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**Adrian Muller, Åsa Löfgren, and Thomas Sterner**

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Department of Economics
School of Business, Economics and Law at University of Gothenburg
Vasagatan 1, PO Box 640, SE 405 30 Göteborg, Sweden
+46 31 786 0000, +46 31 786 1326 (fax)
www.handels.gu.se    info@handels.gu.se

# Decoupling: Is there a Separate Contribution from Environmental Taxation[1]

Adrian Muller
Socioeconomic Institute
University of Zurich, Switzerland

Åsa Löfgren
Environmental Economics Unit
Department of Economics, Göteborg University, Sweden

Thomas Sterner
Environmental Economics Unit
Department of Economics, Göteborg University, Sweden
University Fellow, Resources for the Future RFF

Abstract

Decoupling is a crucial topic in the analysis of sustainable development. Without decoupling, continuing and increasing economic growth in developed and developing countries would come with ever increasing environmental pressures, unavoidably destroying the carrying capacity of ecosystems with corresponding detrimental effects on the environment and societies. The prime example today is climate change. If we do not succeed in drastically decoupling greenhouse gas emissions from economic growth, the mitigation goals necessary to avoid catastrophic impacts will never be reached. Due to this importance of decoupling, it is thus essential to know how different policy instruments may support its achievement.

The aim of this paper is to address the question whether there is a separate contribution from environmental taxation to decoupling and to offer researchers some guidance on how to optimally address this question.

JEL codes: O40, Q50, Q58,
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## 1. Introduction

"The term decoupling refers to breaking the link between "environmental bads" and "economic goods." Decoupling environmental pressures from economic growth is one of the main objectives of the OECD Environmental Strategy for the First Decade of the 21st Century, adopted by OECD Environment Ministers in 2001." (OECD 2002).

Decoupling is a crucial topic in the analysis of sustainable development. Without decoupling, continuing and increasing economic growth in developed and developing countries would come with ever increasing environmental pressures, unavoidably destroying the carrying capacity of ecosystems with corresponding detrimental effects on the environment and societies. The prime example today is climate change. If we do not succeed in drastically decoupling greenhouse gas emissions from economic growth, the mitigation goals necessary to avoid catastrophic impacts will never be reached. Due to this importance of decoupling, it is thus essential to know how different policy instruments may support its achievement.

The aim of this chapter is to address the question whether there is a separate contribution from environmental taxation to decoupling and to offer researchers some guidance on how to optimally address this question.

Key to achieving this goal is to assess the effects of environmental taxes on the environmental pressure and the economic variables, such as emissions and output. Distributional aspects regarding the tax burden (e.g. regressivity vs. progressivity of a tax), questions of environmental tax reforms and the double dividend, of leakage and pollution havens, and the relative performance of different policy instruments play a minor role here and are covered in other chapters in this book. We also focus on methodological and statistical aspects here and address theoretical considerations only occasionally.

We differentiate several fields of analysis. First, there is the empirical question whether there is decoupling or not. "Decoupling occurs when the growth rate of an environmental pressure is less than that of its economic driving force (e.g. GDP) over a given period. Decoupling can be either absolute or relative. Absolute decoupling is said to occur when the environmentally relevant variable is stable or decreasing while the economic driving force is growing. Decoupling is said to be relative when the growth rate of the environmentally relevant variable is positive, but less than the growth rate of the economic variable." (OECD 2002). Decoupling most often refers to decreasing emissions per unit of welfare, e.g. country level GDP, but similar to OECD (2002) we explicitly use it also in relation to emissions per unit of monetary or physical output of an industrial sector. A wealth of empirical studies addresses whether there is decoupling for whole economies or single sectors and for a range of pollutants (cf. section 2). Several problems arise, though. The level of aggregation greatly matters. What looks like decoupling on an all industry level may exhibit different patterns in a sector analysis, e.g. if the decrease in aggregate emissions in a context of continuing growth is not due to increase in technical efficiency in all sectors but due to an increase in size of sectors with low emissions at the expense of the emissions intensive sectors. In this case, no decoupling would have taken place on sector level, while the opposite holds on aggregate. One task of the empirics of decoupling is to separate patterns of decoupling in a context of economic growth from patterns in a context of economic decline, which clearly has very different welfare effects. Further complications for the basic empirics stem from changes in prices if output is measured in monetary terms. Such price dynamics can overshadow the "true" i.e. physical, resp. "service level" dynamics. Decomposition analysis is one approach that helps identifying the presence of decoupling on various levels of aggregation.

Second, we focus on cases, where decoupling is observed, and try to identify the drivers behind this and their importance. A tax directly leads to changes in relative prices. There are, however, various paths how such price changes may support decoupling. A tax can, for example, lead to substitution of the taxed good and/or it may trigger innovations that then drive decoupling. Substitution and innovation in general, however, may or may not be caused by an environmental tax. Identifying the detailed role played by an environmental tax is a daunting task. It is illustrative to think of this in the frame of the cause-and-effect chains as captured in a General Equilibrium (GE) model. The changes in relative prices brought about by the tax will have effects on direct consumption of the goods taxed (e.g. gasoline) or the goods tightly related to the emissions taxed (e.g. fossil energy use under a $CO_2$ tax), on substitutes, on different channels of innovation etc. It will also have effects of the performance and employment in the sectors adversely affected by a tax (e.g. the coal industry under a $CO_2$ tax) and on sectors gaining from it (e.g. solar panel manufacturers under a $CO_2$ tax), and on the demand for inputs used in these sectors. Furthermore, the tax revenues will be used in the economy (e.g. to subsidise R&D in green technology or to implement an environmental tax reform, i.e. to reduce tax on labour), with corresponding effects. Finally, there are likely other policy instruments in place that may interact with the environmental tax. Different types of regressions of some measure of decoupling on tax levels and several control variables can help revealing the role of the tax in a specific case of empirically observed decoupling. Adequately calibrated computable general equilibrium (CGE) models of whole economies can also contribute to identify and understand the effects of environmental taxes in concrete cases.

Complexity and data availability however may hinder such a contextualised approach embedded in the whole economy and simpler paths have to be chosen. Thus, information is also gained from partial analysis, such as estimating price elasticities of demand, e.g. for gasoline under a $CO_2$ tax. This gives the effect of the tax on gasoline use and thus emissions, but it does however not reveal anything on “decoupling” directly, without further information on the change in “output”, e.g., on an aggregate level, such as the effect of the $CO_2$ tax on GDP. However, such partial analysis can provide different pieces of information that can be combined to form a more complete picture.

This chapter is organised according to these fields of analysis. Section 2 covers the empirics of the presence or absence of decoupling with a focus on decomposition analysis. Section 3 deals with the empirical investigation of the specific role of environmental taxes with regard to the contribution to decoupling, focusing on econometric models. It also covers more particular additional information that helps to capture the effect of a tax on decoupling, such as elasticity estimates. Finally, it presents some short discussion of further complementary approaches such as case-study analysis or CGE modelling. Section 4 concludes by summarising how these various techniques optimally complement each other and by pointing out some research gaps to be filled in the context of such combined approaches.

We find that decoupling takes place in many cases, but that for many examples the decoupling currently observed is by far not enough to achieve the goals of sustainable development, such as formulated for the reduction of greenhouse gases. Methodological findings refer to the necessity to go beyond the simple descriptive empirics of decoupling indicators and to apply more elaborate analysis, such as decomposition analysis, which can reveal underlying patterns. Furthermore, causal analysis of decoupling and its drivers needs to account for the specific structure of the data at hand, employing cointegration and other time-series analysis techniques. Optimally, decomposition analysis and econometric analysis are combined. Such combined approaches are however rare and currently focus on either decomposition or econometric analysis, not applying state-of-the art techniques for both these approaches. Finally, additional insights can be gained by complementing these approaches with findings from other types of studies, such as analyses of price and substitution elasticities, insights from equilibrium models or from firm-level interview surveys.

It should be noted that this chapter does not aim at presenting an exhaustive assessment of all the different examples of environmental taxes and their contribution to decoupling, but rather to present a set of tools, which enables the researcher to address the question. Furthermore, it aims at identifying research gaps. Due to the background of the authors, many examples are chosen from the areas of energy use, climate change and air pollution.

## 2. Is there decoupling?

To answer the question whether decoupling is present in a certain case, we need indicators to measure decoupling and methods to identify decoupling in contrast to other patterns. Section 2.1 shortly presents some indicators, building on the topical publication from the OECD (2002). Section 2.2 presents approaches to identify decoupling. Section 2.3 refers to some concrete examples.

### *2.1. Decoupling Indicators*

"Decoupling can be measured by decoupling indicators that have an environmental pressure variable for numerator and an economic variable as denominator. Sometimes, the denominator or driving force may be population growth or some other variable." (OECD 2002). Thus, economy-wide decoupling is measured by indicators such as total $CO_2$ emissions per unit of GDP (for climate change) or total $SO_2$ emissions per unit of GDP (for air pollution). Other aspects such as water resource use, material use, waste management or biodiversity can be measured by similar indicators. The quality of these indicators however varies largely, as some are more robust and data is readily available (e.g. total $CO_2$ emissions per unit of GDP), while others face problems of data availability and reliability or even conceptual problems (e.g. the biodiversity indicator based on the Natural Capital Index per unit of GDP, which aims at capturing several types of pressure on biodiversity). One example of a decoupling indicator with population growth in the denominator is water quality, measured by the "discharge of nutrients from households into the environment versus total population" (also this indicator shows conceptual problems and problems of reliability and data availability).

Besides economy-wide indicators there are sector-specific indicators such as for transport (e.g. passenger-car and freight vehicles (combined) related emissions of $CO_2$, $NO_x$ and VOCs per unit of GDP) or agriculture (e.g. soil surface nitrogen surplus versus agricultural output). Table 1.1. in OECD (2002, p12ff) provides a list of 31 indicators covering a broad spectrum of environmental issues, combined with a judgement of robustness and data availability. Clearly, other institutions and authors also offer sets of or single indicators for specific cases of decoupling. Notable is the fact that the sector-level OECD indicators partly refer to total GDP as the economic variable in the denominator, while sector level indicators in the academic literature usually refer to sector output (cf. below). The detailed definition of the indicators clearly has to be considered when comparing different assessments of seemingly similar quantities.

*2.2 Identification of decoupling*

Identification of decoupling is in principle simple. Having chosen a decoupling indicator and given the data is available, it only has to be checked whether the decoupling indicator of interest decreases over time. Thus the basic of decoupling identification is simple descriptive empirics. Complications however arise due to effects of aggregation and price changes if the denominator is measured in monetary terms.

A simple and adequate method to further investigate aggregation effects in decoupling analysis is decomposition analysis. Decomposition analysis is not widely used in economics, maybe as it is purely descriptive and does neither build on economic theory nor on statistical methods. It is based on integral approximation and relates to index theory, and also to the IPAT equation from ecological economics and the Kaya identity. Besides application in index theory, it is mainly used in some contexts of environmental, resource and energy economics to better understand energy and resource use and emissions or impacts on the environment, and in development economics to investigate the development of poverty measures (c.f. Muller 2008).

Decomposition analysis allows disentangling an aggregate picture of decoupling on the level of a whole economy or a sector into several constituents on a sub-economy (e.g. sector level) or sub-sector level, and also allows to identify, whether the decoupling observed occurs in a context of a growing or declining economy or sector. This is best illustrated by a concrete example. Thus, an observed decoupling of $SO_2$ emissions from GDP growth for a whole economy can be decomposed into several constituents on sector level, such as changes in the $SO_2$ emissions per energy type used (e.g. decreasing sulphur contents of coal), the share of different energy types in the total energy used (e.g. an increasing share of natural gas), the energy intensity of each sector (i.e. energy use per unit of output) and changes in the sector composition (e.g. a decrease of the share of energy intensive sectors in total output).

The most important contribution of decomposition analysis to the mere description of decoupling indicators is the insight how an observed decoupling on aggregate translates into different patterns on a more disaggregate level. Often, decoupling cannot be observed for each sector, for example, and sometimes, a pattern of decoupling on aggregate level does not even translate into any decoupling on sector level but only into effects on sector composition. In such a case, no sector has become "better" in terms of environmental performance, but the best sectors have become larger at the expense of the worst. Part of the decoupling observed on aggregate in this case thus occurs in a context of sector-level economic decline.

It is interesting to point out that such decomposition analysis identifies the contributions of e.g. sectoral change and output growth on emissions in a formally well-framed way, accounting for all potential drivers at once. This contrasts to other approaches to account for these drivers by analysing simple "growth-" or "structure-adjusted" emissions, where total emissions are divided by production volume, resp. sectoral energy intensity is accounted for before summation of sectoral emissions to calculate total emissions. These adjustments however can only account for one variable and do not control for the development of other variables not included in the adjustment procedure. These simpler approaches are thus likely to produce biased results (see e.g. the assessment in chapter 9.3 in the otherwise very recommendable book Enevoldsen 2005).

It has to be emphasised that decomposition analysis is a purely descriptive method for a detailed ex-post analysis of decoupling indicators. A disadvantage is that no statistical inference can be based on it. On the other hand, data requirements for decomposition analysis are low and it can be undertaken with aggregate data, which is often readily available. One methodological problem is that decomposition analysis is based on the approximation of integrals from unknown functions. The different decomposition methods differ in how they achieve this approximation. In consequence, results of different methods can differ. Löfgren and Muller (forthcoming) and references therein (esp. Liu and Ang 2007) can be accessed for a recent methodological discussion of decomposition analysis. Currently, the best method available seems to be the Logarithmic Mean Divisia Index decomposition (for a description, see Löfgren and Muller, forthcoming, and references therein, e.g. Ang 2004). Specific problems of decomposition analysis in particular refer to the level of aggregation, both economy-wise and temporal (for optimal results, the analysis should be undertaken on a level as disaggregate as possible), and to the measurement of the economic variables in monetary terms (changes in prices can disrupt results if interpreted as changes in physical output; due to lack of data, there is often no remedy for this, though). See Löfgren and Muller (forthcoming) for further details.

*2.3 Decoupling – Concrete Examples*

Decoupling is in fact widely observed – although patterns are heterogeneous and the level of analysis should optimally be as disaggregated as possible. OECD (2002, Table 1.2, p14ff), for example, reports decoupling for most of their indicators in most countries, where data is available. Absolute decoupling is observed for air pollution and water quality and for most of the sector level indicators, the other indicators mostly show relative decoupling only. Most notable are the indicators for climate change which mainly show only relative or even no decoupling. The study is encompassing in coverage, but somewhat simplistic in further decomposition of their decoupling indicators into key drivers. It has also to be emphasized, that some of their sector indicators relate to GDP while most sector indicators used in decomposition analysis refer to sector output. In some sample comparisons with results from other studies undertaken for the energy sector (e.g. in Hammar and Löfgren 2001 or Löfgren and Muller, forthcoming), this does however not make a big difference. Another collection of illustrative examples is given in the Swedish Government's report Azar et al. (2002) and there are many more examples of governmental and other institutional reports providing evidence of the presence or absence of decoupling for various pollutants, countries and sectors (e.g. Speck et al. 2006; Speck and Salmons 2007; Kojima and Bacon 2009).

We give some examples of the types of results to be expected from decomposition analysis and others. Hammar and Löfgren (2001) investigate

Swedish $SO_2$ emissions and report considerable decoupling. Their decomposition analysis reveals that structural change did not play a very important role. Thus, the decoupling observed is not mainly due to shrinking of emissions intensive sectors, but rather due to fuel switch and decreasing energy intensity. Similar are the observations of Liaskas et al. (2000) for industrial EU $CO_2$ emissions (1983-1993), where structural change is of some importance in few countries only. This is also shown in the results from Diakoulaki and Mandaraka (2007), who report decoupling for $CO_2$ emissions (1990-2003), with structural change being of considerable importance in some few countries only. Specifically for industrial and business $CO_2$ emissions for Sweden, for example, Löfgren and Muller (forthcoming) find structural change to be important, though. Similar to OECD (2002), decoupling can be observed for the energy sector, but different to this report, no decoupling can be observed in the different transport sectors (land, air, ship). One reason could be the above-mentioned difference in indicators, as the OECD indicators for transportation refer to total GDP in the denominator, while Löfgren and Muller (forthcoming) use sector specific output measures. Finally, Tunc et al. (2009) and Oh et al. (2010) are two examples of recent LMDI decomposition analysis of energy related $CO_2$ emissions for Turkey and South Korea, respectively. Slight decoupling of aggregate energy use is found for Turkey, which is based on considerable decoupling of energy use in the services sector, no decoupling in the industry sector and a strong coupling in agriculture. There is decoupling for South Korea for the manufacturing, services and residential sector, but not for energy and transportation.

Data for the investigation and evidence of decoupling can also be found in country level analyses of the Environmental Kuznets Curve (EKC) Hypothesis, as the declining part of the EKC corresponds to the signature of decoupling. An example is Markandya et al. (2006) for $SO_2$ emissions in 12 Western European countries over the past 150 years, where direct descriptive evidence of decoupling is available, or Stern and Common (2001), which show decoupling of $SO_2$ emissions for developed countries but not so for developing ones (this is understandable in the logic of the EKC, as those have not yet reached income levels that correspond to the turning point in the EKC). We emphasize that for the decoupling empirics, we are interested in the data only and not in the underlying theory behind the EKC hypothesis itself.

The examples show the importance of disaggregate analysis of decoupling, both temporally and spatially (for single countries, for example) and also in particular regarding sector aggregation. In addition, due attention has to be given to the indicators used, in particular if several studies are compared. We emphasise again, that no causal links may be derived from this type of descriptive analysis. Identifying causes of decoupling and quantification of the contribution of a tax is the topic of the next section. Finally, a main issue of identifying decoupling is to clearly separate cases, where decoupling is accompanied with a decrease in the economic variable in the denominator of the decoupling indicator (e.g. in cases where decomposition analysis reveals an important contribution from structural change), and cases, where it is not, thus showing contributions from genuine increases in energy efficiency, for example. Although both these cases correspond to decoupling on an aggregate levels, their welfare effects in an economy will be very different. Correspondingly will the judgements of the welfare effects of a policy leading to decoupling differ.

## 3. Does environmental taxation lead to decoupling?

After the descriptive assessment of the presence and structure of decoupling, we now turn to the purpose of this chapter, namely whether and how a separate contribution from environmental taxation on decoupling may be identified and measured. There are several approaches to answer this question. Ideally, econometric models of a decoupling indicator as dependent variable with some variable capturing the environmental tax as explanatory variable, combined with due control variables can be estimated. This helps to identify the effect of the environmental tax on decoupling, based on a rather aggregate, i.e. economy-wide, sector or sub-sector level analysis (3.1). Second, firm level analysis can be undertaken, trying to estimate the effect of environmental taxes on emissions or energy intensity or fuel mix (3.2). Changes in these variables directly influence measures of decoupling on a more aggregate (e.g. sectoral) level. Third, the effect of an environmental tax on indirect determinants of decoupling such as innovation or technological change (as potential drivers of increased emissions efficiency), or location choice (as potential drivers of sectoral change) can be estimated. For an assessment of the contribution of a tax on decoupling based on such an analysis, the contribution of these indirect determinants on decoupling would need to be estimated. As these linkages are indirect and the estimation of the more direct cases already poses considerable challenges, we do not further pursue these econometric analyses in this chapter. Some of these issues are a topic in equilibrium models (c.f. 3.3.2) and some of the linkages between taxation and these indirect determinants are treated elsewhere in this book (e.g. the effect of environmental taxation on innovation). Finally, analysis of some partial effects is possible, e.g. the estimation of several own price and cross price elasticities of the consumption of different energy sources or the energy price elasticity of emissions or output. Also informative are detailed descriptions of the development of key variables embedded in the description of a broader political and economic context after introduction of a policy instrument, or firm level case study evidence based on interviews. Such more particular or narrative analysis cannot reveal the full contribution of environmental taxation to decoupling, but it can also provide important pieces for an encompassing picture. All this is the topic of section 3.3.

There are many econometric studies addressing the distributive effects of environmental taxation (i.e. whether this is regressive or progressive) or trying to estimate the optimal tax level (i.e based on the damage function of a pollutant or activity). However, we do not address these topics in this chapter.

This section builds on the work from the previous section. Having chosen the best suited decoupling indicator for the case at hand, decomposition analysis helps to identify the adequate level of aggregation, the most important sectors and potential patterns of drivers of decoupling (e.g. changes in efficiency, sectoral composition, size). This information can then help to improve the causal analysis. We will see that this is usually not done in the current literature and optimal combination of decomposition analysis and econometric approaches is part of the suggested future research presented in the conclusions.

### *3.1 Aggregate econometric analysis of decoupling*

Ideally, to answer the guiding question of this chapter, models with a decoupling indicator in dependence of some tax variable should be estimated. Besides insight on the effect of environmental taxation on some aggregate decoupling indicator, it should also be identified which driver of decoupling is influenced to which extent by the tax. It should thus be possible to identify whether a tax affects emissions efficiency within several sectors or rather sectoral composition, for example, as those two cases have very different effects in an economy, although an aggregate decoupling indicator may picture them identically. There are only few studies that go in the direction of estimating the effects of an environmental tax on decoupling (and that do not only estimate price elasticities used to derive effects of a tax on demand), and no study however implements this ideal case, combining both a sound estimation with a detailed decomposition of decoupling.

Enevoldsen et al. (2007a) estimate a demand system for different energy types for ten industrial sectors in the three Scandinavian countries. This aims at addressing the decoupling of $CO_2$ emissions and energy use, based on the effects of price changes on fuel type shares. The demand system estimation calculates own and cross price elasticities and the chosen estimation method (translog demand system estimation for a cross industry pooled model with fixed effects across industries and time) is motivated and discussed in detail, including often neglected aspects such as the discussion of different energy price discounts and tax exemptions for different sectors and fuels, which makes this study exemplary for the own and cross price elasticity estimation for different fuels. The find own-price elasticities of energy demand from -0.35 to -0.44 for Denmark, Norway and Sweden and conclude that environmental taxation will contribute considerably to energy consumption reductions. Despite the title of this paper, this approach cannot estimate the full effect of an energy and $CO_2$ tax on decoupling, though. Due to the elasticity estimates, the effects of price changes (and thus also of a tax) on factor use and emissions can be derived. However, elasticity estimates cannot identify individual drivers behind changes in energy demand or emissions. They cannot identify whether such changes are due to changes in energy efficiency, in emissions efficiency or in output, for example In addition, due to data availability, elasticity estimates are not sector specific (sector specific aspects were captured by fixed effects only). Decomposition analysis however shows, that sector specific differences greatly matter (cf. section 2). Thus, this type of study should be complemented with a decomposition analysis of emissions and energy use, which could be done sector-wise with the data available.

Studies like Enevoldsen et al. (2007a) could also be optimally combined with the results of studies like Enevoldsen et al. (2007b), where the effect of an energy tax on indicators for competitiveness (i.e. variables linked to the denominator in a decoupling measure) is estimated on sector level for 8 sectors in seven EU countries for 1990-2003. They proceed similarly as Enevoldsen et al (2007a) with this different, but complementary focus.

Enevoldsen (2005, chapter 10) contains a similar analysis as Enevoldsen et al. (2007a) but provides many additional details on the concepts and methods used. The basis of these approaches is the observation that prices, energy consumption and the like (i.e. the variables of interest for econometric analysis of decoupling) are non-stationary variables, meaning that "…they meander away from their starting point, thereby giving rise to a moving average instead of returning to a stable, long-term mean." (p192). Such variables thus show a "trend" over time. In addition, one observes that these variables do not move independently in the long run – they are "cointegrated". Cointegration captures a special type of dependence, namely that variables show the "same trend". More technically, two variables are cointegrated, if their differenced series are both stationary, i.e. "without trend" (resp. their at the same, higher order differenced series are both stationary). We point out that in this discussion, the potential role of a time trend (leading to trend-stationary variables without unit root that are thus similar to stationary variables) is not adressed. We will take this up below and in the conclusions. There is a huge specialised body of econometric literature, which can be employed to estimate models with cointegrated variables (cf. e.g. the discussion in Enevoldsen 2005 and any text book on time-series econometrics).

Smith et al. (1995) directly estimate energy and emissions intensities and thus directly estimate some decoupling indicator. They first use a similar cointegration approach with an error correction model to account for the short-term dynamics. The problem with this specification is the exogenous technological change. As the influence on technological change is one path how a tax can affect emissions intensity, Smith et al. (1995) then estimate a new model with endogenous technological change. The drawback in their estimation is the national level (8 countries), not differentiating for different sectors. They do however account for different fuel types and estimate substitution and price elasticities. By their approach, they thus can differentiate between the effect of increased emissions efficiency and the effect of fuel substitution. Sectoral change, however, cannot be captured by their approach. They find that differences between countries greatly matter (without providing further explanation for the differences) and that price elasticity of energy demand is relatively low for some countries. In the short run, gross values for the estimates are -0.05 for Italy, -0.1 for France, Japan and the UK, and somewhat higher levels for Canada and Germany (-0.3). USA is at -0.2. In the long run it is -0.1 for Italy, -0.4 for Canada, -0.5 for France, Germany and the USA, and -0.7 for the UK and Japan. Given the caveats towards the methods used, these numbers have to be used with caution. We report them as examples only.

Hammar and Löfgren (2001) is an example of a decomposition analysis of $SO_2$ emissions that is partly complemented by econometric estimation of the effects of fuel prices on the different drivers, such as fuel-shares of light and heavy oils or substitution from oil by other energy sources. The decomposition analysis reveals a strong contribution to reduced emissions from a switch to cleaner fuels, followed by the contribution from decreased energy intensity. Their regression analysis reveals significant but only small effects of a tax on sulphur emissions (via its effect on changes to oil with less sulphur content and on a switch from oil to other fuels). Their decomposition analysis uses another method than LMDI, but a rerun using LMDI results in small and unimportant changes only. The regression analysis is however done in a very simple manner, not being based on a demand system estimation, for example, and neither taking into account time trends or structural breaks. The results derived for the effects of a tax on decoupling, resp. on underlying patterns are thus to be interpreted with caution.

Similar caution is in place towards the results of Metcalf (2008) who decomposes US energy intensity into an efficiency and an activity (i.e. "sector composition") part and then runs regressions of those variables on several independent variables, such as energy prices. From the decomposition analysis, the author derives that about three quarter of the energy intensity decrease from 1970 to 2003 was due to increased efficiency, while shifting to less energy intensive activities accounted for about one quarter. The author undertakes this analysis on national and state level, but does differentiate between very gross sectors only (residential, commercial, industrial, transportation). He thus cannot account for different developments in different types of industry or transportation, for example. These developments are however very important, as the studies that can account for them show. The regression analysis shows that primarily rising per capita income and also energy prices (thus also a tax) contribute to increasing energy efficiency. The decomposition method is based on a refined Fisher Index and the estimation is done without reference to cointegration techniques. Improving the methods for the same analysis (LMDI for decomposition and cointegration analysis for the estimation) would thus be interesting. The methods chosen may also explain the discrepancy in results to a similar analysis as noted in their footnote 1.

Somewhat stretching the notion of decoupling, we can also count Hammar and Löfgren (2000) as an example of a study directly assessing the impact of an environmental tax on decoupling. They address the specific problem of phasing out leaded gasoline. They estimate the share of leaded gasoline in dependence of the price differential between leaded and unleaded gasoline (i.e. the tax level on leaded gasoline) and other variables. This share can be understood as a decoupling indicator, taking leaded gasoline as the environmental pressure variable and total gasoline as the economic activity variable. They identify a significant (but small) contribution of the tax on the reduction of the share of leaded gasoline. More important were the per capita income and the share of catalytic converters. They estimate both fixed and random effects with and without time trends but undertake no cointegration analysis. Including a time trend leads to lower significance of the theoretically justified variables in their model and they thus decide to not include a time trend. Hausman's test favours fixed effects, but differences between fixed and random effects are small.

*3.2. Econometric analysis of decoupling based on firm level data*

Besides aggregate data, firm level data can be used for the empirical analysis of decoupling. Although decoupling is an aggregate concept, based on the development of aggregate variables, e.g. on a global, country or sector level, the analysis of firm level data on the effect of environmental taxation on emissions and energy intensity, input use, output and other quantities can add insight on the effects of taxation on decoupling as these quantities on firm level are tightly related to patterns of decoupling on a more aggregate level.

The study of Bjorner and Jensen (2002), for example, estimates a translog regression of energy consumption on factor prices and output and control variables, using a single equation company fixed effects energy demand model and panel data of single companies in Denmark, 1983-1997. Energy consumption is measured as an aggregate (according to energy content) of several fuel types. For electricity, specific prices paid by each company are used (based on the prices from each of the 100 different electricity utilities in Denmark), while for the other energy types, general prices are used.

This study estimates price elasticities of energy demand and thus only a part of the decoupling indicator. They find that the elasticities strongly differ between pooled and company fixed effects estimation and that fixed effects should be used. The elasticity estimates also depend on the level of energy price (in the quadratic functional form that has a better fit). The average energy price elasticity is -0.44 and it is lower for energy intensive companies and higher for energy extensive ones (range between -0.2 to -0.7).

The study does not derive effects of an energy tax (viz. increasing energy prices) on output or on some aggregate variable capturing sectoral change. Due to the aggregation over fuel types, this analysis also lacks information to estimate effects on fuel substitution as one driver behind decoupling.

*3.3. Complementary information – elasticity estimates, CGE models and case-studies*

3.3.1 In the previous sections, we have already seen that estimation of the effect of taxation on decoupling often is attempted via some partial analysis only, such as the estimation of price elasticities of energy demand. There is a wealth of such elasticity studies for different goods (e.g. gasoline, industrial energy use, etc.) and they contribute to the understanding of the effect of environmental taxes. On the other hand, they do not provide the full picture if not complemented with further analysis. We refer to some of them, as the assessment of environmental taxation's effect on decoupling will at least partly remain a combination of different pieces of evidence – and in such a context, elasticity estimates and the incidence of a tax based on those alone add important information.

Huntington (2007) estimates US natural gas demand based on 45 years time series data. First, he tests the stationarity of the variables involved and concludes that they are stationary (or time-trend stationary). Correspondingly, simpler estimation procedures can be employed. The stationarity of the key variables is in contrast to the findings in the studies referred in section 3.1. One reason hinted at by Huntington (2007) is the short duration of the time-series employed in these other studies: the usual test for stationarity is not very powerful with few observations and due attention should be given to take potential time trends and structural breaks into account. Price and output elasticities of natural gas demand are then estimated adopting an autoregressive distributed lag relationship with current and lagged values of natural gas consumption and the independent variables. Huntington finds price elasticities for natural gas of -0.25 in the short and -0.7 in the long run (referring results from his preferred model). The drawback of this study is the level of aggregation, which does not differentiate for different sectors and is done on national level. In addition, the drawbacks of mere price elasticity of demand apply, i.e. the impossibility to separate structural change and output effects of a change in prices (viz. of a tax). He tries however to partly capture structural change effects by employing an aggregate output variable across industries that weights output with energy intensity for each industry. The stationarity of key variables found by Huntington (2007) is however of importance, as this influences the optimal estimation methods to be used.

Floros and Vachou (2005) is a further example of a study estimating price and substitution elasticities of industrial fuel demand. They estimate a demand system for the Greek economy and derive the impact of a $CO_2$ tax based on the elasticities estimated. Again, this study is subject to the drawbacks already mentioned for tax incidence estimations based on elasticities.

A large part of studies providing elasticity estimates addresses gasoline demand. We do not report them in detail, but point out some aspects that can inform the econometric analysis of decoupling. First, given the large number of studies on gasoline elasticities, meta-analysis of these results can be undertaken (e.g. Brons et al. 2008). Such an analysis helps to integrate differing results from a wealth of studies and will be important for the econometric analysis of tax incidence on decoupling as soon as enough specific studies are available. It also helps to integrate different aspects of the various studies, such as the estimates of price elasticity of demand, but also of its determinants, i.e. price elasticities of fuel efficiency, mileage per car and car ownership (just as decoupling has underlying determinants such as fuel mix, emissions intensity, output and sectoral change). In the recent and detailed meta-study of Brons et al. (2008), a mean of -0.34 and -0.84, respectively, for the short and long run price elasticity of gasoline demand is found (reporting their estimates from a "seemingly unrelated regression" (SUR) model; standard fixed effects lead to similar results, though). Changes in fuel efficiency and mileage per car are the most important drivers of the impact of gasoline price on demand. Car ownership is somewhat less important. The elasticity estimates in the studies analysed strongly depend on the study characteristics such as geographic area, time period, functional form of the demand equation, etc.

Second, there are recent studies that allow for time-varying coefficients and thus for elasticity estimates that vary over time. Given the large differences of price elasticity estimates for gasoline demand for different periods, this is a potentially important differentiation also for the econometric analysis of decoupling (see e.g. Park and Zhao 2010 on US gasoline demand, reporting values of -0.15 to -0.3 for 1976-1983 / 2006-2008 and 0 to -0.2 for 1984-2005, or Hughes et al. 2008, also on US gasoline demand, reporting -0.034 to -0.077 for 2001-2006, vs. -0.21 to -0.34 for 1975-1980, analysing two

periods with similarly high gasoline prices, using somewhat simpler econometrics than the former study).
As already mentioned, price elasticities of demand allow for some indication of the incidence of a tax on demand, but do not account for the various paths how such price signals may be transmitted in an economy and do not allow for an estimate of the incidence on decoupling. Sterner (2007) is an illustrative example attempting such an incidence analysis with simple means for gasoline use in Europe, mainly building a counterfactual with lower taxes and using elasticity estimates to derive corresponding demand. He concludes that “Had Europe not followed a policy of high fuel taxation but had low US taxes, then fuel demand would have been twice as large.”

3.3.2 Complementary to the econometric approaches to particular aspects are economy-wide models such as computable general equilibrium models. At the expense of many assumptions (in particular the assumption of a general equilibrium, assumptions on the functional form and the values of relevant parameters of how inputs are combined in the production process, resp. on how utilities for single goods add up to aggregate total utility of consumers), such models can capture some of the complexities of the cause-effect chains in a real economy. There are many examples of such models and corresponding publications. Accessible is the description and graphical representation in Bruvoll and Larsen (2004), for example, which model the incidence of the Norwegian $CO_2$ tax on emissions (1990-1999), based on a model run with the real carbon tax and a counterfactual model run without. They find an only modest contribution of the carbon tax to $CO_2$ emissions reductions (namely 2%). This small effect may be compared to the large effect of fuel taxation identified by Sterner (2007). This difference can be traced back to the fact that the carbon tax accounts for only a fraction of total fuel taxes. The level of the carbon tax in Norway was thus much lower (and allowed for many exceptions) than the fuel taxes considered in Sterner (2007). The key contribution of such models is the ability to provide some intuition on how a $CO_2$ tax, for example, affects the use of inputs (capital, labour energy, materials, services), intermediate goods and output in various sectors, how it affects technological progress and innovation, and how it affects the consumption of goods by individuals. Depending on the focus of interest, different parts of the economy can be pictured in more or less detail. In the end, all these different causal chains and linkages give rise to some aggregate effect on emissions and output and thus on a decoupling indicator. A key input thereby are price and substitution elasticities and thus

the results from the studies described in the previous subsection 3.3.1. A further drawback of these models is their often very high complexity that makes them inaccessible to many readers who thus have to accept (or criticise) them as a “black box”.
On the other hand it is impossible to intuitively capture all the complexities of a real economy and these models offer a simplification and clarification along the lines of well-defined causal chains. It is, for example, doubtful to derive the incidence of an environmental tax on emissions or output just by referring to its level and the corresponding price elasticity. Calculating these effects in the framework of a well-built equilibrium model is more reliable, as all the indirect effects are captured as well. If the equilibrium model itself is doubtful, though, the analysis may only lead to wrong confidence. These models are thus to be used with big caution. Goulder et al. (1999) present a detailed but relatively accessible example of an equilibrium model illustrating how it can support the understanding of more complex cause-effect chains in an economy. They address the question of the double dividend on a theoretical/numerical level, but their approach is exemplary on how GE models may be used to identify how and over which paths policy instruments become effective in an economy.

3.3.3. A very different type of complementary information is provided by case-study analysis. The empirical analysis of $NO_x$ emissions per GWh in Sweden (Sterner and Höglund Isaksson 2006, Höglund Isaksson 2005) contains also some results based on descriptive analysis of single plant data combined with interview results and information of the timing of the policy instrument. This simple analysis provides strong evidence that the refunded emission payments (i.e. a tax with refund) were the main cause for the extensive emissions reductions observed (-40% in mean emission rates).
Another example is chapter 11 in Enevoldsen (2005). It is based on interviews with persons from industrial firms, branch associations, industry and labour associations, industrial energy technology expert organisations, government agencies and academics. Such an approach gives case-study like evidence that can complement a statistical analysis with concrete “stories” on how environmental taxation may affect single firms, in particular allowing some assessment of within-firm aspects, such as internal decision structures and barriers. Enevoldsen finds that energy decision-making is well organised and professional in energy intensive firms and the overriding goal is cost minimization with respect to energy input, but this is at times interpreted in a long-term perspective. The central concern there is

the pay-back time of energy investments. Such interview studies clearly provide only very indirect evidence of the incidence of environmental taxation on decoupling, though.

## 4. Conclusions

First, we can state that on an aggregate level (e.g. nation level) considerable decoupling takes place according to many indicators: energy use or local air pollutants decouple from GDP or total industrial output. However, this has to be investigated in more detail. For $CO_2$, for example, no or only weak decoupling can be identified in most cases, while $SO_2$ shows a clear pattern of decoupling. Many pollutants also only show relative and not absolute decoupling. This means, that the environmental pressures still increases, albeit at a lower rate than economic performance (e.g. $CO_2$). This is by far not enough to reach certain environmental goals, such as the greenhouse gas emissions reductions necessary to limit climate change to manageable levels, say keeping warming below 2ºC in the 21st century. The presence of decoupling is thus by no means an indicator for a sustainable economic development. To get sufficient decoupling strong policies may be required.

Second, the simple descriptive empirics of decoupling indicators should be complemented with analysis to identify underlying patterns, such as decomposition analysis. This reveals that a disaggregate picture is necessary to understand decoupling in detail. Annual instead of decennial and sector or sub-sector level analysis instead of national is necessary to gain a realistic picture.

Third, causal analysis of the effects of environmental taxation on decoupling is notoriously difficult. Ideally, decomposition analysis revealing detailed disaggregate patterns of decoupling should be combined with econometric estimation to identify the contribution of key variables. Such combined studies are rarely undertaken, and if so, either the decomposition or the econometric part is not very elaborate. Decomposition analysis should use the LMDI method. Further research is however still needed on optimal decomposition methods and how they relate to the underlying integral approximation problem. The specific statistical characteristics of the time-series analysed (cointegration, stationary vs. non-stationary, etc.) may be employed to optimise these methods. The econometric estimation should also account for this and cointegration techniques may often be the first choice. Due attention has however to be given to several tests for time-trends, structural-breaks, non-stationarity, resp. unit-roots, etc. in particular in the light of shorter time-series.

Fourth, such detailed combined descriptive and econometric analysis can further gain from more partial insights, e.g. on price and substitution elasticities or firm-level interview studies. This information should be included more systematically in the assessment of decoupling. Especially the rich knowledge from elasticity studies, including the newer insights on changing elasticities over time, should be used in such a way as to also account for the effects of changes in the economic variables and not only for the effect of price change on the environmental pressure. There, complementary analysis with whole-economy models, such as CGE models can be very informative.

Coming back to our question - is there a separate contribution from environmental taxation on decoupling? In some cases, there is automatic decoupling simply through technical progress or other forces. In many cases however, particularly when abatement or decoupling implies bigger costs it will not happen without strong policy instruments. These instruments may be either taxes or conceivably some other policy instrument such as tradable permits. For many examples, the tax has been crucial to make decoupling happen. In other cases, there is a big contribution from taxation to reducing emissions, but analysis does not directly address decoupling. However, employing complementary information on GDP development, for example, sometimes points to a crucial contribution to decoupling as well (e.g. in the case of gasoline taxation). Further cases show an only weak contribution of taxation on decoupling. In parts, other drivers are more important. For some cases though, the tax level is low and higher taxes likely would lead to decoupling. Detailed answers can be derived employing the methods described in this chapter.

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