements for making climate policy politically acceptable. Carbon pricing is in reality the exception rather than the norm and if at all implemented, it is often complemented with tax-exemptions, subsidies, regulations and other policy instruments. This is especially true for EIIs, for which, with the EU as an example, energy taxes are low compared to other sectors, the price signal from the implemented carbon price (EU ETS) is weak, and where most of the abatement so far can be attributed to various regulations and subsidies (Åhman and Nilsson 2015). Climate policy research has so far not fully acknowledged i) how instruments along the value chain may interact, ii) how the different conditions of various EII subsectors affect the feasibility of different policy instruments, and iii) how the feasibility of various instruments depend on the studied time-scale (short- or long-term effects).

In this paper, the complex reality of climate policy is addressed through a structured analysis of potential policy instruments targeting mitigation for the EIIs. The analysis is mainly qualitative where we use an extended typology that takes its starting point in the classic typology of "stick, carrots and sermons" (Vedung 1998) with an added category of "cushions". This categorisation is mainly based on how various policy instruments restrain or add resources to the regulated entity (in this case the industry).

The paper is structured as follows. First, we state the analytical perspective we choose for studying potential policy instruments for EIIs. It is followed by a short introduction of the characteristics of the EII and the variations between different EIIs. Thereafter we present the extended typology that we use for analysing the various types of policy instruments that could be used for EIIs. This analysis follows in the subsequent section. Finally, we take a broader discussion regarding potential policy strategies with regard to low-carbon industrial transformation.

Analytical perspective

This paper takes a normative perspective and a starting point in four factors that are generally considered important for policy design. Their relative importance can vary depending on the context.

- Effectiveness: A factor, which might seem evident, is that a good policy actually delivers on the goal that it is intended to meet. In this paper the main focus is on policies for GHG mitigation, and thus a feasible policy should be effective in meeting long-term mitigation targets.
- Cost-efficiency: The policy should be cost-effective both in the short and long-term, i.e., meet the goal at low cost. It is here interpreted as a policy that encourages a low-cost mitigation pathway while keeping administrative costs at a low level. A low-cost pathway does not, however, mean that only the measures with the *currently* lowest marginal abatement costs should be preferred but it should also include policies (e.g. R&D support and early deployment and upscaling support) that support technologies that are not yet market ready but viable alternatives for the future. To support the dynamics for developing technologies for GHG-emission free processes, an innovation perspective should be applied, acknowledging the need for different instruments and initiatives depending on the technology readiness level and market maturity of specific technologies. For example, the creation of niche markets is at certain times key to make room for learning effects to develop. As a consequence, at this time a certain amount of measures with initially higher costs will have to be implemented. A continued focus on energy and materials efficiency across the value chain is important as future resources in a low-carbon world may be limited either physically or economically.
- Carbon leakage: This can be seen as a dimension of effectiveness but deserves highlighting in the context of EIIs. A well-designed policy should not lead to relocation of industries beyond what is motivated by the relative comparative advantages for production in various regions. Such comparative advantages would be the availability of suitable feedstock, low carbon energy, vicinity to consumer demand, relevant industrial clusters, competence, wage level etc. Although comparative advantages to some extent result from policy, relocation that is only the result of different climate ambitions should be avoided. In order to combine cost-effective approaches, a combination of push and pull polices might be needed as well as flanking policies handling some of the negative side-effects of climate policy (Hildingsson and Johansson, 2016).
- Fairness: A policy and its outcomes should be regarded as fair (e.g., all actors contribute reasonable shares for reaching the goal) and not be opposed to general governing principles in the countries in which they are applied (e.g., equality under the law). They should also be possible to implement in a global context, where principles such as the "common but differentiated responsibilities" (CBDR) article in the UNFCCC have to be observed.

Characterising energy intensive industries

The specific character of the EIIs is important to take into consideration when designing climate policies for this sub-sector. The EIIs discussed here produce basic materials such as steel, basic plastics, aluminium, paper and pulp, and cement. The EIIs are parts of a value chains that start with mining or recy-

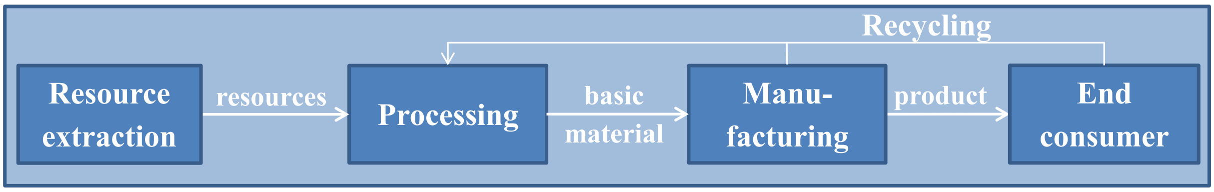

Figure 1. The industrial value chain from resources to end-consumer including the processing industries.

cling of resources all the way to the end-consumer, see Figure 1. The EEIs are found in the processing part where resources are refined to usable materials.

EIIs have many common features but each sub-sector has also specific challenges when it comes to decarbonisation options and its consequences. Below we will briefly review both the common and the unique challenges.

The main feature of the EIIs is that high energy intensity in itself makes these industries strongly exposed to any policies that target industrial energy use and/or carbon emissions. In addition, some of the EIIs (e.g., steel and cement) produce significant non-energy process emissions that also have to be reduced. Climate policy will thus lead to increasing costs for producing essentially the same materials. In contrast, for the manufacturing industry that work downstream, climate mitigation also provide opportunities to develop and find new niches for cleaner technologies (e.g., energy efficiency technologies and electric vehicles).

The problem with high energy intensity is amplified by the fact that the products of the EIIs are often traded globally and thus also exposed to the risk of competitiveness loss that potentially could result in carbon leakage. It is a fundamental problem that climate policy is largely implemented at the national and regional levels whereas these industries mainly operate on global markets.

The lack of readily available options for deep decarbonisation is also a major challenge. The literature on options for EIIs is growing, see (Åhman et al 2012; Bataille et al 2018; Lechtenböhmer et al 2017; Napp et al 2014). Efficiency options for existing process-technologies exist but reductions of GHGs beyond 50 % and down to 90 to 100 % cannot be reached without changing the core components of the process. Even with CCS, it would be necessary to develop and rebuild major parts of the production processes in order to capture more than 90 % of the emissions (Åhman et al 2012). Meeting climate policy targets in a growing global economy also necessitates a focus on overall system efficiency including high energy efficiency in new processes, and material efficiency through both low-waste manufacturing processes and in the end-user phase with through better product design and changes in consumption.

A challenge to the transformation of the EIIs is the "lock-in" to current technologies. The carbon lock-in is both technical and institutional. EIIs are capital intensive and typically have long investment cycles of at least 20 to 40 years (Åhman and Nilsson 2015; Lempert et al. 2002) for core process technologies (e.g., blast furnaces and lime kilns). This substantially reduces the willingness to take risks with new technologies. The EIIs have also a strong political embeddedness stemming from a long history (being the historic engine for the industrialisation of Western Europe), and industrial plants are often a major local or regional employer and part of the identity of the local community.

In the climate policy literature, the EIIs are often lumped together as one sector with one main solution (e.g., CCS), see e.g., (IEA, 2012), but in reality there are large differences between the different EII subsectors that need careful attention when designing policy packages. The various subsectors differ in decarbonisation possibilities due to differences in (i) feedstock, (ii) recyclability of the material, (iii) decarbonisation options at hand, and (iv) markets and trade patterns.

For feedstock, plastic is the most difficult materials to decarbonise as the feedstock in itself is from fossil origin. A GHG-emissions- and fossil free industry here would mean changing feedstock to either biomass or hydrocarbons produced from captured CO_2 streams with the help of electricity from renewable energy. Increased mechanical and chemical recycling of plastics is important not only from a climate policy view but also to reduce plastics pollution.

Recycling is a key component of decarbonisation policy for all materials but the recyclability differs between materials. Steel and aluminium is 100 % recyclable (in theory and almost in practice) but due to growing demand, especially in the developing world, and high quality requirements in some applications, virgin materials are likely to be needed for a very long time. For cement, recycling is not an option but the used cement can be down-cycled to be used as filling material for roads and other construction.

The decarbonisation options also differ. CCS is the option that requires least changes to the current production mode. For cement, using other materials for constructions or developing alternative cements may be possible in some applications but CCS appears to be the main mitigation option. For steel, CCS is still a major option but various options for electrification are also considered, e.g., hydrogen direct reduction or electro-winning. Biomass for feedstock is an obvious option for the plastics industry to replace fossil naphtha, but also for fuel everywhere in industry where heating is needed. However, biomass, although theoretically abundant, suffers from several sustainability drawbacks and is dependent on a strong regulated market that secures the sustainability and fair production of biomass. Competition for sustainably harvested biomass may be strong in the future and its use will always involve a trade-off with other interests (e.g., biodiversity and nature conservation).

The markets and the exposure to international competition differ between the sub-sectors. All are to some degree exposed to international trade but, for example, the cement markets are typically more local and regional due to the high cost of transport compared to the value of the product. However, with increasing production costs due to climate policies, external pressure on national markets could increase as larger cost differentials could motivate longer transport distances. In contrast, aluminium has a high value and can be transported long distances. As a result it is almost a "footloose industry" with a genuinely global market restricted mainly by trade regulations. The aluminium industry is now locating itself close to low cost and "stranded" energy sources such as hydropower in Mozambique and on Iceland and cheap natural gas in the Middle East. Steel is globally traded but there are large variations in the price of steel depending on the product quality. Chinese steel production has grown tremendously the last 10 years but is mainly for lower value bulk steels. A large share of the steel produced in the EU is of high quality and higher value.

A typology of policy instruments

There are several existing typologies for characterising policy instruments, stressing different aspects of the instruments. A useful typology is determined by its purpose but also by the context in which the instruments are applied. Therefore, Vedung (1998) argues that there is a need for a variety of classifications depending on theoretical and practical perspectives. This echoes with Daugbjerg and Sönderskov (2012) who argue that it is more promising to develop separate typologies for different policy fields rather than to try to find generic typologies.

An often used triptych is that of regulation, economic instruments and information (Vedung, 1998) where the different groups differ in the degree of authoritative force, from coercion, through remuneration or deprivation of economic and material resources to the least forcing, using information and intellectual or moral appeals to induce action. In other typologies these categories are complemented with organisational changes[1] (see e.g. Howlett, 2009, Daugbjerg and Søndeskov, 2012), R&D funding, co-regulation and self-regulation (Taylor et al., 2013). Investments in infrastructure and regional and land-use planning can also be seen as separate enabling instruments that indirectly affect the actors' opportunities to act.

Another way to structure the instruments is whether they are in the form of incentives that rewards positive action (carrots) or restricts or provides negative incentives for unwanted phenomena such as CO_2 emissions (sticks). Unlike Vedung, who equals economic instruments with carrots we argue that economic instruments can be both in the forms of carrots (various forms of subsidies) or in the form of sticks (taxes or other pricing systems). Following a market governance mode (cf. Howlett, 2009), economic climate policy instruments are today to a growing extent in the form of pricing of negative externalities (i.e. is in fact a kind of stick) in line with polluters pays principle. For example, the share of global GHG emissions that is subject to pricing is growing rapidly (today equal to about 15 %) although the levels are often quite low (World Bank et al., 2017). The concepts of carrots and sticks are by Vedung (1998) complemented by sermons which we interpret as similar to informative instruments but could also include activities that changes perceptions and norms.

1. One common way to prioritise an issue is by organisational changes, e.g., by starting new authorities or government agencies. Vedung (1998) however distinguishes between policy instruments and organisation strategies to which organisation belongs.

For the EIIs, the impacts of the instruments on competitiveness are central (Wesseling et al 2017). Therefore, the incentive structure of the instruments is especially important, and thus the typology of carrots, sticks and sermon seems especially relevant, as the choice between carrots and sticks have a direct impact on allocation of resources and thus on competitiveness. In addition, we recognise that policies may be needed to protect industry from unfair competition that follows from different climate policy ambitions (we present a popular term, cushions, for this in line with the informal terminology of carrots, sticks and sermons). Thus, the four categories in a first dimension of the typology of instruments are:

- Sticks that make negative aspects of current systems less attractive through inflicting higher costs or by forcing emission reductions through regulation.
- Carrots which act through positive incentives such as investment grants and production subsidies,
- Sermons that argues for and informs about emissions reductions, and contributes to changes in norms and perceptions.
- Cushions that help protecting the actors from negative side-effects of policies for GHG mitigation.

It is worth noting that the impact of the same instrument can be negative (a stick) for some actors and positive (a carrot) for others in the value chain. In an analysis, it is important to define from whose perspective we evaluate. We choose the perspective of the actor that actually conducts the mitigation measure, e.g. investing in energy efficiency or new process technology, chooses to buy environmentally friendly products or leaves its products or production wastes to recycling. Sometimes it is not always the same as the one who is regulated.

Following from this, we choose to introduce a second dimension relating to where in the value chain, see Figure 1, the instrument has its active effect (which as mentioned above can be different from the point of intervention). The position where the instrument is applied will have an impact both on the responsiveness and how precise the instrument will be in relation to the problem solved. It is also important in relation to competitiveness issues and to what degree domestic and imported products are treated equally. With regard to preciseness there is a broadly accepted principle that policy instruments should target the sources as closely as possible, e.g. for industrial emissions policy intervention should thus target the plant. This is, however, not always possible, or even wanted, depending on what kind of response the policy makers are anticipating for the intervention. Policies directed towards final consumption might be an alternative as a second best solution. Policies directed to consumer markets will also be important for creating a market for green products. These interventions can include consumer taxes, consumer standards, labelling and public procurement.

What a suitable policy instrument is will vary depending on if they intend to affect product demand levels, product service, material and energy efficiency, fuel choice or the overall process design (some instruments have impact on all these measures but with different effectiveness). They will also differ if they mainly aim at implementing existing technologies or the development and introduction of new, not market ready

Table 1. Examples of "sticks" with the purpose of GHG mitigation applied along the supply chain. The instruments in parenthesis has a stick function (regulation) at the point of intervention, but acts as "carrots" for the industry conducting the actual measure (investing in emission mitigation technologies or providing green materials), see Table 2.

STICKS	Resource extraction	Processing industry	Manufacturing industry	End-use
Economic	Carbon tax/EU ETS Extraction fee	Carbon tax/EU ETS	Carbon tax/EU ETS Material tax	Consumption tax
Regulation	Recycling regulation IED-regulation	Recycling regulation IED-regulation	Recycling regulation IED-regulation Eco design regulation (Building codes)	Recycling regulation (Quota regulation) (Mandatory feed in tariffs) (Regulated green public procurement)

technologies. As the implementation of these measures meet different market barriers different instruments may be preferable. Different market and institutional contexts among industrial subsectors also suggest that different approaches have to be adopted among the subsectors. Such differentiations can, however, meet legal challenges as it is expected that different actors should be treated in an equal way.

The potential role of different policy instruments

In the following chapter, various potential instruments applicable along the value chain are discussed. The examples of instruments are collected from e.g. (Allwood et al., 2011; Wooders, 2012; Åhman et al., 2012; Napp et al., 2014; Neuhoff et al., 2015; Al-Saleh and Mahroum, 2015; Åhman et al, 2017; Wesseling et al., 2017). Examples of various policy instruments defined as either sticks, carrots, sermons, or cushions are given in Table 1 to 4, structured according to where in the value chain they are implemented.

The effects of up-stream policy instruments propagate down the value chain in the form of price changes (if it is possible to the regulated to pass-through some of their extra costs). It is less straightforward how a down-stream instrument (e.g., a carbon-based consumption tax) propagates to the upstream part of the value chain. Instruments implemented early in the value-chain are likely to generate a broader variety of mitigation measures than will instruments close to the consumer where many potential up-stream measures may be forgone. However, an up-stream carbon price signal will often be rather weak downstream, when compared to the total price of the end-user product.

STICKS – NEGATIVE INCENTIVES FOR THE UNWANTED

In this paper, we classify sticks as instruments that provide negative incentives for unwanted action. These could be in the form of regulations or, in the case of economic instruments, as a price increase on energy or emissions, e.g. in the form of taxes and prices of allowances in ETS, see Table 1. This approach fits well with the Polluter Pays Principle as all costs fall on the emitter or energy consumer. In both the regulation case and the economic case the actors will have to pay for mitigation. However, with an economic stick, in the tax case or an emission trading system without free allocation, the actors will have to pay for the unmitigated emissions as well. This may have further negative consequences for competitiveness, why from industries' point of view, regulation might be preferable to economic instruments (Johansson, 2006).[2] The extra costs incurred through any of these instruments could lead to increased risk for carbon leakage. Although the historical evidence of carbon leakage is weak (see e.g. Bolsher et al., 2013) the risk could not be dismissed for a future in which significantly stricter policies are implemented to drive transition. With a strong emphasis on using sticks as the main policy instrument (polluters pay principle), there might be a need for flanking policies of the type discussed as "cushions "below.

Whereas regulation for large-scale industrial plants according to for example the IED directive occurs with defined intervals or with major reconstructions, economic instruments have the advantage of driving continuous improvements. This is not so important when it comes to major process changes, which anyway will require new permits, but more so with regard to operational measures including those increasing energy efficiency. In addition, regulation is often criticised as inefficient as it requires that the regulator has full knowledge of the regulated entities' mitigation opportunities.

Where, along the supply chain, should the "stick" work? In order to give incentives to all types of mitigation efforts it is generally accepted that it should be applied as close to the emission as possible. Increased costs will also, ideally, propagate along the value chain and cause adaptive behaviour as well. The drawback with this is, for globally trade goods such as steel, aluminium etc. that imported and exported products will not be treated in the same way. This would motivate that the price/regulation is implemented later along the value chain or the use of border tax adjustments, see below. However, this will omit several mitigation efforts as the propagation is a one-way process. For example, a tax on end-use products using steel will not give any incentives for improving production processes. Recycling regulations are in turn important for increasing system efficiency but miss measures that deal with process improvements.

Eco design regulation is an example of a regulation that acts in the middle of the value chain, on the manufacturer. This level can sometimes be a key point between the material industry

2. Even if a policy instrument (e.g. emissions trading or carbon taxes) is regarded cost-efficient from a societal perspective it is not necessary preferable for every single actor.

and end-use giving incentives to find the synergies between using less (but better) materials and enabling higher end-use energy efficiency. This could enable reduced impact from resource extraction, material production as well as end-use of the final products.

A specific issue is the fossil feedstocks used for plastics. They are usually not taxed or regulated in the beginning of the value chain, but rather when it comes out as waste. Here they might be affected by recycling regulation, ban on landfills or taxes on waste incineration. The latter follows the argument of taxation as close to the actual emission as possible, but as the used emission and energy use factors are often based on static average estimates, they give small incentives for substituting fossil resources with renewable. Here it would be preferable to implement the instrument not where the CO_2 is emitted to the atmosphere but instead at the *strategic point of action* when it comes to emissions mitigation, i.e. at the place where the feedstocks are introduced into the system.

CARROTS – INCENTIVES TO SUPPORT WHAT IS DESIRED

"Carrots", see Table 2, in the form of subsidies or other supportive action as public R&D funding or infrastructure investments have great advantages for the industry as the policies do not inflict any costs. Typical instruments on the production side would be financial support for demonstration plants or risk sharing arrangements. There are several potentially problematic aspects with these instruments such as their impact on the state budget, the difficulty to make them compatible with state aid regulation, and finally the risk of getting hi-jacked by the interests of incumbent actors leading to resources being spent on options that are aligned with their short-term rather than potential long-term solutions. Nevertheless, different forms of financial support for technology development and implementation will be necessary for a successful transition.

The economic resources for subsidies could be taken directly from the consumer in similar ways as is made for green electricity through quota obligations or feed in tariffs. Such systems put an obligation on consumer to buy a certain amount of the product (quota obligations) or any supplied amount at a higher than market price for the product (Feed-in-tariffs) than would otherwise be the case. Transferred to the materials market a similar system could consist of obligations to buy a certain fraction of "green" cement and steel in the construction sector or for renewable plastic materials in packaging. This kind of "regulated privatisation" of subsidies might however for two reasons be more complicated for materials than for electricity. First, many of these products and sectors are less homogenous than electricity making it more difficult to decide what exactly should be regulated. Second, the electricity market consists of several different monopolistic markets that therefore have to be regulated, which differentiate it from markets for other products in most countries. New obligations therefore will be more difficult to integrate in existing regulations but this has to be analysed more.

Other consumer-oriented instruments would be regulations of public procurement, which in addition to requirements of renewable energy and energy efficiency also could focus on green materials. As public organisations are responsible for large material-intensive infrastructure investments the role of green public procurement has the potential to be important.

SERMONS –BUILDING NORMS AND ENCOURAGING VOLUNTARY ACTION

Sermons, used for norm building and encouraging voluntary action can be of different types and act along the value chain, see Table 3. Perceptions and norms of what is doable and desirable are often seen as important aspects to encourage action (see e.g. Borup et al., 2006; Späth and Rohracher, 2010). Communicating visions and developing roadmaps illustrating in what direction and how far the industries have to go and that transition is possible, could be important to convince industries and consumers of the necessity to act. The development of low carbon roadmaps have for example clarified that it is not possible to protect the EIIs from action and that marginal emission reductions are not enough. In Sweden, it has resulted in e.g. new initiatives for a zero-carbon steel industry (IEA, 2017). As it might not be sufficient with voluntary programmes for the industry to decarbonise it has to be combined with the other type of instruments presented above. However, shifting norms and perceptions both within industry and in society as a whole, is likely to be necessary for a successful implementation of the adequate policy instruments.

Information about energy efficiency opportunities, energy management systems and eco-labelling of products are other key instruments for decarbonisation that falls under the category "sermons". The development of standards for green products (e.g. for plastics and cements) will also help building confidence in the market. The standards will need to be both quality standards securing the quality of e.g. low clinker cement, and standards that enable the consumer to distinguish between "green" and "brown" products.

Table 2. Examples of "carrots" with the purpose of GHG mitigation, applied along the supply chain. The instruments in parenthesis has a stick function (regulation) at the point of intervention, see Table 1 but acts as "carrots" for the industry conducting the actual measure (providing green materials) and will have its transformative impact on the stages presented in this table.

CARROTS	Resource extraction	Processing industry	Manufacturing industry	End-use
Economic	Support for electrification of mining operations	R&D support Investment subsidy Risk sharing arrangements (Privatised subsidies through Quota regulation, mandatory feed in tariffs and regulated green public procurement and building codes)	R&D support Investment subsidy Risk sharing arrangements (Privatised subsidies through Quota regulation, mandatory feed in tariffs and regulated green public procurement)	Refund schemes for packaging

Table 3. Examples of "sermons" with the purpose of GHG mitigation, applied along the supply chain.

SERMONS	Resource extraction	Processing industry	Manufacturing industry	End-use
Informative	General information on efficiency options	General information on efficiency options Energy management systems	General information on efficiency options Energy management systems	General information on efficiency options Eco-labelling Quality standards
Norm building		Visions and roadmaps	Visions and roadmaps	
Voluntary actions		Voluntary agreements	Voluntary agreements	Voluntary green public procurement

Table 4. Examples of "cushions" with the aim to soften the consequences of policy instruments applied along the supply chain.

CUSHIONS	Resource extraction	Processing industry	Manufacturing industry	End-use
Economic		Border tax adjustments Production subsidies Free allocation of emission allowances Compensation for ETS-induced electricity price increases		Economic compensation to end-users

CUSHIONS – MANAGING ADVERSE SIDE-EFFECTS

Policies that incur cost increases for industry could potentially be handled with flanking policies acting as cushions to protect the industries' competitiveness, see Table 4. Border adjustment taxes have been proposed both by governments and researchers. The intention is to put domestic and international companies at a level playing field. The consistency of such instruments with international trade regimes has been debated and has not been conclusive, see e.g. (Swedish National Board of Trade 2009; Quirico 2010; Weber 2015). In addition to this, the efficiency of the combination of carbon pricing and border adjustments in an export-oriented country could be discussed (most of the CO_2 emissions are "exported" and will thus be refunded) and would depend on how the levels are set. Finally, the flow of materials in complex products seem administratively complicated to handle.

An alternative approach that can minimise the risk of carbon leakage while maintaining the pressure to increase energy efficiency and decarbonise would be to combine carbon pricing and production subsidies (e.g. as Euro/tonne steel). Production subsidies would not remove the incentives for low carbon production technologies as they are not correlated to emissions, while removing the competitive disadvantages of carbon pricing. Production subsidies would, however, most likely also be challenged by other countries as incompatible with the trade regime. From both these examples it is quite clear that it is impossible to separate climate and trade policy.

Cushions could be used not only to protect industries from the most negative consequences of policy but also the end-consumers. However, the likelihood that climate policies would lead to such severe consequences for the consumers that it would require major public interventions, such as those used to deal with e.g. energy poverty, is probably low. For example, as Rootzén and Jonsson (2015 and 2016) show, the impact of a stringent climate policy on the cost of a building or a passenger car, following increased material costs resulting from climate policy, will be quite low (a few percent). In the case of plastics this might be different where the costs for "green" polymers can be 2–3 times higher than for fossil-based polymers (Palm et al., 2016).

Discussion

This paper explores, on a principal level, how various policy instruments can contribute to a transition of EIIs to a zero emissions future in which the EIIs still can contribute with materials that are necessary for the societal metabolism. Resource and energy efficiency will be even more important in the future than today, due to resource constraints, but will not be enough to meet the challenges. New technologies, currently not available on the market, will have to be developed, tested and introduced on a large scale in the forthcoming decades. The systemic changes needed for the whole value chain in order to first develop and then introduce low-carbon materials suggest that a variety of instruments will be necessary in order to meet the various barriers for existing and future "green" technologies.

Strengthening the price instruments, internalising a greater fraction of the negative externalities of energy use and process emissions, would provide important incentives for continuous efficiency improvements and emission mitigations but it is, for competitiveness and efficiency reasons, not realistic to introduce a price at such high level that it alone would motivate the development of the necessary new technologies. The first reason comes from our evaluation that a single global carbon price is not realistic in the near future, while the transition has to start now even though many of the technologies will perhaps not be market ready in decades, see e.g. (IEA 2012). High carbon prices would put the industries in climate ambitious countries under severe stress. Second, although price incentives are important for technology change other instruments are more important in the early stages of technology development and market building (see e.g. Popp, 2010). In addition to energy pricing instruments we see carrots in the form of R&D funding, risk sharing arrangements and consumption-based instruments such as public procurements, standards and quota obligations as interesting complements, but the exact design has to be further researched. "Sermons" inducing shifts in norms and perception are most likely necessary to motivate the industries to participate in the transition. And finally, combining sticks with cushions is an alternative that is worth to continue to research, allowing for the implementation of economic incentives to a level where it would really have an impact, without severely damaging the domestic industry.

Economic instruments e.g. various forms of carbon pricing are often suggested as the most efficient instruments for decentralised decision making and continuous improvements. A potential advantage with regulative measures such as individual permitting is its integrative character, where several environmental aspects can be taken into account simultaneously during the permitting procedure thus increasing the opportunities for harvesting synergies. From the perspective of competitiveness it has also the advantage that companies will not have any cost from emissions difficult to mitigate (see e.g. Johansson, 2006). However, on the negative side, regulation requires that the administrator possesses a detailed knowledge of mitigation opportunities. Furthermore, regulation provides small incentives to continuous improvements between the intervention points.

Our interest in long-term transformative changes is motivated by the specific challenges this will pose with regard to governance. Concerted efforts to drive industrial innovation into new process technologies must, however, for several reasons be complemented with continued focus on efficiency in a broad sense. First, as mentioned previously, it is necessary to develop resource and energy efficient systems together with zero emission technologies, in order to make the transition economically doable and keep the use of renewable energy sources within sustainable limits. This includes not only technical energy efficiency but also materials efficiency and end-user efficiency along the whole value chain. Second, during the long transition period (40–50 yrs.) to a zero emission world, efficiency improvements could significantly limit cumulative emissions and thus the ultimate magnitude of climate change.

Many of the instruments needed for the energy transition are technology specific. This introduces several of the traditional potential problems such as risks of betting on the wrong horse and support-schemes getting hi-jacked by vested interests. It is also important that risk sharing schemes do not only leave the risks to the public actors, while the gains all fall on the industries.

Combining sticks with cushions, as discussed above, would be one alternative for creating a level playing-field for domestic and foreign producers. Another alternative would be to direct a greater fraction of the instruments to the end-user which would enable similar treatment between domestic and imported products. The negative aspect of this is that it might provide incentives for only some mitigation efforts such as material recycling and demand reduction but little incentives for process improvements. Although environmental labelling schemes combined with other incentives could take some aspects of the production processes into account it introduces some administrative complications into the system. It is a general consequence of indirect steering that the more "correct" in terms of environmental preciseness the steering should be, the more complicated the system will be.

Policy packages must evolve over time and adapt to technology levels and changing markets. The long-term direction must, however, appear trustworthy and make the actors confident that a transition in production technologies is necessary. Short term interventions should not be designed in a way that leads to lock-in or conflict with longer term needs for fundamental shifts in feedstock and process technologies (e.g., bio-based materials and electrification with clean electricity). For system-wide and long-term transitions in how we produce and use materials it will be difficult to evaluate single policy instruments, attribute emission reductions and calculate abatement costs. The evaluation of transition policy packages therefore requires new approaches to evaluation.

The challenges and solutions differ among the EII subsectors steel, cement and plastics and thus the potential steering solutions. While cement works on a less globalised market and a major part of the emissions are non-energy related, the road to zero emissions seems non-viable without CCS. The sector could, however, perhaps manage a higher price on CO_2 than the other sectors. While both the steel and plastic materials are more or less recyclable cement is not, and focus has instead for on recycling been on how to produce concrete with other material mixes. The substitution of concrete for wood constructions is also a potential strategy.

Steel on the other hand is totally recyclable and resource efficiency seems a key strategy in CO_2 mitigation. CO_2 intensity of scrap steel production is only a fraction of that of current technology producing steel from iron ore. Recycling is therefore clearly an important option. Due to increasing production levels, even maximum recycling efforts have not been enough to balance scrap supply with potential demand. In the longer run, this might however change. Despite the necessary efforts to increase recycling, primary steel production using iron ore, will continue to play an important role for many decades and the emissions from this production routes has to be handled. CCS, could play a role, but will not be enough for zero emissions. New technologies, which are not expected to be market ready in decades (see e.g. IEA, 2012) has to be developed in a process that starts today. Therefore various public support efforts for technology development seem necessary.

With regard to plastics, the choice of feedstock is the main issue. Regulation and pricing efforts must start to include fossil feedstocks. For example, existing exemptions from carbon taxation and emission trading schemes seems contra-productive and have to be removed. In several uses, such as packaging the exposition to the consumer is close and it seems reasonable to get people to pay for green plastics in a similar way as for ecological products but this is unexplored. Regulation of these end-use products seems neither unrealistic as the EU directive on plastic bags illustrates (European Union, 2015).

Conclusions

Low carbon transitions in energy intensive industries require changes across value chains, from extraction of natural resources to consumption and end-of-life recycling of different materials. Energy efficiency, material efficiency, clean energy and emission-free processes are the four pillars of such transitions. Policy instruments for interventions across these value chains may come in the form of sticks, carrots, sermons and cushions. Which policy instruments to use at different places in the value chain, and when to use them, depend on the characteristics of the specific industry (e.g., in terms of technology options for energy and resource efficiency, energy system implications, markets and international climate policy). With a whole-system and long-term perspective on industrial transformation it becomes clear that new and broader approaches to policy evaluation are needed to complement the current mainly one-instrument-evaluations.

In the absence of international agreements, and for materials with strong international competition, policy packages can be balanced more towards carrots, and the sticks used may need to be balanced with cushions. Plastics and steel are examples of such materials. Cement is a more homogenous and easy to trace material, and here policy packages may lean more towards sticks. Government investments in R&D and demonstrations are necessary in areas where the time is long from now until market ready solutions are available (e.g., electricity based steel making).

Finally, without changes in perceptions and norms, a transformation of industry seems unlikely. Intentional change requires direction, in our case (a) accepting the necessity of zero emissions and (b) identifying the pathways to reach this goal. Without direction, or a shared vision, businesses will not put the necessary effort in terms of personnel, competence and capital into the processes. In addition it will be difficult for governments to motivate, get acceptance for, and implement the necessary policies without such shared visions.

References

Åhman M., Nikoleris A., Nilsson L. J. (2012). *Decarbonising industry in Sweden – an assessment of possibilities and policy needs*. Report 77, Environmental and Energy Systems Studies, Lund University, Lund.

Åhman M. and Nilsson L.J. (2015) Decarbonising industry in the EU – climate, trade and industrial policy strategies, Ch. 5 in Dupont C and Oberthur S. (eds*) Decarbonisation in the EU: internal policies and external strategies,* Palgrave MacMillan, Basingstoke, Hampshire.

Åhman M., Nilsson L.J & Johansson B. (2017). Global climate policy and deep decarbonization of energy-intensive industries, *Climate Policy 17,* 5, 634–649, DOI: 10.1080/14693062.2016.1167009

Allwood J. M-, Ashby M. F., Gutowski T. G., Worrell E. (2011). Material efficiency: A white paper, *Resources, Conservation and Recycling, 55*, 362–381.

Al-Saleh Y. and Mahroum S. (2015). A critical review of the interplay between business models: greening the built environment a case in point. *Journal of Cleaner Production, 109*, 260–270.

Bataille C., Åhman M., Neuhoff K., Nilsson L.J., Fischedick M., Lechtenböhmer S., Solano-Rodriquez B., Denis-Ryan A., Steibert S., Waisman H. Sartor O., and Rahbar S: (2018). A review of technology and policy options for making heavy industry products consistent with Paris Agreement compatible deep decarbonization pathways. *Submitted to Journal of Cleaner Production*,

Bolsher, H., Graichen, V., Graham, H., Healy, S., Lenstra, J., Meindert, L., Regerczi, D., v. Schickfus, M., Schuacher, K. & Timmons-Smakman, F. (2013). *Carbon Leakage Evidence Project – Fact Sheet for Selected Sectors*, ECORYS, Rotterdam.

Borup M., Brown N., Konrad K., Van Lante H. (2006). The Sociology of Expectations in Science and Technology. *Technology Analysis & Strategic Management, 18*, 285–298.

Daugbjerg K. and Sønderskov K. M. (2012). Environmental policies performance revisited: designing effective policies for green markets, *Political Studies, 60,* 399–418.

Edenhofer O. et al. (2014). *Technical Summary*, In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, UnitedKingdom and New York, NY, USA.

European Union (2015), Directive (EU) 2015/720 of the European Parliament and of the Council of 29 April 2015 amending Directive 94/62/EC as regards reducing the consumption of lightweight plastic carrier bags.

Fischedick M., Marzinkowski J., Winzer P., Weigel M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production. 84,* 563–580.

Hildingsson R. and Johansson B. (2016). Governing low-carbon energy transitions in sustainable ways: Potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy, 88*, 245–252.

Howlett M. (2009). Governance modes, policy regimes and operational plans: A multi-level nested model of policy instrument choice and policy design. Policy Sci (2009) 42: 73–89.

IEA. (2012). *Energy technology perspectives 2012. Pathways to a clean energy system*. OECD/IEA, Paris.

IEA. (2017). *Energy technology perspectives 2017. Catalysing Energy Technology Transformations*, OECD/IEA, Paris. 2017.

Johansson B. (2006). Climate Policy and Industry - Effects and Potential Responses in the Swedish Context, *Energy Policy*, *34*, No. 15, pp. 2344–2360.

Lechtenböhmer S:, L J. Nilsson , M Åhman , C Schneider (2017) Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy 115*, 1623–1631.

Lempert, R. J., Popper, S. W., Resetar, S., Hart, S. (2002). *Capital Cycles and the Timing of Climate Change Policy*, PEW Centre on Global Climate Change.

Napp T.A., Gahmbir A., Hills T. P. Florin N., Fennell P.S. (2014). A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renewable and Sustainable Energy Reviews 30*, 616–640.

Neuhoff K. et al. (2017). *Innovation and use policies required to realize investment and emission reductions in the materials sector*. Climatestrategies.org.

Palm E., Nilsson L.J., Åhman M. (2016). Electricity-based plastics and their potential demand for electricity and carbon dioxide, *Journal of Cleaner Production, 129*, 548–555.

Popp D. (2010). Innovation and climate policy, *Annual review of Resource Economics, 2,* 275–298.

Quirico O. (2010).EU border tax adjustments and climate change: reaching consensus within the international legal context, *European Energy and Environment Law Review, 19*, 230–238.

Rootzén J. and Johnsson F. (2015). Perspectives on the costs of reducing CO_2 emissions from industry-the case of Nordic Cement Industry in Rootzén J. *Pathways to deep decarbonisation of carbon-intensive industry in the European Union – Techno-economic assessments of key technologies and meas*ures. Doctoral Dissertation, Chalmers University of Technology, Göteborg, Sweden.

Rootzén J. and Johnsson F. (2016). Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry. *Energy Policy, 98*, 459–469.

Späth P. and Rohracher H. (2010). 'Energy regions': The transformative power of regional discourses on socio-technical futures, *Research Policy, 39*, 449–458.

Swedish National Board of Trade. (2009). *Climate measures and trade. Legal and economic aspects of border carbon adjustment.* Stockholm.

Taylor C.M., Pollard S. J.T. Angus A. J., Rocks S. A. (2013). Better by design: Rethinking interventions for better environmental regulation, *Science of the Total Environment, 447*, 488–499.

Vedung E. (1998). Policy Instruments. Typologies and Theories, In Bemelmans-Videc M-L., Rist R. C. Vedung E. (Eds.) *Carrots, Sticks & Sermons. Policy Instruments and their Evaluation.* Transaction Publishers, New Brunswick, New Jersey.

Weber R. H. (2015). Border adjustment taxes – legal perspective, *Climatic Change, 133*, 407–417.

Wesseling J. H. Lechtenböhmer S., Åhman M., Nilsson L.J., Worrell E., Coenen L. (2017). The transition of energy intensive processing industries towards deep decarbonisation: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews, 79*, 1303–1313.

Wooders P. (2012). *Energy-Intensive Industries: Decision making for low-carbon future.* The case of steel, International Institute for Sustainable Development.

World Bank, Ecofys and Vivid Economics. (2017). *State and Trends of Carbon Pricing 2017* (November), by World Bank, Washington, DC. Doi: 10.1596/978-1-4648-1218-7.

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