SWEDISH COMPARATIVE CARBON ADVANTAGE IN WORLD EXPORTS

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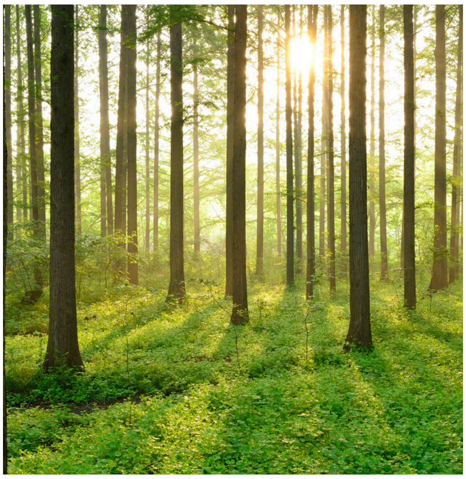

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Energiforsk

Swedish Comparative Carbon Advantage in World Exports

The role of the electricity sector

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Foreword

These are the results and conclusions of a project that is part of a research program EFORIS run by Energiforsk. The author/authors are responsible for the content.

Sammanfattning

Sverige har historiskt haft en betydande fördel i en låg koldioxidintensitet i sin tillverkning såväl som export av varor. Denna fördel är till betydande del en följd av landets specifika elproduktionsmix med framförallt vatten- och kärnkraft. I detta dokument introduceras ett nytt koncept, ’comparative carbon advantage’, som ett potentiellt sätt att mäta klimatpåverkan från en exportsektor. Genom att utnyttja länders skillnader mellan olika sektorer i koldioxidintensitet kan faktiskt en ökad industrikoncentration och exportintensifiering leda till välfärdseffekter när det gäller minskade globala koldioxidutsläpp. I artikeln används årliga data mellan 1995 och 2008 för att observera eventuella förändringsmönster inom en period som ofta har beskrivits som en tid av absolut "frånkoppling" eller decoupling (kontinuerlig ekonomisk tillväxt i en tid med absoluta minskningar av de territoriella koldioxidutsläppen). Totalt bidrog Sverige med en minskning på nästan 590 miljoner ton CO_2 globalt sett, då exporterade varor tillverkades med ovanligt koldioxidsnåla processer. Den totala mängden av 590 miljoner ton koldioxid avser besparingen jämfört med om samma mängd och sammansättning av svensk export producerats med hjälp av världens genomsnittsteknik för varje produktgrupp. I studien analyseras och kvantifieras vidare det svenska bidraget som just en effektiv elproduktion ger Sverige i form av det s.k. comparative carbon advantage. Koldioxidfri elproduktion stod för över 34 % av de totala besparingarna, eller 200 miljoner ton CO_2, varav cirka 20 % var direkt export av el och 80 % var el som en del av faktorinsatsen i exporterade produkter. Denna forskning bidrar till förståelse för effekten av en effektiv och koldioxidfri elektricitetssektor för att ge en koldioxidsnål tillverkningssektor - en politiskt relevant aspekt i den ökande globala handeln. Dessutom ger artikeln stöd för den europeiska energiintensiva industrin och dess betydelse för det globala klimatet, eftersom det under denna period lett till ökade koldioxidutsläpp globalt att flytta energiintensiv produktion till utvecklingsländer. En slutsats blir därför att Sverige och EU behöver stödja och främja sina energiintensiva industrier, eftersom en minskning av dessa sektorer i Europa under nuvarande förhållanden skulle innebära en klimatförlust för hela världen.

Summary

In the past, Sweden has shown some significant advantage in carbon intensity of its production as well as exports, an advantage which is to some degree a consequence of the country's specific electricity transformation system. This paper introduces a new concept of *comparative carbon advantage* as a potential climate mitigation tool. Through the exploitation of cross-country sectoral differences in carbon intensity, increased industrial concentration and export intensification can lead to welfare gains in terms of reduced global carbon emissions. The paper utilizes annual data between 1995 and 2008 in order to observe possible pattern of change within a period which has often been referred to as an era of 'decoupling' (continuous economic growth in a time of absolute reductions in territorial carbon emissions). Overall, Sweden contributed nearly 590 million tons of CO_2 potential savings through its exports by having an efficient and low-carbon production. This total amount of 590 million tons of CO_2 relates to the total savings made if the same amount of Swedish exports was produced using the world average technology. Furthermore this report analyzes and quantifies the contribution of efficient electricity generation to Sweden's comparative carbon advantage. Carbon-free electricity generation accounted for over 34% of the total savings, of which some 20% were direct exports of electricity and 80% was electricity embodied in exported products. This research provides a critical understanding of the impact of efficient and low carbon electricity in generating relative *comparative carbon advantage* – a policy relevant aspect in the only increasing global trade. Last, it provides evidence in support of European heavy industry and its importance for the global climate as moving energy-intensive production to developing countries will inevitably lead to higher carbon emissions. Sweden and the EU needs to more proactively support and promote its energy-intensive industries, because simply closing those sectors down would also mean a climate loss for the whole world.

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1 Background

The urgency of climate change and the need of the world leaders to adopt ambitious while realistic climate goals are rarely questioned, often fueled by the growing material and energy consumption associated with low-income countries adopting Western patterns of consumption (Nielsen, 2017). There is little doubt that the world's energy needs will only continue to grow in the future to a magnitude never previously experienced on planet Earth. Continued increase in global emissions is expected to be driven by growth in global population and economic growth (IPCC, 2014). It has been shown that between 1995 and 2008, increases in carbon dioxide emissions in both advanced and emerging economies were linked to rising levels of domestic consumption (de Vries and Ferrarini, 2017). Increasingly, much of the consumption induced by increases in per capita incomes is satisfied by foreign produced goods (de Vries and Ferrarini, 2017). International trade has, indeed, become the fastest growing driver of global carbon emissions (Liu et al., 2016).

Generally, the world is intensifying its efforts to reduce carbon emissions, though much of the efforts remain localized in a handful of regulated countries. The current absence of a global effort to curb the GHG emissions thus becomes increasingly problematic in a world with virtually free trade and carbon emissions embodied in traded goods. As a result, there is a danger that emission reductions in regulated countries become offset (or exceeded) by emission increases in unregulated areas. If this is the case, then any national efforts in lowering emissions may be undermined. So far, much attention has been devoted to the studies on the potential danger of carbon leakage (Ghertner and Fripp, 2007; Pan et al., 2008; Suri and Chapman, 1998; Weber et al., 2008). However, trade does not only lead to geographical shifts in global production and structural change. Trade can also contribute to reduced global emissions if countries with access to low carbon energy and energy efficient production that are normally associated with very high energy intensity, are the exporting parties. Thus national efforts can contribute positively to the global climate if production takes place in more carbon-efficient countries as this could potentially lead to a net decline in global emissions.

The major motivation of this research paper is to quantify the magnitude of potential carbon savings if trade patterns increasingly exploit national differences in carbon intensity. The focus will be on the role of efficiency and decarbonisation in Sweden and its impact on the embodied emissions in its trade. Sweden is a particularly interesting case as it is a country with good access to cheap and virtually carbon-free electricity as well as substantial exporter of energy-intensive industrial goods. In 2008, the Swedish carbon intensity was $\frac{1}{5}$ of the European average carbon intensity and less than $\frac{1}{10}$ of the global average.

The major economic theory is that countries with a comparative carbon advantage in one specific sector can have a beneficial effect on the global environment by focusing on the exports from this sector. Sweden, for example, with its ambitious environmental protection laws, could possibly contribute to 'welfare gains in terms of reduced global carbon emissions by exploiting differences in sectoral carbon efficiency through international trade' (Kander et al., 2015). It is the aim of this paper to further identify those sectors which have been the major drivers of the welfare gains in the past, but also show which sectors are likely to make the most contribution in absolute levels if efficiency improvements are more focused. Contrary to other paper, the role of **trade is thus studied as a potential climate mitigation tool.**

2 Introduction and debates

With the prospects of future increases in energy use and its associated emissions, there are two large streams of research, each of which aims for the reduction of the negative consequences of our energy use: making more economic use of the existing energy resources (efficiency) and gradual transition to low carbon energy resources (sustainable transition). It has also become clear that a sustainable transition does not only involve the transition to a fossil fuel-free society but is also largely embedded in other areas, such as technological, social, institutional and economic change (Geels, 2011; Grübler, 2012).

But it becomes problematic if these efforts in limiting future emissions of GHG remain limited to a handful of countries, as trade may erase any efficiency improvements achieved. Within this research paper we argue that trade (and the predicted future increase in the global trade flows) can also be used as a climate mitigation tool. This is because there is a potential to limit the global GHG emissions if countries increasingly exploit the national differences in efficiency and carbon-intensity levels of its traded goods.

This paper studies and quantifies the global environmental benefits of Sweden's exposure to foreign trade. The role of foreign trade as a possible emission reduction tool has rarely been explored in the past, but the continuous rise in emissions (and energy) embodied in foreign trade provides an important motive to study this phenomenon further. It is the aim of this paper to quantify the benefits of Swedish trade given the country's high efficiency and low-carbon energy system.

2.1 EFFICIENT AND DECARBONISED ECONOMY

2.1.1 Efficiency

Historically, there have been substantial differences in the efficiency of global production, particularly in energy and carbon efficiency. After 1970, energy productivity differences across countries are larger than the differences in labor productivity (Mulder and de Groot, 2004). Indeed, although there has been some degree of energy productivity convergence in world manufacturing sectors since 1970 and particularly after 1990s, the cross-country differences in the utilization of energy, and resources in general, remain larger than those in labor productivity (Mulder, 2015; Mulder and de Groot, 2004; Schandl and West, 2010). The cross-country variations in energy productivity are often closely related to cross-country difference in carbon efficiency (Fischedick et al., 2014).

2.1.2 Decarbonisation and the role of electricity

Decarbonisation of the economy is one of the prerequisites of meeting our climate objectives. Decarbonisation can be induced through increased energy efficiency, material efficiency and the decarbonisation of the energy system (low-carbon energy production or CCS) (Lechtenböhmer et al., 2016). It was thus proposed, that an increased electrification of the major energy-intensive processes could be one of the potential drivers of the decarbonisation of the economy. Previous research has shown that improvements in energy efficiency through applying best available technology in industry can potentially reduce the energy intensity by 20-25 percent, before the limit for maximum energy efficiency is exhausted. Even though, this represents potentially satisfactory levels of carbon efficiency, clearly other mechanisms will need to be employed. The increased deployment of bioenergy and the diffusion of the CCS technology have been explored in other studies as a potential to combat some of the share of the carbon emissions (Fischedick et al., 2014). Although the potential for savings, as the results show, have been found substantial for the four most energy intensive industrial sectors (cement, iron and steel, chemicals and paper and pulp) and in a range of 70-90 percent reduction of the sectoral carbon emissions, the feasibility of this large-scale transformation remains uncertain.

In the light of this development, an attempt has been made to model the potential carbon savings if electricity is increasingly used in the energy and feedstock supply for the production of seven key basic materials in EU28 (Lechtenböhmer et al., 2016). Clearly, to be beneficial in terms of carbon reductions, this scenario would be pursued under the condition that much of the electricity would be produced using renewable sources. In a what-if simulation, the authors argue that all energy and feedstock needs can be substituted by electricity produced from low-carbon sources and the potential for future decarbonisation of the EU28 industrial sector are thus large (Lechtenböhmer et al., 2016). Electricity can thus be seen as the main future energy carrier in a decarbonised world (ibid). Although feasible, this further electrification of the industrial processes would result in tremendous demands on electricity production and an integration and adaptation of the existing electricity system would be necessary. It would also entail 'substantial changes in relative prices for electricity and hydrocarbon fuels' (Lechtenböhmer et al., 2016).

In terms of comparative carbon advantage, the further electrification of the Swedish industrial production would likely be an important driver of the increases in the comparative carbon advantage. The replacement of primary energy, predominantly fossil-fuel based, of the major export industries would clearly place the carbon advantage of the Swedish goods on the carbon efficiency frontier, while at the same time further deepening the potential of carbon savings at a global level if the most carbon efficient sectors are further explored. Especially, the substitution of coke for new reduction agents (for example the use of hydrogen to reduce iron ore) would be revolutionary to the carbon intensity of the sector, in which at a moment 80 percent of emissions come the consumption of coal as a reduction agent only.

2.2 COMPARATIVE (CARBON) ADVANTAGE

The concept of comparative advantage dates back more than two centuries. According to the Ricardian theory, it is mainly the relative differences in countries' abilities to produce goods and services that determine their pattern of trade (OECD, 2011). It is therefore not the absolute costs of production given by the countries' factor endowments, but rather how these opportunity costs compare across countries. Countries can then benefit from the increased openness to trade through specialization in goods in which they are relatively more productive (have comparative advantage) and importing other goods where they lack this comparative advantage. This can, in turn, allow for increased economies of scale and further improvements in its comparative advantage, the so called 'gains from trade'. The concept has also been used for domestic policies such as import tariffs or infant industry protection (OECD, 2011), often implemented under more restrictive protectionist regimes. Through these measures, countries could protect their domestic production or establishment of new industries.

Sources of comparative advantage are often dynamic and complex, but often a result of specific factor endowments required for the production, stemming from the constant interaction between the industries and countries and their ability to provide these requirements. It is thus differences in relative factor endowments across countries which have been proposed as the major source of comparative advantage (OECD, 2011). If a country has a relative abundance of unskilled labor, the country will more likely specialize in the production and exports of labor-intensive goods etc.

But comparative advantage in carbon efficient production – one that is characteristic for countries such as Sweden – is often a costly measure and in a sense not an advantage when compared to other countries as the additional costs may lead to the loss of competitiveness in the international markets. Not even in the presence of carbon cap and trade schemes (such as EU-ETS), the more carbon efficient production will often be poorly positioned due to oversupply of the emission allowances (given the uncertainties in the future emissions) and consequently low carbon prices. To limit the competitiveness effect and prevent carbon leakage in the absence of realistic carbon prices, border carbon adjustments (BCA) have flooded the political debates in recent years. Although some argue that BCAs may result in trade wars while having only a very limiting impact on the global climate gains, other proponents highlight the ability of BCA to enhance the competitiveness of domestic firms, especially energy-intensive and trade-exposed industries (Condon and Ignaciuk, 2013). Imposing border carbon adjustment on certain goods would then lead to additional costs and make the European market less attractive to a number of countries given their high energy intensity. A simulation exercise has shown that the total sales of EU firms (to domestic and foreign consumers) increase if BCA measures are implemented as opposed to situation without such measures (Kuik and Hofkes, 2010). On the other hand, there are some significant re-distributional effects associated with BCAs as changes in the terms-of-trade against the developing world shift the burden of emissions abatement to developing countries which in turn further intensifies existing income inequalities (Böhringer et al., 2012).

Despite these shortcomings, this paper introduces a new concept of **comparative carbon advantage**. This concept entails very much the same characteristics as that of comparative advantage. Sources of comparative carbon advantage are then a result of the interaction between industries and the governments, and conditioned upon the availability of factor endowments in relation to other countries. Importantly the gains from specific factor endowments (low-carbon energy reserves such as solar, wind, nuclear, hydro or geothermal) are exploited only in collaboration with often stringent environmental regulation and national climate targets.

In the Swedish case the sources of comparative carbon advantage could be summarized as a dynamic interaction between the legislative forces and industries (stretching for number of decades), together with the availability of relatively cheap and carbon-free electricity. Especially, the role of electricity has been important in case of Sweden. Historically, Sweden had some of the world's lowest electricity prices with a bulk of electricity produced in carbon-free hydropower and a large nuclear power plants. This has contributed to the competitiveness of Swedish electricity-intensive industries in an international perspective. Comparative carbon advantage thus relates to the differences in cross-country carbon efficiency of production. Other example of a country which exploits its comparative carbon advantage is Iceland. This small, export-driven economy in the Atlantic Ocean has access to hydro and geothermal power and has used this specific factor endowment for aluminium smelting. In fact, in Iceland aluminum smelting accounts for up to 90% of total electricity consumption. The flow of foreign investment in aluminium smelting was, however, still very much a result of government negotiations and bargaining starting already during 1960s (Skúlason and Hayter, 1998).

The interaction between the industry and the government can thus be seen as an important aspect of the comparative carbon advantage. This is because this interaction precedes the actual firms’ decision on industrial location by establishing the renewable infrastructure and designing efficiency frameworks, but also at a later stage regulates other further environmental consequences of the increased concentration of energy intensive sectors (such as hazardous waste etc).

2.3 ENVIRONMENTAL POLICY AND COMPARATIVE ADVANTAGE

Commonly, stringent environmental regulation has been perceived as having detrimental properties on the levels of global competitiveness. Environmental regulations impose costly adjustments, often leading to slower productivity growth and reduced competitiveness in the international markets (Jaffe et al., 1995). Forcing companies to adapt to more stringent rules and limit the amount of negative externalities produced has been perceived as a driver of reduced profits (Ambec et al., 2013). This has been a common belief among academics and policy makers until the publication of, what has since been referred to, the Porter’s hypothesis (1991). In the past, Porter has not only pioneered the field of global comparative advantage, his 1991 contribution to the Scientific American radically transformed the field. According to Porter, ‘strict environmental regulations do not inevitably hinder competitive advantage against rivals; indeed, they often enhance it’ but the evidence remains mixed (Porter, 1991). In Sweden, assessing the static and dynamic effects of environmental policy on productivity among industries has, for example, not confirmed the Porter hypothesis (Broberg et al., 2013). On the contrary, stringent environmental regulation was found to lead to efficiency losses, particularly in the paper and pulp sector which is one of the most environmentally regulated sectors of the Swedish economy (Broberg et al., 2013).

Carbon tariffs are intended to discourage emissions of carbon in foreign-produced goods by placing additional tariffs on goods imported from mainly unregulated areas (countries lacking in the adoption of environmental legislation). Among climate-aware countries, carbon tariffs represent a popular policy instrument as it offers regulated a way to "protect the competitiveness of energy-intensive, trade-exposed industries" (Böhringer et al., 2016).

2.4 TRADE – HOW BAD IT IS FOR THE ENVIRONMENT

The magnitude of international trade has increased substantially and so has the amount of energy and emissions embodied in trade. Between 1970 and 2009, the global trade increased by some 7% annually (World Trade Organization, 2013). Numerous studies emerged over the last decades to quantify the energy and carbon content of the increased trade flows. In general, most studies find that developed countries are often net importers of embodied emissions while developing countries are net exporters. Clearly, this poses a threat to any ambitious global sustainability goals as this could potentially mean that the developed world is basically only shifting emissions to other countries, and not necessarily solving the urgency of global climate change. This occurs if much of the production is shifted to countries which lack stringent environmental legislation and efficient modes of production, where relative carbon intensity is far higher than that of the developed countries. The role of foreign trade has therefore numerous times been put forward as one of the possible drivers of the relative decoupling of economic growth from domestic energy consumption. In the past, energy use, emissions and economic growth were closely related; though since 1970s the growth in absolute energy consumption slowed down while economic growth continued its rise. Structural change (away from heavy energy-intensive industrial production towards more light industries) together with the technological change (the efficiency in energy use) have been put forward as the prime drivers of this decoupling in the developed world, while the evidence of the increased engagement in foreign trade (and with it the danger of outsourcing) showed conflicting results.

2.5 SHIFTING TRADE PATTERNS

Optimal resource allocation and its consequences for the global CO_2 emissions have been studied in the past few years. Fujii and Managi, for example, assess the CO_2 emissions reduction potential for 13 manufacturing sectors in 39 countries between 1995 and 2009 (Fujii and Managi, 2015). The authors' major motivation lies in the fact that firms can reallocate its production to other countries, often cost-driven but also due to changes in the environmental legislation. This option can naturally be taken into account when designing national emissions reductions targets, but it can also be used to study the potential effects of more effective resource reallocation in a search to limit the global carbon emissions. This would imply that firms can relocate their production to countries which are more carbon efficient and this has in turn a reducing effect on the global carbon emissions. The optimal level of the production reallocation would then be determined by production technology, capacity, and environmental policy regarding CO_2

emissions in the respective countries (Fujii and Managi, 2015). Through the application of a DEA model (Data Envelopment Analysis), the authors calculate the optimal level of resource reallocation on CO_2 emissions and quantify the potential CO_2 savings if production was reallocated to the most efficient countries. This exercise has shown that applying optimal production resource reallocation has a reduction potential of 2.54 Gt-CO_2 in the year 2009. The largest potential to reduce CO_2 emissions was then identified in case of former communist countries; in sectoral analysis the potential was the largest in basic material industry including chemical and steel sectors (Fujii and Managi, 2015).

Shifting trade patterns in order to reduce global carbon emissions was also studied by Strømman and colleagues (Strømman et al., 2009) in an illustrative exercise in which the authors analyze how changes in the geographic distribution of production would reduce global carbon emissions. The authors find that in a global model with tighter carbon constraints, some production located in carbon intensive economies has moved, as countries lost their comparative advantage to economies using cleaner fuels and/or more energy efficient technologies.

Clearly, a follow up question arises as to what extent production resources reallocation is realistic in the global world. This is because any large scale reallocation of a country's production will have some dynamic effects on the overarching economic structures, in particular social implications in form of increased unemployment or incomes from corporate taxation (Fujii and Managi, 2015). Also, the increased production concentration in some countries might lead to growth in trade and thus an increase in trade-related CO_2 emissions. Last, the study does not include the electricity sector from being traded, either directly in exports of electricity or indirectly as electricity embodied in the manufacturing goods. As the empirical results of this paper show, this omission might change the overall results especially for countries with fossil-fuel based electricity transformation sector, as electricity intensity of some manufacturing sectors is very high. For example the production of electronic goods is primarily using electricity as one important input factor, though in the traditional accounts of carbon intensity (CO_2 emissions/produced unit) related to the actual production of the electricity are not considered.

3 Methods

3.1 NAVIGATING THROUGH THE CARBON ACCOUNTING FRAMEWORKS

As a result of the continuous expansion of global trade and its impact on the global carbon emission levels, researchers have ventured into integrating carbon emission transfers into the actual policy-making (Springmann, 2014). Besides traditional consumption-based accounting (CBA), multiple versions of other approaches surfaced in the past decade even though the current UN emission scheme remains confined to only those emissions which incurred during the production process within a country (PBA) (Steininger et al., 2016). There are multiple versions of the carbon accounting frameworks which can be divided into three methodological approaches (ibid). Let’s imagine global production of goods as a supply chain of activities which take place across countries. First, the emissions can be attributed to the country which extracted the fossil fuels and thus allowed for the actual carbon emissions to occur (extraction based approach), which is the extreme downstream approach accounting for carbon emissions. Moving up through the value chain brings us to the second major approach, which takes into account that countries do indeed benefit from being engaged in polluting production activities (mainly by earning income) and should therefore be responsible for those emissions according to the value they have produced in the production (Steininger et al., 2016). Third, and last major approach, reaches the very end of the supply chain – the actual final user and its country of residency. This usually relates to various measure of consumer based accounting (CBA), which has been widely discussed in a literature, but never implemented in practice or for climate mitigation targets (ibid).

3.1.1 Consumption-based approaches

Although there have been heated debates around the need for new measures of national carbon accounting which would take into account the country’s actual consumption pattern (CBA), climate negotiations targets remain set to production based accounting methods (PBA). The major drawback of the PBA perspective is the fact that it does encourage displacement or carbon leakage as countries simply relocate part of its production abroad. At the same time, countries producing export goods are being penalized for doing so (Grasso and Roberts, 2014). Additionally, as empirical evidence have shown this relocation of carbon-intensive production to the often emerging economies can lead to even larger emissions, as developing countries are more likely to lack the most energy and carbon efficient technologies of the developed world. This difference in energy and carbon intensity between countries does not only raise the global carbon emissions, but also penalizes countries with ‘cleaner’ production and stricter environmental regulation (Kander et al., 2015).

3.1.2 Adjusted consumption-based approach

The method employed in this paper departs from the consumption-based approach of carbon accounting (CBA). According to traditional CBA, countries should not only be responsible for the emissions of their domestic production but also for the emissions embodied in imports which are then consumed domestically. The introduction of CBA approach was largely due to the fact that policy makers and academics became concerned about the absolute improvements in domestic carbon emissions and were puzzled to what degree these domestic improvements are due to carbon leakage to other countries. The basic formula of the CBA approach thus considers the flow of CO_2 emissions which are finally consumed within a country and is a sum of territorial emissions or PBA (production-based emissions) and emissions embodied in imports, from which emissions embodied in exports are deducted:

$$CBA^s = \sum_i f_s^i + \sum_{i,r\neq s} q_i^r \neq x_i^{rs} - \sum_{i,r\neq s} q_i^s \neq x_i^{sr} \qquad (1)$$

Where f_s^i refers to direct emissions, q is an emissions multiplier, ≠ is elementwise multiplication, x_i^{sr} is the output from production sector i in country s that is produced for final consumption in country r.

To emissions multiplier is then calculated simply by dividing the direct emissions with total output allocated amongst all final consumers for the relevant sector as shown in equation 2. According to equation 2, y is defined as a collection of final demand bundles and L is the classical Leontief inverse, $L = (I - Z\hat{k}^{-1})^{-1}$, where I is the identity matrix, Z is a multi-region input-output table of economic flows between countries and sectors, $\hat{k}$ is the diagonal of k, and k_i records gross output of sector i.

$$q_i^s = \frac{f_i^s}{\sum_r x_i^{sr}} = \frac{f_i^s}{\sum_{j,t} L_{ij}^{st} y_j^{tr}} \qquad (2)$$

The major advantage of this approach is the fact that countries are now also made accountable for the emissions embodied in the import of goods which are then consumed domestically. Obviously, this is a very valid concept which shifts responsibility onto the final consumer. Consumption can then be seen as one of the potential factors which nations can influence, either through changes in absolute volumes or its composition. But as Kander et al. (Kander et al., 2015) has shown, although the CBA concept captures the changes in domestic consumption which a nation can influence, it does not capture a country's efforts to improve its domestic carbon efficiency (only efficiency improvements that relate to domestic consumption). In the CBA concept, thus, two countries trading identical product (let's say one ton of steel) may look entirely different in the balance of emissions in trade. Sweden, an example of energy efficient low-carbon economy produces one ton of steel with considerably lower CO_2 emissions than for example China. If those two countries, Sweden and China, then only trade in one specific good and exchange equal amounts of steel, Sweden becomes a net carbon importer while China will be a net carbon exporter. In this respect, energy and carbon efficient Sweden would be penalized for exporting its carbon efficient steel as its CBA carbon balance would be larger than its PBA emissions (and conversely for China where responsibility for inefficient carbon-intensive steel production was shifted onto Sweden). Therefore, Kander et al. (Kander et al., 2015) developed an adjustment to the traditional CBA accounting of emissions to accommodate for technology differences between countries. In the adjusted CBA framework (the technologically adjusted CBA or TCBA), the emissions multiplier is calculated using the world average technology instead of the specific carbon intensity of the domestic production:

$$TCBA^s = \sum_i f_i^s + \overbrace{\underbrace{\sum_{i,r\neq s} q_i^r \# x_i^{rs}}_{\text{imports}} - \underbrace{\sum_{i,r\neq s} \dot{q}_i \# x_i^{sr}}_{\text{exports}}}^{\text{net trade balance}} \qquad (2)$$

Where the emissions multiplier is calculated $\dot{q}_i = \frac{\sum_{s,r\neq s} q_i^s \neq x_i^{sr}}{\sum_{s,r\neq s} x_i^{sr}}$

The use of world average technology (and thus world average emissions) can be understood as emissions which would have occurred if the traded good was not produced in a specific country. For countries like Sweden which have an efficient and low-carbon production the amount of emissions embodied in exports would therefore increase (as world average carbon intensity is higher than Swedish carbon intensity). Higher volumes of emissions in exports would then, following the equation 2, lead to lower balance of TCBA. Conversely, for countries with polluting production, the level of TCBA would then increase.

$$NEGA_i^s = CBA_i^s - TCBA_i^s \qquad (3)$$

The difference between the newly computed TCBA and the traditional CBA approach has been named NEGA emissions (Kander et al., 2015). NEGA is a measure of global emissions that have not occurred as a result of production being relocated to a less, instead of a more, carbon-intensive country. NEGA emissions can be both positive (credits) as well as negative (penalties). In the above mentioned comparison of Sweden and China, Swedish TCBA would be lower than it's CBA and Sweden would receive NEGA credits (a 'reward' for having a better than world average carbon efficiency). China, on the other hand, would be partly made responsible for its carbon intensive production of steel and its TCBA would be higher than the traditional CBA approach. Importantly, the sum of all NEGA credits and penalties at a global scale equals 0, and the sum of all nations' CBA equals a sum of all nations' TCBA. Figure 1 shows the results of the new technology-adjusted carbon footprints for Sweden.

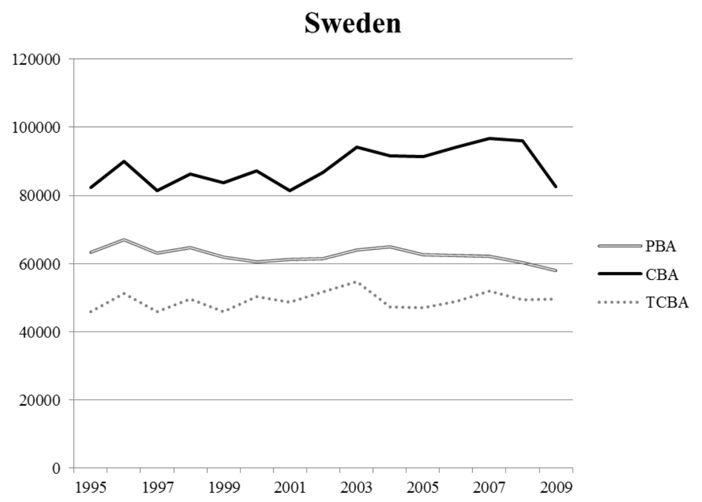


Fig. 1 Technology-adjusted CO_2 footprints (TCBA) of Sweden compared to national territorial emissions (PBA) and national carbon footprints (CBA).

In the case of Sweden, the difference between CBA and TCBA is positive and Sweden thus has NEGA credits for its efficient production. In other words, the amount of the NEGA credits corresponds to the amount of emissions which did not occur owing to the Swedish comparatively more climate-efficient exports. But overall, while Sweden has recorded substantially high NEGA credits throughout the period of study (1995-2009), the amount of NEGA credits might differ per industrial sector.

3.1.3 Adjusted consumption-based approach with electricity

An initial investigation into the sectoral composition of NEGA credits in Swedish exports, however, assigns the largest contribution to the electricity transformation sector (as is the case for the global perspective as well – see Fig. 2). This is because electricity sector is treated as any other productive sector, though much of its production is embodied in the production of final goods / exports.

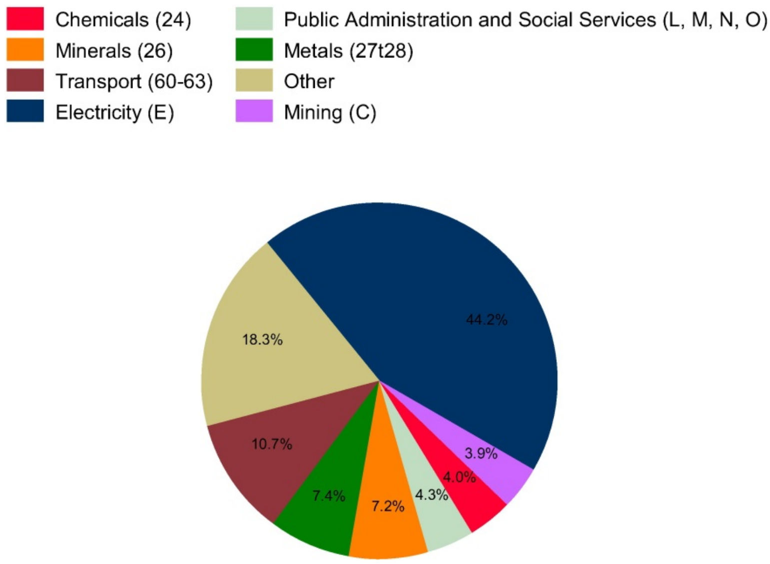


Fig. 2 Global CO_2 emissions by sector in 2008

Source: (de Vries and Ferrarini, 2017) based on WIOD (Timmer et al., 2015) (including 40 world economies)

Within a traditional I-O framework, the largest share of improvements in electricity generation is assigned to the utilities sector. This is because electricity assigned to other sectors such as paper and pulp or iron and steel only includes direct emissions, whereas emissions embodied in the actual electricity generation (the indirect emissions) are allocated to the electricity generation sector. As a result, efficiency gains in electricity generation are visible primarily in the utilities sector while gains from electricity use in the manufacturing sectors and others remain understated. This may be a problematic assumption when quantifying gains from electricity consumption in the Swedish industry and its exports. The method employed in this paper follows production from each sector downstream to final consumer and everything that is finally consumed abroad is treated as exported. To address this issue, indirect emissions of electricity generation were redistributed to each economic sector in order to capture the combined emissions of each sector. Simultaneously, the same proportion of carbon was deducted from the Electricity generating as total emissions of the Swedish economy need to remain equal after redistributing emissions to other sectors.

To capture the real contribution of Swedish low-carbon electricity, the NEGA credits from the electricity production sector were redistributed to the respective productive sectors according to the logic outlined in Figure 2 and following:

$$NEGA_i^s = NEGA_i^s + \dot{\sum}_{\iota,r\neq s} NEG\dot{A}_{elect}^r \neq x_i^{rs} \qquad (4)$$

Where $NEGA_i^s$ is the previously defined measure of global emissions that have not occurred as a result of production being relocated to a less, instead of a more, carbon-intensive country and which are the sum of the direct NEGA emissions which occurred at the individual sector and the secondary $NEGA_{elect}^r$ emissions which are a result of the Swedish carbon-free electricity production and which are assigned to the specific consuming sectors. Overall NEGA emissions, be it from direct primary energy sectoral consumption as well as from the electricity sectors can be both positive (credits) as well as negative (penalties) depending on the specifics of the national energy system.

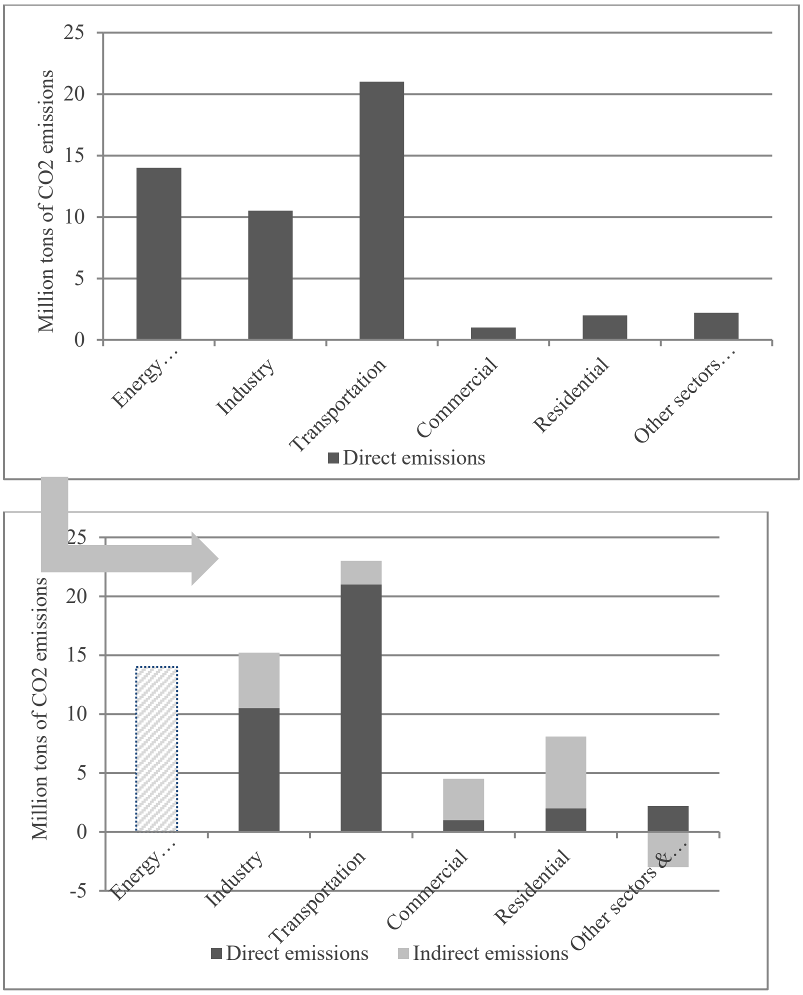


Fig. 3 Re-distributing emissions from the utilities sector to the productive sectors (an illustrative example based European Energy Agency data)

The reallocation of the NEGA credits from the electricity transformation sector to the productive sectors had two major consequences:

(1) The magnitude of the NEGA credits from the electricity generating sector decreased substantially. The remaining NEGA credits which can still be seen as reported in the Results section are NEGA credits embodied in the exports of electricity, so only foreign sales of Swedish produced electricity (here the final product exported is the electricity, and not a product with embodied electricity as is the case for the remaining sectors).

(2) On the other hand, other productive sectors will increase their absolute volumes of NEGA credits, which is a sum of NEGA credits stemming from the primary energy consumption and the NEGA credits from the outsourced / purchased in electricity.

It is one of the core arguments of this paper that reallocation of NEGA credits is important to fully capture the climate-effectiveness of Swedish export sectors.

4 Results

4.1 OVERALL NEGA CREDITS

The overall results of the NEGA credits of Swedish productive sectors can be seen in a cumulative form in Figure 4 and as annual data for three benchmark years in Figure 5, together with the absolute levels of exports (in bil. USD). The results are shown only for three benchmark years 1995, 2002 and 2008 (other years are available upon request). Due to the onset of the global financial crisis, the year 2009 as the final year of observation in our data was excluded and 2008 was used instead. It can be observed that after reallocating NEGA credits from the electricity transformation sector, the sector's NEGA credits diminish substantially and the final results reflect only NEGA credits from direct export of electricity. On the other hand, some sectors increase their absolute levels of NEGA credits even further after reallocation. In absolute terms, those sectors which increase their NEGA credits the most include clearly the paper and pulp as well as basic metals in all three benchmark years. Other substantial improvements are also visible in the production of chemicals and transport and electrical equipment.

For the export volumes, Sweden has generated most exports in the transport equipment sector, followed by electrical equipment and machinery. The traditional Swedish productive sectors of basic metals and paper and pulp also recorded significant trade volumes. Overall, one can see that the volumes of exports have been increasing but accelerated especially after 2002 with 2008 being one of the record years in Swedish exports. The year 2009 brought about disruptions to the volumes of Swedish exports due to the international financial crisis and this is also a major reason for why we have omitted this year from further analysis.

Overall, Sweden 'generated' over 36 million tons of NEGA credits in 1995 which could also be expressed as the amount of emissions saved as a result of Swedish efficient and low-carbon production. Due to the further expansion of Swedish exports, this has further increased to well over 46 million tons of CO_2 by 2008. Within the whole period of 1995-2009, the amount of emissions saved globally due to Sweden's more efficient and low carbon production reached a cumulative total of nearly 590 million tons of CO_2, emissions which would have otherwise released into the atmosphere if the same amount of production occurred using the world average technology instead of the specific Swedish production system. To put this into perspective, this cumulative volume of 580 million of CO_2 (which were prevented between 1995 and 2009) can be compared to the total CO_2 emissions of EU28 in 2014 which was over 4,000 million tons of CO_2, so roughly 15% of the total. This represents a relatively high share considering the fact that Swedish economy accounts for roughly 3% of the European GDP.

Before redistributing of the NEGA credits, much of the total accumulated 590 million tons of CO_2 savings originated in the electricity sector (34%). Figure 3 shows the relative sectoral shares of the total NEGA credits accumulated throughout the period of study and how these shares change once electricity is assigned to the final consuming sectors.

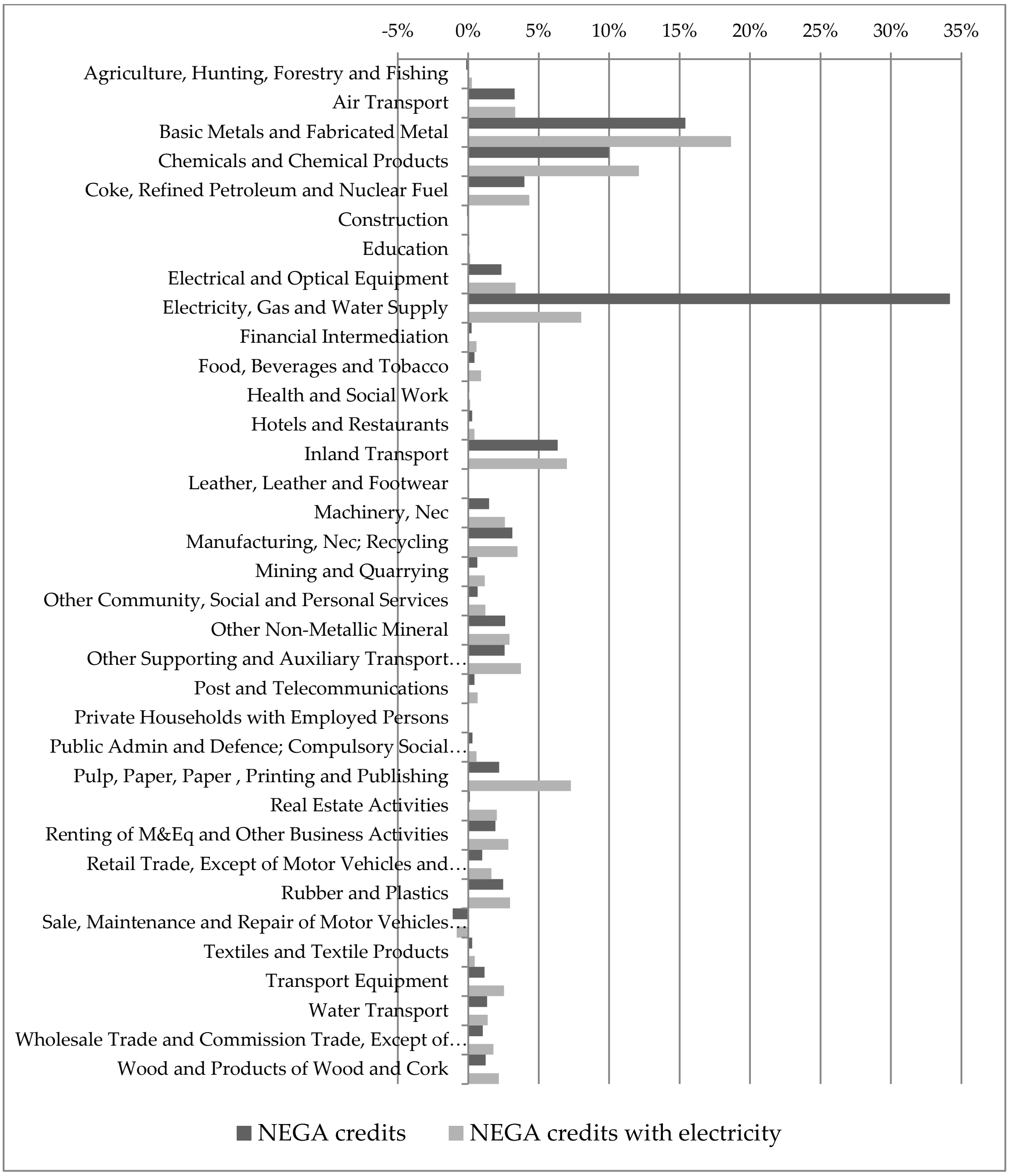


Fig. 4 Accumulated NEGA credits of Sweden between 1995-2009 by sectoral share (%)

Source: Own calculations based on WIOD (Timmer et al., 2015)

Of the absolute total of 590 million tons of CO_2 saved (as NEGA credits), the Swedish exports of steel accounted for the largest share with a contribution at nearly 20% of total NEGA credits generated between 1995 and 2009 (this is including primary energy combustion as well as electricity embodied in final produce). The other important sectors were the chemicals (12% of the total of cumulative NEGA credits), pulp and paper (8%) and electricity (8%). Here electricity relates only to exports of electricity where electricity is the final product and not electricity embodied in exports of other goods.

Figure 5 shows absolute levels of sectoral climate gains from NEGA credits for the respective three benchmark years 1995, 2002 and 2008. Of the total NEGA credits generated in 1995, 27 percent originated from the electricity transformation sector. In 2002 and 2008, the contribution of the electricity generation sector to the overall number of NEGA credits was 26 and 28 percent respectively.

Figure 6 then shows the annual developments in total NEGA credits and the share of which that can be attributed to the Swedish carbon-free electricity. The decline in the total amount of NEGA credits in 2009 is entirely due to the drop in Swedish exports as a result of the global financial crisis.

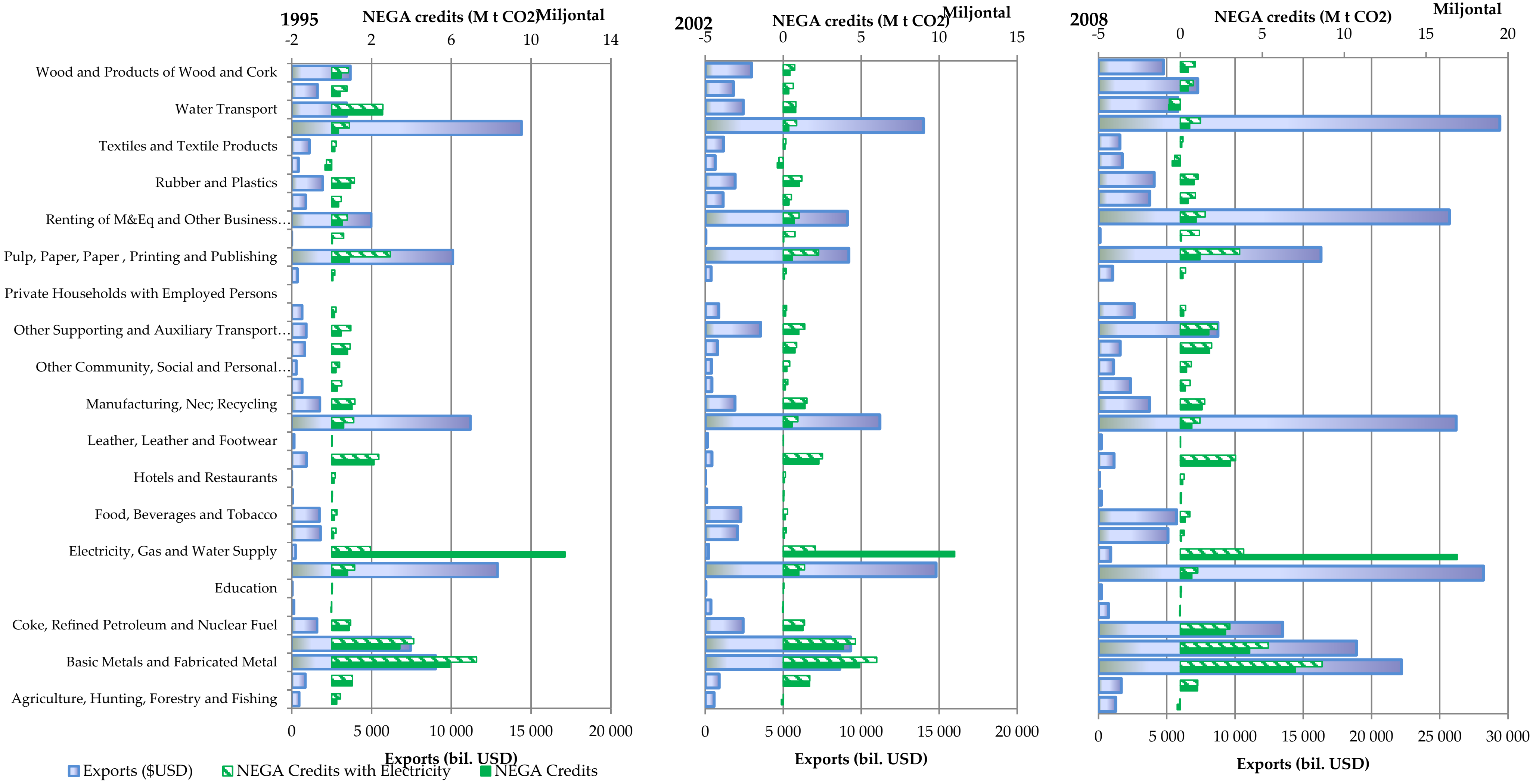


Fig. 5 The distribution of NEGA credits per productive sector in Sweden in 1995, 2002 and 2008. NEGA credits in mil. ton of CO_2 before electricity reallocation (green) and after reallocation of NEGA credits from the electricity production (dashed green).

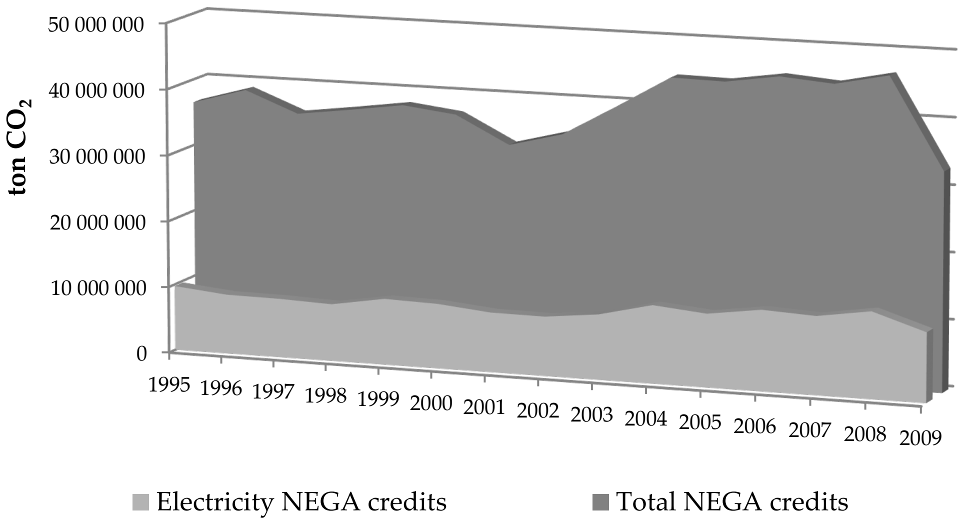


Fig. 6 NEGA credits in the Swedish exports (total NEGA) and of which embodied NEGA credits from electricity consumption (electricity NEGA).

4.2 COMPARATIVE PERSPECTIVE

Figure 6 illustrates how Sweden compares to other countries in respect to total NEGA credits and the contribution of the electricity sector to the total NEGA credits. Negative signs for certain countries can be interpreted as NEGA penalties, where respective countries exported goods manufactured with worse than world average technology. Within the concept of NEGA credits, countries can thus be penalized for not having carbon efficient production and this is then reflected in the negative values for the obtained NEGA credits.

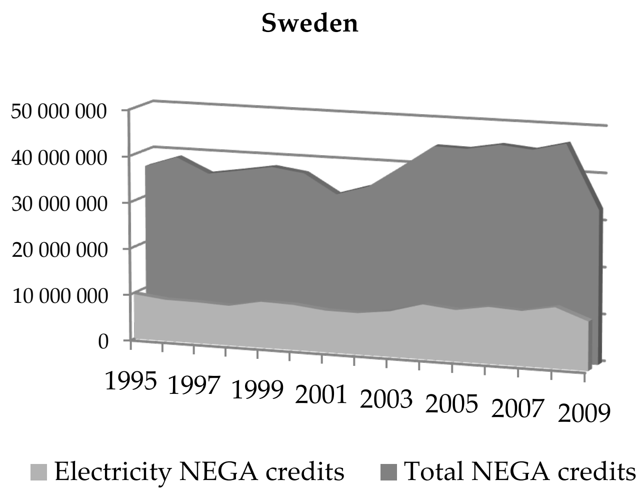
Generally, in line with previous research (Kander et al., 2015), European countries have on average more carbon efficient production and this can be seen in the relative surplus of NEGA credits. On the other hands, countries differ to what extent these NEGA credits can be attributed to low-carbon electricity production. Sweden has, for example a relatively significant proportion of NEGA credits in exports due to its specific electricity production system (between 26 and 28 percent of all total NEGA credits in 1995-2009). Denmark and Germany, on the other hand also generate NEGA credits but much less so due to their higher carbon emitting electricity sectors. The share of electricity in the total NEGA credits was on average 11 percent in Denmark and 21 percent in Germany throughout the period of study. One exception is the year 2008, where temporarily electricity's contribution to the total NEGA emissions increased to over 50 percent, both driven by drastic decline in NEGA credits from primary energy consumption and an increase in electricity NEGA credits. For a full understanding of this deviation, however, a more thorough sectoral decomposition would be required.

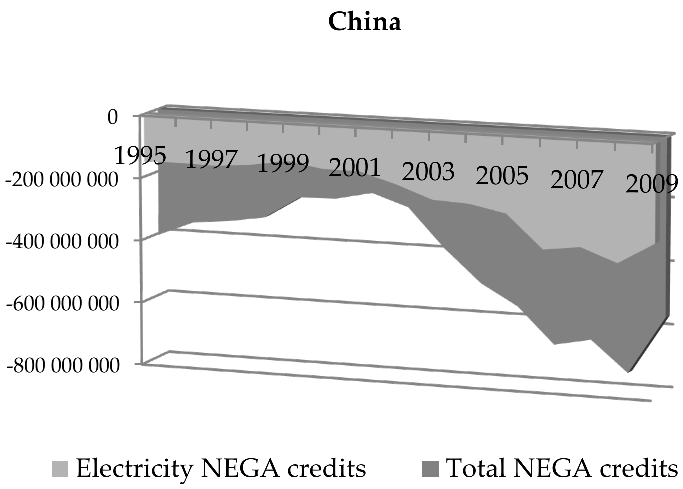
Czech Republic illustrates an interesting example of how legislative changes can alter the picture. While the country has always been a net exporter of embodied energy, the relative high carbon intensity (at least compared to the world average) led to NEGA penalties well into 2002 (Nielsen, 2016). The newly acquired membership of the EU with its legislative pressures on efficiency improvements and the further expansion of volumes of the Czech exports, led to an increase in the absolute levels of NEGA credits. This transition from NEGA penalties to NEGA credits of the Czech exports was also driven by the declining share of coal-fired electricity production. Between 1995 and 2009, the share of coal in electricity generation in the Czech Republic declined from 74 to 59 percent.

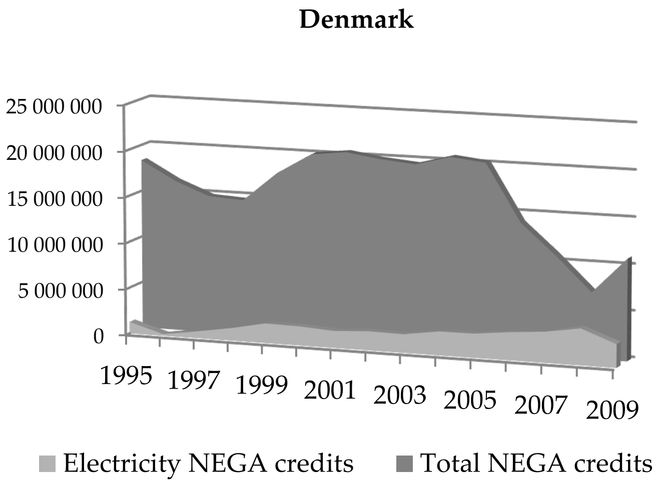
China and the USA represent counterparts to much of the European countries. China, as Figure 7 illustrates, had on the whole carbon efficiency of its exports below the world average level throughout the period of study, which can be seen from the constantly negative NEGA credits. The contribution of the carbon-intensive electricity production to this negative in China is relatively high and averages at 50 percent of the total NEGA penalties. In the USA, on the other hand, a period of positive NEGA credits can be seen between 1998 and 2004 which is likely a result of the transition from coal to gas; however, a more thorough sectoral decomposition would be needed to explain this sudden increase. Otherwise, the pattern of development of the NEGA emissions for the USA identifies carbon efficiency of its exports below the world average level as was in case of China. In the USA, this negative trend is further accentuated by substantial NEGA penalties originating in the electricity sector after 2007.

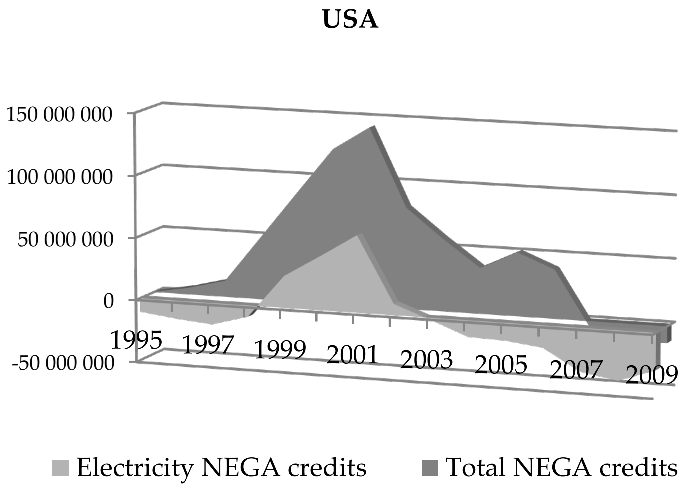
Fig. 7 NEGA credits in exports (total NEGA) and embodied NEGA credits from electricity consumption (electricity NEGA) in a comparative perspective, in M tons of CO_2 emissions.

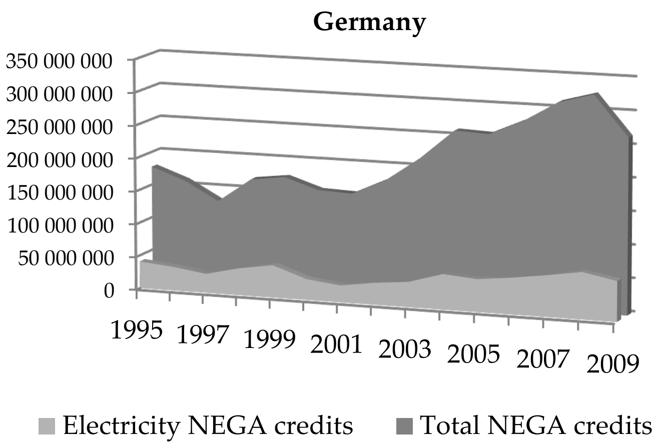
Note: Negative NEGA credits correspond to 'penalties' for having worse than world average carbon efficiency

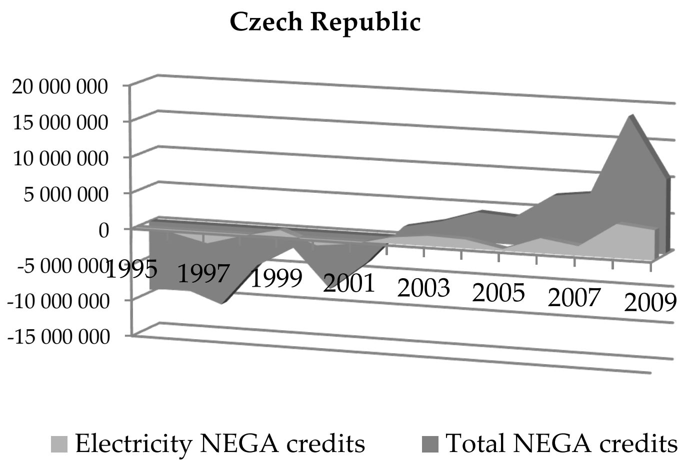












4.3 SECTORAL DIFFERENCES

Within the period of study 1995-2009 Sweden generated relatively substantial volumes of NEGA credits due to its specific electricity production sector. Electricity derived NEGA credits accounted for a total of 26-28 percent of Swedish NEGA credits. But the sectoral distribution of the electricity NEGA credits differed substantially across each productive sector and had various impacts on the total volume of electricity NEGA credits. Table 1 summarizes those productive sectors which accounted for the highest shares of electricity NEGA credits. Of the total of 35 productive sectors which exported outside of Swedish borders, five manufacturing sectors accounted for over 50 percent of all electricity NEGA credits as well as more than 50 percent of Swedish exports (in monetary terms). Especially two sectors were overrepresented in the relative shares: the pulp and paper and the basic metals sectors. Both sectors also accounted for substantial shares of the Swedish exports, though the paper and pulp exports have declined its relative share by 2008.

Table 1. The distribution of Swedish NEGA credits due to electricity production and the relative sectoral share in Swedish exports

	1995		2002		2008	
	Electricity credits (% all electricity NEGA)	Exports (%)	Electricity credits (% all electricity NEGA)	Exports (%)	Electricity credits (% all electricity NEGA)	Exports (%)
Pulp, Paper, Paper , Printing and Publishing	**21%**	**10%**	**19%**	**9%**	**18%**	**7%**
Basic Metals and Fabricated Metal	**14%**	**9%**	**12%**	**8%**	**13%**	**9%**
Chemicals and Chemical Products	**7%**	**8%**	**9%**	**9%**	**9%**	**8%**
Transport Equipment	**6%**	**15%**	**6%**	**13%**	**5%**	**12%**
Machinery, Nec	**5%**	**12%**	**4%**	**11%**	**4%**	**11%**
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	4%	2%	3%	2%	2%	3%
Wood and Products of Wood and Cork	4%	4%	3%	3%	3%	2%
Electrical and Optical Equipment	4%	13%	4%	14%	3%	11%
Renting of M&Eq and Other Business Activities	3%	5%	3%	9%	4%	10%
Rubber and Plastics	2%	2%	2%	2%	2%	2%
Manufacturing, Nec; Recycling	2%	2%	1%	2%	1%	2%
Textiles and Textile Products	1%	1%	1%	1%	0%	1%
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	1%	1%	2%	1%	3%	2%
Other Non-Metallic Mineral	1%	1%	1%	1%	1%	1%
Coke, Refined Petroleum and Nuclear Fuel	1%	2%	1%	2%	2%	5%
Total	**74%**	**86%**	**72%**	**85%**	**71%**	**84%**

At the same time, there are differences between the paper and pulp sector and basic metals. When looking into each specific sector and the contribution of the low-carbon electricity for the sectoral NEGA credits, the relative shares differ. Table 2 reports the results on the relative contribution of electricity NEGA credits to the total sectoral NEGA credits. This is another way of measuring the contribution of low-carbon electricity and differs from the Table 1 which reports the sectoral share in the total of Swedish electricity NEGA credits (which account for roughly 26-28 percent of total Swedish NEGA credits). While table 1 highlights mainly manufacturing sectors which inherently have higher energy and electricity intensities than other sectors and services, Table 2 shows which export sectors have the highest relative contribution of low carbon electricity. The contribution of electricity in basic metals (19 percent) is, for example, far more limited than in the paper and pulp sector (70 percent), due to the sector's dependence on coke. Traditionally coke has been used as a reduction agent in the production of pig iron from iron ore (Jiborn et al., 2017) and is a necessary production input without, at the moment, any potential substitute. Recently, research effort has been concentrated into carbon-free substitutes as a reduction agent. In June 2017, a new joint-venture formed by SSAB, LKAB and Vattenfall was created to continue to drive the research into fossil-free steel. The three companies will attempt to develop a steelmaking process that emits water instead of carbon. The average contribution of low-carbon electricity to the total NEGA credits of Swedish exports was around 27 percent. A more detailed analysis of the major sectors and the contribution of low-carbon electricity in generating a comparative carbon advantage in the world market are discussed in the next subsection.

Table 2. The sectoral dependence on low-carbon electricity in total NEGA credits (relative share of electricity NEGA credits in total sectoral NEGA credits)

	1995		2002		2008	
	Electricity credits (% sectoral NEGA)	Exports (%)	Electricity credits (% sectoral NEGA)	Exports (%)	Electricity credits (% sectoral NEGA)	Exports (%)
Pulp, Paper, Paper , Printing and Publishing	**70%**	**10%**	**74%**	**9%**	**67%**	**7%**
Transport Equipment	**61%**	**15%**	**58%**	**13%**	**54%**	**12%**
Machinery, Nec	**45%**	**12%**	**40%**	**11%**	**42%**	**11%**
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	45%	2%	46%	2%	39%	3%
Wood and Products of Wood and Cork	45%	4%	41%	3%	47%	2%
Electrical and Optical Equipment	**31%**	**13%**	**27%**	**14%**	**35%**	**11%**
Renting of M&Eq and Other Business Activities	**31%**	**5%**	**30%**	**9%**	**37%**	**10%**
Textiles and Textile Products	30%	1%	39%	1%	40%	1%
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	27%	1%	29%	1%	50%	2%
Basic Metals and Fabricated Metal	**19%**	**9%**	**18%**	**8%**	**19%**	**9%**
Chemicals and Chemical Products	**17%**	**8%**	**17%**	**9%**	**21%**	**8%**
Rubber and Plastics	16%	2%	14%	2%	21%	2%
Other Non-Metallic Mineral	15%	1%	13%	1%	7%	1%
Manufacturing, Nec; Recycling	13%	2%	8%	2%	11%	2%
Coke, Refined Petroleum and Nuclear Fuel	8%	2%	7%	2%	9%	5%
Total	**27%**	**100%**	**26%**	**100%**	**28%**	**100%**

4.3.1 Paper and pulp

The Swedish paper and pulp sector has undergone a substantial transformation in terms of energy efficiency after being hit by the oil crisis in 1973. This has led to reductions in the sectoral consumption of oil and increased deployment of electricity (Bergquist and Söderholm, 2016). The shift towards mechanical pulp production (as opposed to the traditional Kraft pulp production in other producing countries) led to increased electricity intensity of sector. Mechanical pulp production allowed for increases in the wood yield and further refining of the pulp, which over time required increased electricity use (Bergquist and Söderholm, 2016). The paper and pulp sector accounted, in relative as well as absolute terms, for the largest share of NEGA credits from low-carbon electricity production. Overall, 21 percent of all NEGA credits from the electricity sector were embodied in the exports of paper and pulp sector. The sector's electricity intensity was also one of the highest as more than 70 percent of absolute sectoral NEGA credits could be traced back to the deployment of the low carbon electricity.

The share of the sector in the volume of Swedish exports was also relatively high, though diminished from 10 to 7 percent between 1995 and 2008. Consequently, this decline in the export shares has also led to declines in the relative shares of the electricity NEGA credits of the sector from 21 percent in 1995 to 18 percent in 2008. Despite that, however, the Swedish paper and pulp sector remains the largest supplier of embodied NEGA credits from the electricity sector.

Given the high share of electricity NEGA credits and its importance for the Swedish exports, the paper and pulp sector thus represents one of the largest potential contributors for further exploitation of the comparative carbon advantage of the Swedish electricity. The sector accounted for a total of 42.9 million ton CO_2 NEGA credits accumulated over a period of 1995 to 2009, which corresponds to more than 7 percent of all Swedish NEGA credits and 20 percent of all electricity NEGA credits. These are virtually emissions which have been saved globally by having the paper and pulp production located in Sweden and utilizing Swedish low-carbon electricity.

Figure 8 illustrates the large share of electricity NEGA credits in the absolute levels of NEGA credits from the pulp and paper exports, and their development between 1995 and 2009. The increase in the absolute volume of NEGA credits from the sector was driven by the increase of the volumes exported (in monetary terms), though this was to some extent offset by the decline in the NEGA credits per output (M ton CO_2/bil. USD). While in 1995, one million of USD of paper and pulp exports generated 290 tons of CO2 credits, this has declined to less than 230 tons of CO2 saved on the global market. This change in the relative contribution of the Swedish NEGA export intensity does not necessarily mean that Swedish paper and pulp's efficiency is deteriorating. Rather, it implies that the state of the world average technology is improving at a faster rate than that of Sweden.

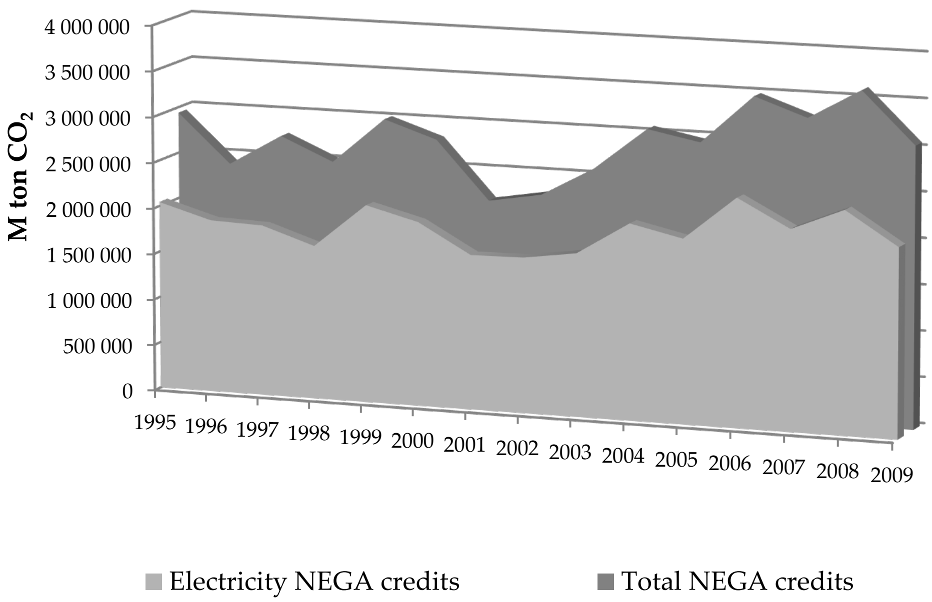


Fig. 8 Total NEGA credits in the exports of the Swedish paper and pulp sector and of which NEGA credits derived from the electricity production (in tons of CO_2)

4.3.2 Basic metals and fabricated metal

The contribution of fossil-free electricity for the basic metals sector was one of the lowest among other manufacturing sectors. This is almost entirely due to the production specifics of the sector where the potential use of electricity is currently relatively low. Much of the NEGA credits generated by the sector (and those are indeed substantial) are a result of efficiency production process compared to the world average. At the same time the low utilization of electricity in the sector represents one of the largest and most substantial potentials in further increasing the Swedish NEGA credits – and that is through increased electrification of the sector. Swedish Energy Agency is therefore investing heavily in project of carbon-free electricity where hydrogen (produced with the use of Swedish carbon free electricity) is used as a reduction agent. Clearly, it the results of the project prove its feasibility, this would be a path-breaking development having a huge impact on the absolute levels of Swedish carbon emissions (in Sweden, 20 per cent of emissions embodied in Swedish exports are not energy related but result from industrial processes, in particular in the steel and cement industry).

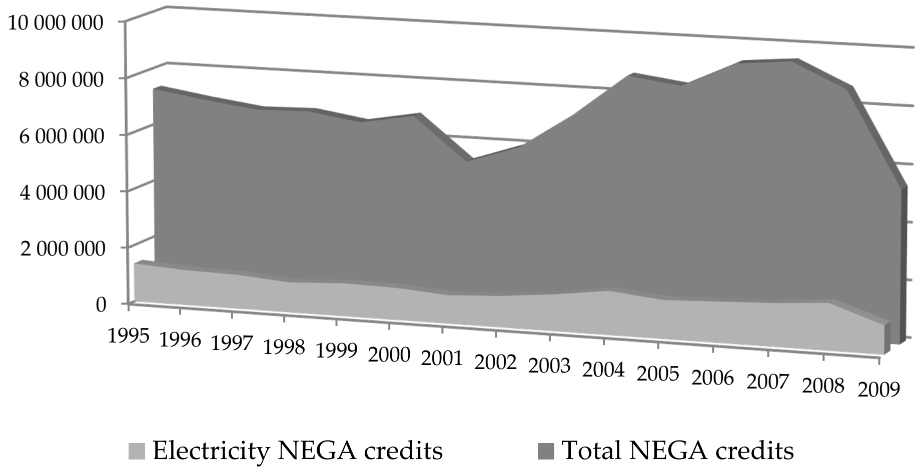


Fig. 9 Total NEGA credits in the exports of the Swedish basic metals sector and of which NEGA credits derived from the electricity production (in tons of CO_2)

4.3.3 Chemicals and chemical products

The chemical is the third largest user of industrial energy in Sweden, accounting for a total of 9% of industrial energy use. Here, electricity is used mainly for electrolysis processes and any further electrification of the sector is conditioned by the type of output produced. Overall, the contribution of carbon-free electricity to total NEGA credits was relatively low at around 9% in 2008. The sector is, as the iron and steel sector, characterized by the use of fossil energy for non-energy purposes, mainly in the form of raw materials. Much of the potential for this sector to reduce its carbon emission therefore lies in the use of alternative raw materials (new bio-based chemicals) and in the storage of carbon emissions (Sveriges Ingenjörer, 2009). Currently, there are pilot projects in Sweden whose aim is to engineer bio-based chemicals and plastics by replacing traditional fossil fuels as raw materials in the production.

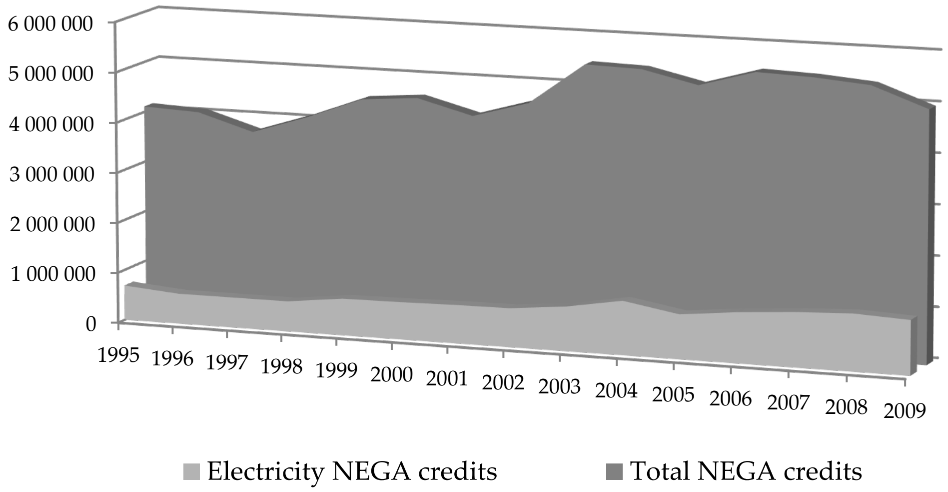


Fig. 10 Total NEGA credits in the exports of the Swedish chemical sector and of which NEGA credits derived from the electricity production (in tons of CO_2)

4.3.4 Transport equipment and machinery

The relative contribution of carbon-free electricity in the exports of transport equipment and machinery was fairly high given the high utilization of electricity in the production process. Overall, the sector is not regarded as energy intensive, though given the high proportion of Sweden's total industrial output as well as exports, the engineering sector accounts for relatively high share of industrial energy use (and also the NEGA credits).

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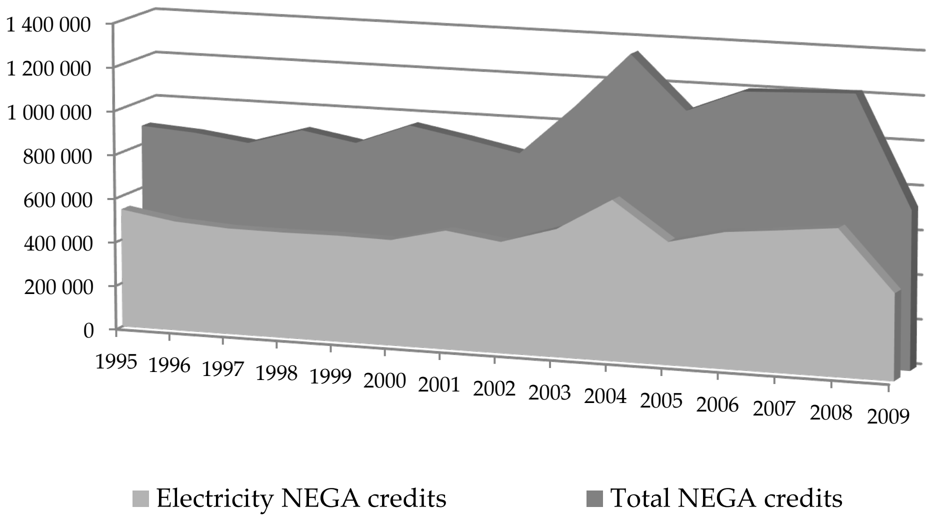

Fig. 11 Total NEGA credits in the exports of the Swedish transport equipment sector and of which NEGA credits derived from the electricity production (in tons of CO_2)

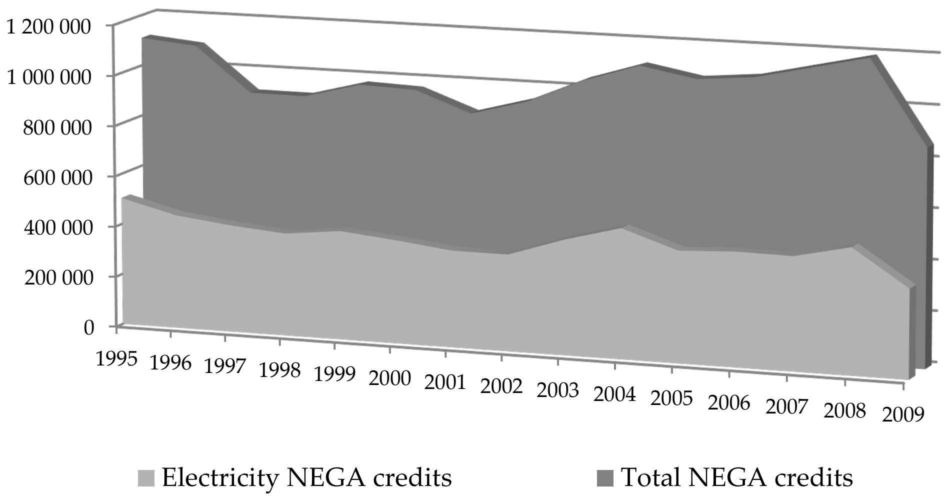

Fig. 12 Total NEGA credits in the exports of the Swedish machinery sector and of which NEGA credits derived from the electricity production (in tons of CO_2)

4.4 COMPARATIVE CARBON ADVANTAGE

Throughout the period of study Sweden had a comparative carbon advantage in majority of its export sectors, both before the credits from the electricity were redistributed but also including electricity credits. Figure 13 below summarizes the development in comparative carbon advantage of Swedish export sectors relative to the world average. Of the total 35 productive exports including in our dataset, Sweden had a comparative carbon advantage in at least 31 of them. The sectors where Sweden scored below the world average were the construction sector and sale, maintenance and repair of motor vehicles. Later two more sectors lost its relative comparative carbon advantage – the agricultural sector and water transport.

Overall, Sweden has a comparative carbon advantage in a vast majority of its export sectors. This means that exports from these 31-32 sectors are actively contributing to increased global 'welfare' as these reduce the global carbon emissions. Should the same volumes of goods be produced elsewhere using world average technology, the total stock of carbon emissions would increase at a faster pace. What is important, however, is to assess to what extent is the comparative carbon advantage exploited throughout the time and what is its relative development when compared to the world-average. Are there sectors whose comparative carbon advantage further improved/deteriorated? Does Sweden's overall comparative carbon advantage improve or is the rest of the world catching-up?

4.4.1 Development across time

Overall, between 1995 and 2009, Sweden has generated increasing amounts of NEGA credits; much of it was however due to the growing trade surplus of the country. The EU, which as Sweden, also generated increasing amounts of NEGA credits. Other countries or regions, such as China or India, for example barely produced any positive NEGA credits, as much of their exports remain to be produced with a below world average technology so generating additional emissions rather than saving.

Figure 13 captures the development in absolute level of Swedish NEGA credits in exports (right-hand side of the graph) and the change in the intensity of NEGA credits (NEGA credits/value of exports) for Sweden and an EU-average. Although in absolute volume the NEGA credits have increased between 1995 and 2009, largely due to the growing volumes of trade the intensity of NEGA credits declined in both Sweden and the EU, converging to a more similar level towards the end of the period. This does not necessarily mean that Sweden or the EU are losing their comparative carbon advantage, but it is more of a sign that other parts of the world are simply catching up, thus improving faster on lowering their carbon intensity of exports (see 4.6 for more elaborate discussion)).

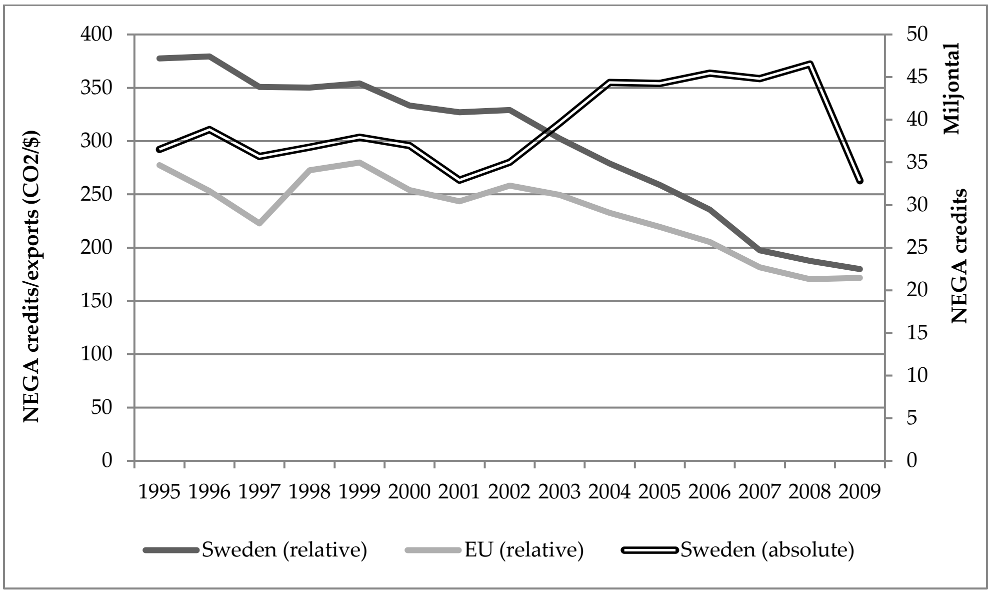

Fig. 13 Annual development in total Swedish NEGA credits (left-hand side) and NEGA intensity of Sweden and the EU (right-hand side)

4.4.2 Sectoral development

Figure 14 shows the differences in carbon efficiency (after electricity re-allocation) between Swedish and world average exports. A visualization of the average annual changes in the sectoral carbon intensity for Sweden and for the world average can be seen in Fig 15. The red area of the graph shows sectors which on average increased its carbon intensity between 1995 and 2009 (an outcome less desired), while the green area captures all sectors which lowered its carbon intensity. On the positive side it can be seen that for the world average the average annual rate of change in carbon intensity was negative, thus indicating a decline in carbon intensity. Also, the average rate of change in carbon intensity of world exports was substantial at nearly 7% decline annually within the period of study. On the other hand, a more thorough inspection of the Swedish developments shows some less desirable development. First, a couple of Swedish export sectors increased its carbon intensity (compared to the world average where no export sector recorded an increase in carbon intensity). Second, the average rate of decline in carbon intensity was somewhat slower and below that of the world average at 4% annually. This does not imply that Swedish carbon efficiency in exports is deteriorating, but this rather illustrates that the rest of the world is catching up (especially, as majority of world export sectors is improving faster).

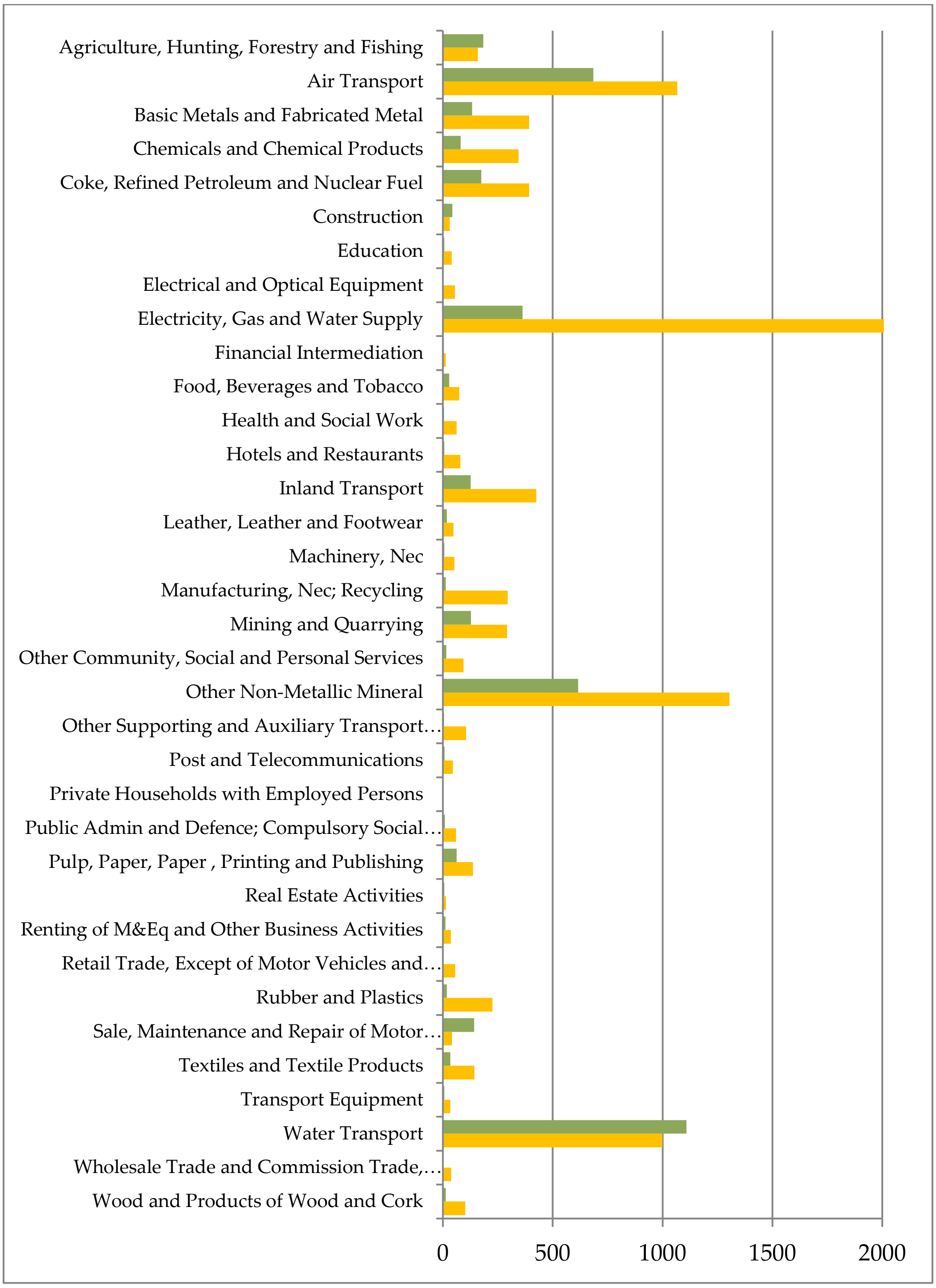

Fig. 14 Domestic carbon efficiency (CO2/$ of production, in green) v. world average (yellow) in 2008

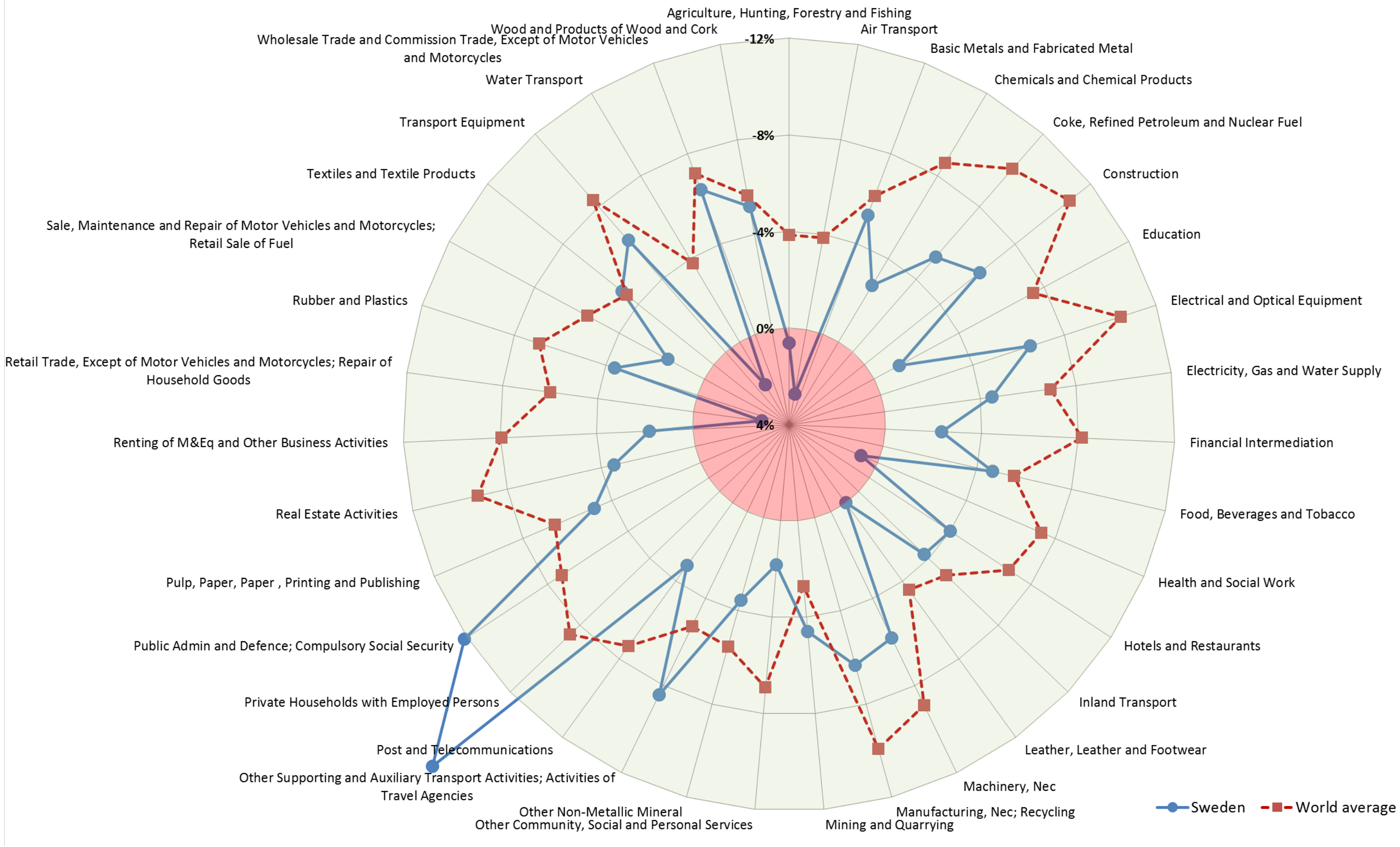

Fig. 15 Average rate of change (compound annual growth rate) in sectoral carbon intensity (tons of CO_2/$exports) in Sweden and the world average

To focus more on the 5 sectors which accounted for the largest share of Swedish NEGA credits between 1995 and 2009, the picture draws more positive findings though. For 4 of the sectors (basic metals, paper and pulp, transport equipment, and machinery) the annual rate of change in carbon intensity decline was relatively fast in Sweden, somehow on par with the rest of the world. This would imply that although rest of the world is catching up in terms of carbon efficiency, Sweden continues to improve the carbon efficiency of its production and exports in a similar pace. This is a rather remarkable development taking into account that efficiency improvements become progressively exhausted and the already initially low carbon intensity of Swedish production in mid-1990s. Obviously, the rest of the world has far more space to exploit existing efficiency enhancements and the rate of decline can often be very rapid. Only one sector, the chemicals, recorded far slower rate of decline in carbon intensity in Sweden than the rest of the world. This implies that the rest of the world was far more successful in catching up, though the carbon intensity is still far higher than in Sweden even by 2009. One issue which could potentially effect this development is the difference in the composition in the output of the chemical sector between Sweden and the rest of the world. Much of the Swedish exports of chemicals constituted of pharmaceuticals (high in value), while the rest of the world produced particularly bulk chemicals such as acids (low in value and with substantial potential for economies of scale).

4.5 DOES SWEDEN TRADE ACCORDING TO ITS COMPARATIVE CARBON ADVANTAGE?

In Jiborn et al. (2017) a new decomposition method was introduced to capture to what degree decoupling of CO_2 emissions from economic growth in the developed world was due to emissions displacement to other parts of the world. For Sweden, the method has found, taking technology differences into account, that since 2000 Sweden has become a net importer of heavy industrial (carbon intensive) goods, and the reason that Sweden still retains a positive balance of emissions embodied in trade (BEET) is explained by a consistent positive monetary trade balance (figure 16 illustrates this decomposition).

This finding has two major implications which may have a negative effect on the future development and potentially a loss of the comparative carbon advantage. First, even though Swedish carbon intensity of exports continued its decline throughout the period of study, the relative comparative carbon advantage has diminished as the rest of the world has been catching-up at a faster pace. Second, the export structure has become less carbon intensive and the import structure more carbon intensive (Jiborn et al., 2017).

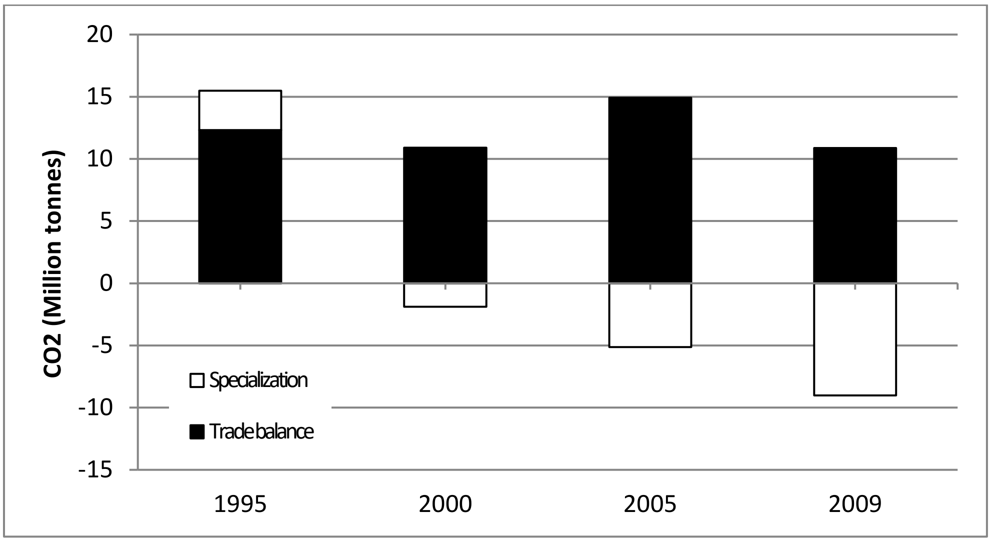

Fig. 16 Decomposition of the Swedish balance of embodied emissions into trade balance effect and specialization effect. Adapted from Jiborn et. al (Jiborn et al., 2017)

This supports the finding that Sweden has reduced domestic emissions, at least partly, by reorienting domestic production structure towards less carbon intensive goods and imports towards more carbon intensive goods (Jiborn et al., 2017). So Sweden has not only lost some of its comparative carbon advantage between 1995 and 2009, it has also reduced the exploitation of this advantage in relative terms (though not in absolute levels).

A visualization of the average annual rate of change in exports is shown in Figure 17. The graph pinpoints all export sectors of Sweden against the changes in carbon intensity of those export sectors between 1995 and 2009. The upper left area of the graph highlights the most desirable situation, where ideally most Swedish sectors would be located – those are all sectors which achieved above average improvements in carbon intensity while at the same time growing fastest in terms of export volumes. To have a desired impact on the global climate, it would therefore make most sense if sectors on the left hand side of the graph were those also accounting for the red area, on the other hand, assigns to an area where actually carbon intensity increased within the period of study and it would thus be desirable if those export sectors reduced its export volumes. Even though only Sweden has export sectors in the red area, in relative shares those sectors do not account for substantial shares of Swedish exports.

In Sweden, one of the largest export sectors with substantial declines in carbon intensity was the 'Other supporting and auxiliary transport activities' sectors. This service sector is basically a support of the transport sector and entails cargo handling services, storage and warehouse services and others (WTO definition). Its significance in the export shares as well as growth is subsequently a natural consequence of Sweden's growth in exports and the growing need for transport support services. Interestingly, many of the traditional manufacturing sectors have, despite increases in absolute export volumes and substantial declines in carbon intensity, grown exports at a below the average growth rate.

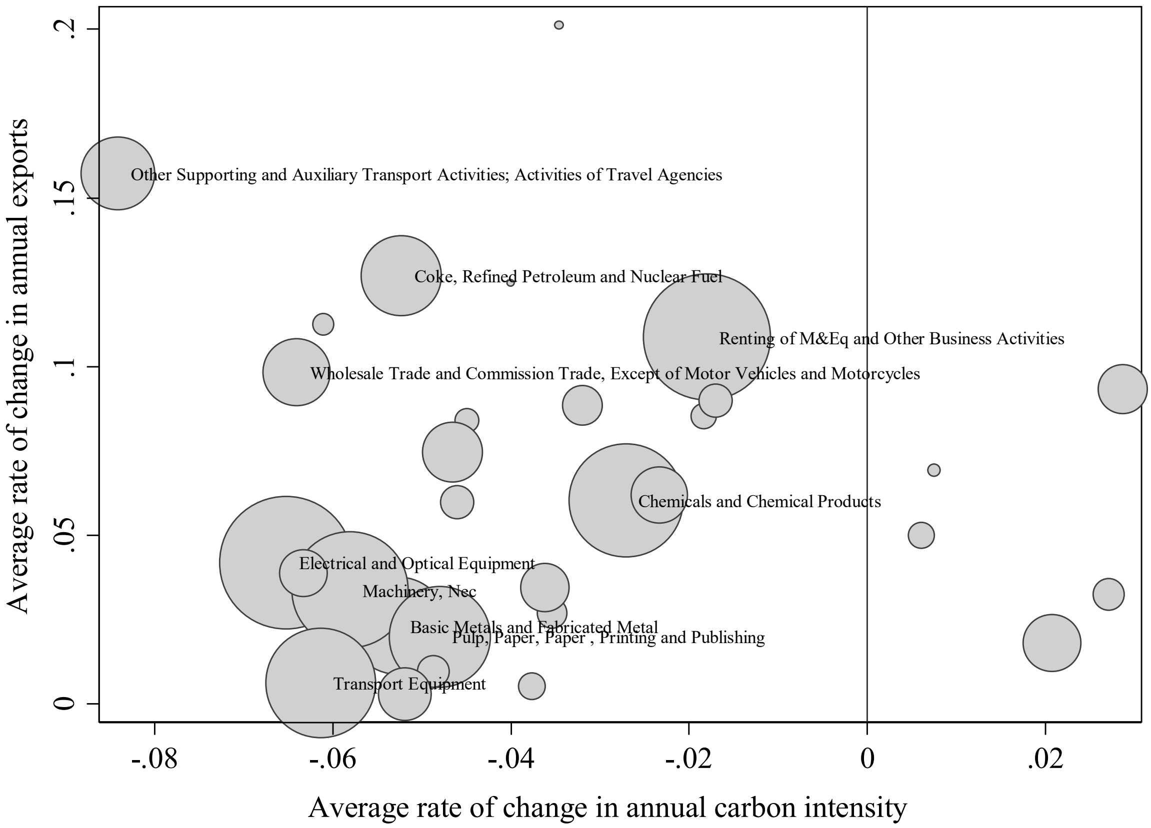

Fig. 17 Average annual rate of change in carbon intensity versus export volumes

Note: The size of the circle indicates the relative share of the sector in total exports in 2009.

4.6 POST-2009 DEVELOPMENTS

The absence of post-2009 satellite accounts in the WIOD database do not allow for any precise estimations of the later development. Though, the availability of world trade data enables some rough approximations of the possible trend under the assumption that there were no sudden shocks to the pattern of sectoral carbon intensity after 2009. In other words, this section calculates new carbon intensity levels up to 2014 using the same rates of decline as recorded between 1995 and 2009 (the calculated compound average growth rate as discussed in section 4.5.2. This prolongs the period of study by 5 additional years.

Overall, the trade data indicate that after a dip in global trade in 2009 (Fig. 18), the volumes of trade embarked on a path of continuous growth until 2014 (this is the last year where WIOD database provides updates). The average annual growth rate of Swedish exports was relatively high between 2009 and 2014 at 4,6% compared to 5,4% growth in the world traded volumes.

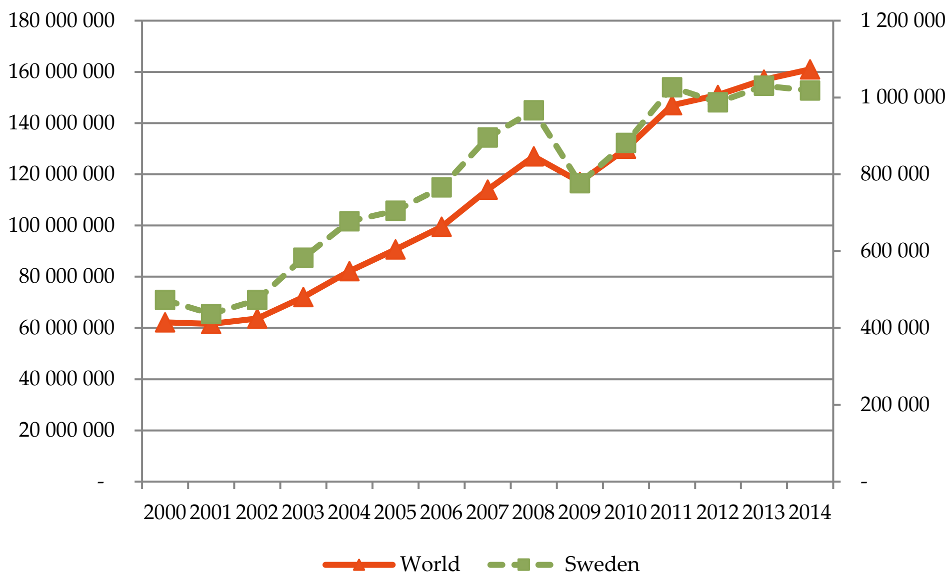

Fig. 18 Volumes of trade in Sweden and the World (in million USD)

In Sweden, those sectors which recorded the fastest rates of growth in export volumes between 2009 and 2014 were services and other support activities sectors, rather than the traditional manufacturing sectors. Of the traditional manufacturing sectors (see table 3), Sweden recorded relatively high rates of growth in the exports of the mining sector, coke products and metals and products thereof (including machinery and motor vehicles). Exports of the traditional sectors such as wood, paper and pulp or chemicals (here among other also the pharmaceuticals) grew at a far slower pace, or even declined between 2009 and 2014. With the exception of mining and quarrying, the overall global average rates of growth in exports of the manufacturing sector were faster than those recorded in Sweden.

Table 3. Comparison of average annual growth rates (%) in export volumes in Swedish and global perspective (compound annual growth rate)

	Sweden	World
Manufacture of basic metals	4,86%	7,98%
Manufacture of basic pharmaceutical products and pharmaceutical preparations	-0,02%	4,79%
Manufacture of chemicals and chemical products	0,91%	7,93%
Manufacture of coke and refined petroleum products	6,65%	9,07%
Manufacture of computer, electronic and optical products	0,17%	8,15%
Manufacture of electrical equipment	2,99%	8,14%
Manufacture of fabricated metal products, except machinery and equipment	4,51%	5,45%
Manufacture of food products, beverages and tobacco products	3,24%	6,29%
Manufacture of furniture; other manufacturing	0,05%	3,49%
Manufacture of machinery and equipment n.e.c.	4,54%	5,81%
Manufacture of motor vehicles, trailers and semi-trailers	7,11%	8,53%
Manufacture of other non-metallic mineral products	6,48%	7,21%
Manufacture of other transport equipment	2,85%	7,06%
Manufacture of paper and paper products	2,34%	3,59%
Manufacture of rubber and plastic products	3,73%	5,99%
Manufacture of textiles, wearing apparel and leather products	1,71%	7,22%
Manufacture of wood and of products of wood and cork	1,62%	6,91%
Mining and quarrying	10,77%	10,11%

4.6.1 Comparative carbon advantage

In 2009, Sweden had a comparative carbon advantage in 31 of its 35 export sectors. If the development in the carbon intensity in Sweden as well as of the world average continued in a similar pattern as seen between 1995 and 2009, then by 2014 Sweden loses comparative carbon advantage in two more sectors (construction and real estate activities). In those sectors, where Sweden completely lost any comparative carbon advantage, the export volumes further increased until 2014, but their overall share in the Swedish exports remained relatively low. In four sectors (mining and quarrying, other supporting and auxiliary transport activities, public administration and textiles), on the other hand, Sweden improved its comparative carbon advantage compared to the rest of the world. In the remaining sectors, Sweden maintained its favorable position against the world average though the gap between the Swedish and world average carbon intensity diminished. Table 4 summarizes the major manufacturing sectors of Sweden with their respective developments in exports and carbon efficiency.

Table 4. Swedish exports of the manufacturing sectors 2009-2014 and the development in relative carbon efficiency

	Carbon efficiency (Sweden relative to World average)
Manufacture of basic metals	Sweden marginally losing its comparative carbon advantage
Manufacture of basic pharmaceutical products and pharmaceutical preparations	Sweden substantially losing its comparative carbon advantage
Manufacture of chemicals and chemical products	Sweden substantially losing its comparative carbon advantage
Manufacture of coke and refined petroleum products	Sweden substantially losing its comparative carbon advantage
Manufacture of computer, electronic and optical products	Sweden substantially losing its comparative carbon advantage
Manufacture of electrical equipment	Sweden substantially losing its comparative carbon advantage
Manufacture of fabricated metal products, except machinery and equipment	Sweden marginally losing its comparative carbon advantage
Manufacture of food products, beverages and tobacco products	Sweden marginally losing its comparative carbon advantage
Manufacture of furniture; other manufacturing	Sweden marginally losing its comparative carbon advantage
Manufacture of machinery and equipment n.e.c.	Sweden marginally losing its comparative carbon advantage
Manufacture of motor vehicles, trailers and semi-trailers	Sweden marginally losing its comparative carbon advantage
Manufacture of other non-metallic mineral products	Sweden marginally losing its comparative carbon advantage
Manufacture of other transport equipment	Sweden marginally losing its comparative carbon advantage
Manufacture of paper and paper products	Sweden marginally losing its comparative carbon advantage
Manufacture of rubber and plastic products	Sweden marginally losing its comparative carbon advantage
Manufacture of textiles, wearing apparel and leather products	Sweden improving its comparative carbon advantage
Manufacture of wood and of products of wood and cork	Sweden marginally losing its comparative carbon advantage
Mining and quarrying	Sweden improving its comparative carbon advantage

It is not possible to estimate the actual developments of the Swedish NEGA credits, as more detailed data on the world average carbon intensities and their annual development would be required. Though based on the estimates presented in 4.7 Sweden maintained its comparative carbon advantage in a majority of the export sectors and together with the positive trade balance 2009-2014, it is likely that the amount of Swedish NEGA credits did not diminish substantially in the later period of study. The Swedish competitiveness in terms of carbon efficiency has, however, been increasingly challenged between 2009 and 2014 with the world carbon efficiency improving at a faster pace.

If we focus entirely on those export sectors which accounted for significant shares of the Swedish total exports in 2009, then a simple comparison of the average annual rate of carbon intensity decline and export volumes shows that:

- Pulp and paper: the comparative carbon advantage likely deteriorated slightly and with world exports growing at a faster rate, the total Swedish NEGA is estimated to have declined by over 3%.
- Transport equipment: up to 3-4% decline in total sectoral NEGA credits.
- Electrical and optical equipment: up to 9% decline in total sectoral NEGA credits
- Renting of M&E: up to 11% decline in total sectoral NEGA credits
- Basic metals and fabricated metal: up to 4% decline in total sectoral NEGA credits
- Chemicals: the largest potential of losing NEGA credits was estimated in the chemicals sector. This is largely due to the fact that the world carbon efficiency increased substantially between 2009 and 2014 together with the volumes of export. The estimated decline of sectoral NEGA credits reached nearly 13% by 2014, which given the high share of the sector in the total Swedish NEGA credits could have an overall impact on the absolute levels of Sweden.

These estimated declines in total sectoral NEGA credits are only rough estimates. Overall, the traditional paper & pulp and metals sector seem to maintain its comparative carbon advantage and high levels of NEGA credits until 2014. Chemicals, on the other hand, seem to be the sector progressively loosing behind the world average. At the same time, one should keep in mind that as the trade patterns develop with an increasing share of the service and other auxiliary services, Sweden might be gaining additional NEGA credits elsewhere which will also affect the absolute levels of Swedish NEGA credits. This conforms to the conclusion that Sweden has reduced domestic emissions, at least partly, by reorienting domestic production structure towards less carbon intensive goods and imports towards more carbon intensive goods between 1995 and 2009. The structural change of Swedish exports and correspondingly also of Swedish comparative carbon advantage is likely to have continued also after 2009. A more detailed study of this development is planned to be conducted in the future once data availability allows for a more thorough analysis.

5 Discussion and conclusion

This paper has analyzed and discussed the developments of Swedish comparative carbon advantage in world exports and its beneficial contribution to the global environment. Having an energy efficient production and low-carbon electricity network was found to be an important mechanism behind this advantage in the global trade arena. Overall, by Sweden exporting its production globally between 1995 and 2009, Sweden contributed nearly 590 million tons of CO_2 potential savings through its exports by having an efficient and low-carbon production. This total amount of 590 million tons of CO_2 accumulated over those 15 years relates to the total savings made if the same amount of Swedish exports was produced using the world average technology. In other words, if Sweden did not produce that one ton of steel for export, this would have been produced elsewhere using world average technology.

Furthermore this report analyzes and quantifies the contribution of efficient electricity generation to Sweden's comparative carbon advantage. Carbon-free electricity generation accounted for over 34% of the total savings, of which some 20% were direct exports of electricity and 80% was electricity embodied in exported products. The role of electricity embodied in the export goods (and service) is thus substantial and an important contributor to Sweden's comparative carbon advantage.

Overall, throughout the period of study Sweden maintained its comparative carbon advantage in a majority of its export sectors, though the gap between the Swedish and world carbon efficiency narrowed within this period. Despite this, Sweden likely maintained high levels of comparative carbon advantage and consequently NEGA credits also in the later period of 2009-2014 (to some extent also fueled by growing exports after the 2009 decline). The preliminary results also highlight an ongoing structural change of Swedish exports and trade in general, with increasing role played by service and other auxiliary service sectors. . While this might not have an effect on the levels of Swedish NEGA credits (under the assumption that Sweden maintains a substantial efficiency gap in those sectors), it is likely an indication that Sweden is becoming an outsourcing economy. This implies that Sweden increasingly imports energy intensive products, while exporting goods and services from less energy intensive sectors.

The role of electrification of the Swedish industry has brought, to some extent, this comparative carbon electricity. Particularly sectors such as paper and pulp hugely benefited from this technological development which commenced as early as 1970s. But the potential for further electrification of the Swedish industry is far from exhausted. The electricity-fueled hydrogen-based steel production is currently under testing and the potential for the substitution of fossil fuels through bio-based alternatives in the production of chemicals could have a substantial impact. Although with the ongoing structural change in the Swedish exports, this might have a limited impact on the overall levels of NEGA credits in the future, the electrification of particularly the steel and chemicals sector could have a huge impact on the overall Swedish carbon efficiency.

Clearly, the carbon efficiency of Swedish exports was and remains substantial. It is also here that Swedish companies can more pro-actively market its produce abroad from an environmental perspective. Because in a vast majority of cases, choosing a Swedish produced good the customer is in a way doing the global climate a favor – an aspect which should be further exploited. Also, companies, public bodies and other institutions can use the comparative carbon advantage to attract foreign investments.

By relocating (part) of its production to countries like Sweden, other foreign firms can indeed lower the carbon footprint of their produce and indeed actively contribute to the global mitigation efforts. The concept of comparative carbon advantage can thus have some profound policy implications and can be used as a climate mitigation tool.

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SWEDISH COMPARATIVE CARBON ADVANTAGE IN WORLD EXPORTS

Sverige har historiskt haft en stor fördel i att ha en låg koldioxidintensitet i sin tillverkning och i export av varor. Här introducerar forskare på Lunds universitet ett nytt koncept, kallat comparative carbon advantage, för att på ett potentiellt sätt mäta klimatpåverkan från en exportsektor.

Genom att utnyttja länders skillnader mellan olika sektorer i koldioxidintensitet kan faktiskt en ökad industrikoncentration och exportintensifiering leda till välfärdseffekter när det gäller minskade globala koldioxidutsläpp.

Mellan 1995 och 2008 bidrog Sverige totalt med en minskning på nästan 590 miljoner ton koldioxid globalt sett, genom att exporterade varor tillverkades med ovanligt koldioxidsnåla processer. Den mängd koldioxid avser besparingen jämfört med om samma mängd och sammansättning av svensk export producerats med hjälp av världens genomsnittsteknik för varje produktgrupp.

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