Influences of various drivers of the CO2 emissions in the US with a special focus on the fuel mix

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Abstract

The CO2 emissions in the US decreased by roughly 10% between 2007 and 2013, whereby the causes have been much debated. Feng, Davis, Sun, and Hubacek concluded, based on a structural decomposition analysis, that the main driver for the decline was the economic recession and that the shift in the fuel mix only played a minor role. In this thesis, I compiled an extended data set, taking the differences between the national accounting framework and energy statistics into account, and conducted a structural decomposition analysis by means of that data. My results show that during the years where the financial crisis was felt the strongest, between 2007 and 2009, the economic recession did have the strongest influence on the decline of the CO2 emissions. However, between 2010 and 2013, the strongest driver with a negative effect on the CO2 emissions was indeed the fuel mix.

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Abbreviations

BEA	Bureau of Economic Analysis
EIA	U.S. Energy Information Administration
IDA	Index Decomposition Analysis
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NAICS	North American Industry Classification System
SDA	Structural Decomposition Analysis
UNFCCC	United Nations Framework Convention on Climate Change
WIOD	World Input-Output Database

1 Introduction

After the CO2 emissions in the Unites States of America had been on the rise for decades, they experienced a decline between the years 2007 and 2013. Various publications attribute said decline to a change in the economy-wide fuel mix from coal to natural gas. In this way, the report on *the third national climate assessment* by the U.S. Global Change Research Program (Melillo, Richmond, & Yohe, 2014) states that the decline in CO2 emissions is largely due to a shift from coal to less CO2-intensive natural gas for electricity production. This line of argument is supported by Trembath, Luke, Shellenberger, and Nordhaus (2013) who claim that:

> “The rapid replacement of coal by cheaper and cleaner natural gas has helped drive emissions down in the United States more than in any other country in the world in recent years. Cheap natural gas is crushing domestic demand for coal and is the main reason for the rapid decline in US carbon emissions. The gas revolution offers a way for the United States and other nations to replace coal burning while accelerating the transition to zero-carbon energy.”

They further state that the uprising technology of hydraulic fracturing, which is used to extract gas from shale and other unconventional rock formations, has the potential to be as groundbreaking as past energy technology revolutions. They mention that legitimate concerns about noise, air, water, and methane pollution should and can be raised, however, they argue that the evidence of natural gas replacing coal points towards an improved air quality and reduced greenhouse gases.

Feng, Davis, Sun, and Hubacek (2015a) allege that the different factors, which potentially influenced the decline in CO2 emissions between 2007 and 2013, have not yet been quantitatively analyzed. Consequently, they argue that the role of natural gas in said decline remains speculative.

By means of a structural decomposition analysis (SDA), Feng et al. (2015a) derive various conclusions, where two stand out. First, they deduce that between the years 2007 and 2013 the most important driver of the decline in CO2 emissions was the economic recession. Second, they conclude that the change of the fuel mix in the same period of time did merely play a comparatively minor role in the decline of CO2 emissions.

Mohlin, Camuzeaux, Muller, and Wagner (2015) conducted an index decomposition analysis (IDA) to examine the exact same matter and came to different results. They conclude that three factors played equally important roles in the decline in CO2 emissions after the year 2007, namely the economic recession, the change in the fuel mix from highly CO2-intensive energy sources to natural gas, and the change in the fuel mix from CO2-intensive energy sources to renewable energy sources.

In this master thesis, I reassess the influences of various drivers of the CO2 emissions in the US with a special focus on the fuel mix. Thereby, the research question reads as follows:

> *What are the main driving factors behind the decline in CO2 emissions between 2007 and 2013 and what role does the fuel mix play?*

I conduct the reevaluation by means of a structural decomposition analysis based on the structural decomposition analysis by Feng et al. (2015a). However, I disaggregate the contributing factor *fuel mix* used by Feng et al. into two factors to obtain a more detailed perspective on the development of said contributing factor.

This thesis is structured as follows: First, after this introduction, I give an overview on the theoretical background of this thesis including Input-Output tables, the method of the structural decomposition analysis, and a contrasting juxtaposition of national accounts and energy statistics. Second, I explain the data compilation I carried out for the subsequent analysis on the one hand, and a replication of the data compilation by Feng et al. (2015a) on the other hand. A description of the structural decomposition analysis, which lays the foundation of this thesis, and a description of the structural decomposition analysis by Feng et al. also form part of the method section. Third, I present the results of the structural decomposition analysis that I conducted, the results of the replication of the analysis by Feng et al., and I compare the results of my analysis with the ones by Feng et al. (2015a). Finally, I put the results into context in the discussion and close with a summarizing conclusion.

2 Background

2.1 Basic Input-Output analysis

In their book by the name of *Input-Output Analysis*, Miller and Blair (2009) introduce the general concept of Input-Output analysis as well as numerous specific applications such as environmental Input-Output analysis or the Commodity-by-Industry approach in Input-Output models. The latter was the most relevant for this thesis besides the general concept, therefore, in the following, I briefly present these two subjects.

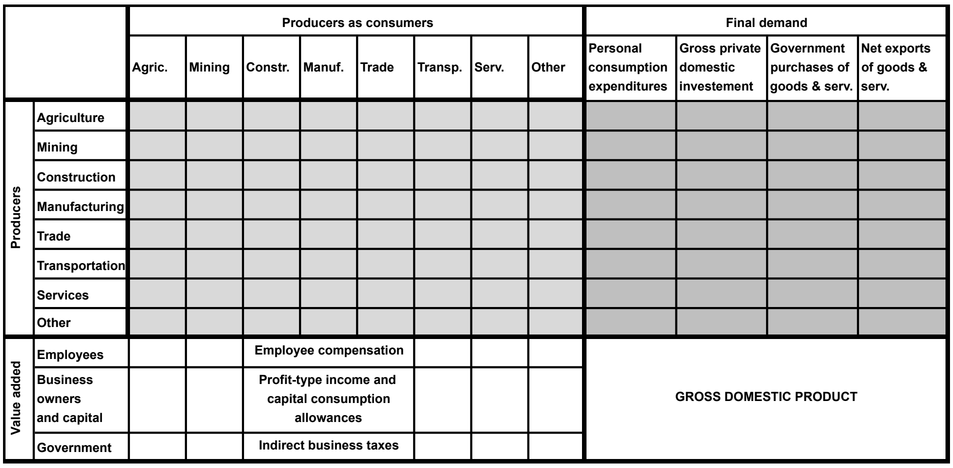
Input-Output tables are constructed based on observed data for a specific area such as a country or a state. The entire economy is spilt into segments, which can be large sectors like “Manufacturing”, single industries such as the “Steel industry”, or a rather small category like “Steel nails and spikes”.

The focus of interest are, first of all, interindustry flows, which are the transactions from one industry to another for the entire economy within a certain time period under consideration (usually a year). These transactions are measured in monetary terms, since monetary terms can be applied equally to all goods and services in an economy. Even though, physical terms might be more precise in various cases, the lack of comparability makes it almost impossible to apply physical terms equally to an entire economy. Examples of said transactions are the steel industry selling steel to the car manufacturing industry or the leather industry selling leather to the shoe industry. Both transactions depend on the demand for cars or shoes, respectively, in the observed time period. Included in the interindustry transactions are intraindustry transactions, e.g. a manufacturer of shoe laces that is part of the shoe manufacturing industry sells laces to a boot manufacturer who is also part of that very industry.

Second of all, each producing industry needs to pay not only for goods and services from other industries but also for labor and capital, so called value added. Last, another category of transactions are those between industries and more external purchasers, e.g households, government, or export, so called final demand.

The overall structure of an Input-Output table is depicted in the following figure. The interindustry flows are represented by the light grey area, the flows from the industries to the different final demand categories are described by the dark grey area, and the the diverse value added categories are represented by the white area. The columns describe the composition of inputs by each industry that is required to produce the industry's output, which is described in the rows (Miller & Blair, 2009).

Figure 1: Exemplary Input-Output table



		Producers as consumers								Final demand			
		Agric.	Mining	Constr.	Manuf.	Trade	Transp.	Serv.	Other	Personal consumption expenditures	Gross private domestic investement	Government purchases of goods & serv.	Net exports of goods & serv.
Producers	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other												
Value added	Employees			Employee compensation						GROSS DOMESTIC PRODUCT			
	Business owners and capital			Profit-type income and capital consumption allowances									
	Government			Indirect business taxes									

Based on Figure 1.1 by Miller and Blair (2009)

Formally, Figure 1 can be represented as follows: Assume that an economy can be split into n industries, where x_i is the total output of industry i, z_{ij} denotes the interindustry transaction from industry i to industry j and f_i indicates the demand for industry i's output by all final demand categories. Thereby, each industry's production corresponding to the rows in Figure 1 can be constituted according to Equation 1.

$$x_i = z_{i1} + \ldots + z_{ij} + \ldots + z_{in} + f_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{1}$$

Depicting Equation 1 for all n industries looks as follows:

$$\begin{aligned} x_1 &= z_{11} + \ldots + z_{1j} + \ldots + z_{1n} + f_1 \\ &\vdots \\ x_i &= z_{i1} + \ldots + z_{ij} + \ldots + z_{in} + f_i \\ &\vdots \\ x_n &= z_{n1} + \ldots + z_{nj} + \ldots + z_{nn} + f_n \end{aligned} \tag{2}$$

Each z_{ij} fully depends on x_j, i.e. each transaction from industry i to industry j is fully depended on the output of the latter. This becomes apparent by considering an example such as the following: If the production of the car manufacturing industry (industry j) is very low in a certain period of time, then the the steel production (industry i) consequently sells a relatively low amount to the car manufacturing industry. This dependency can be outlined as follows, where a_{ij} is called the technical coefficient.

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{3}$$

With the aid of Equation 3, Equation 2 can be rewritten by replacing all z_{ij} by $a_{ij}xj$ showing the dependency of each interindustry transaction.

$$\begin{aligned} x_1 &= a_{11}x_1 + \ldots + a_{1j}x_j + \ldots + a_{1n}x_n + f_1 \\ &\vdots \\ x_i &= a_{i1}x_1 + \ldots + a_{ij}x_j + \ldots + a_{in}x_n + f_i \\ &\vdots \\ x_n &= a_{n1}x_1 + \ldots + a_{nj}x_j + \ldots + a_{nn}x_n + f_n \end{aligned} \tag{4}$$

Assuming that the only amounts known for a coming period of time are the demands by the final demand categories, Equation 4 can be rearranged as follows:

$$\begin{aligned} (1 - a_{11})x_1 - \ldots - a_{1i}x_i - \ldots - a_{1n}x_n &= f_1 \\ &\vdots \\ -a_{i1}x_1 - \ldots + (1 - a_{ii})x_i - \ldots - a_{in}x_n &= f_i \\ &\vdots \\ -a_{n1}x_1 - \ldots - a_{ni}x_i - \ldots + (1 - a_{nn})xn &= f_n \end{aligned} \tag{5}$$

When $\boldsymbol{\hat{x}} = \begin{bmatrix} x_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & x_n \end{bmatrix}$, according to the definition of an inverse

$(\boldsymbol{\hat{x}})(\boldsymbol{\hat{x}})^{-1} = \boldsymbol{I}$, then $\boldsymbol{\hat{x}}^{-1} = \begin{bmatrix} 1/x_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & 1/x_n \end{bmatrix}$. $\boldsymbol{Z}$ can be defined as

$\boldsymbol{Z} = \begin{bmatrix} z_{11} & \dots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \dots & z_{nn} \end{bmatrix}$, which allows the representation of a $n \times n$ technical coefficient matrix:

$$\boldsymbol{A} = \boldsymbol{Z}\boldsymbol{\hat{x}}^{\boldsymbol{-1}} \tag{6}$$

When $\boldsymbol{I}$ is the $n \times n$ identity matrix, then

$\boldsymbol{(I - A)} = \begin{bmatrix} (1 - a_{11}) & -a_{12} & \dots & -a_{1n} \\ -a_{21} & (1 - a_{22}) & \dots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \dots & (1 - a_{nn}) \end{bmatrix}$. Denoting $\boldsymbol{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$

and $\boldsymbol{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix}$ allows to define Equation 5 in matrix notation.

$$\boldsymbol{(I - A)x} = \boldsymbol{f} \tag{7}$$

Finally, if $\boldsymbol{(I - A)}$ is non-singular, the unique solution to Equation 7 is denoted in Equation 8, where $\boldsymbol{L}$ is the so called *Leontief inverse* or also the *total requirements table.* In conclusion, Equation 8 elucidates the dependency of the gross output on the total demand by the final demand categories and acts as an indicator for the production structure of the entire economy in the structural decomposition analysis introduced further below (Miller & Blair, 2009).

$$\boldsymbol{x} = \boldsymbol{(I - A)}^{\boldsymbol{-1}}\boldsymbol{f} = \boldsymbol{Lf} \tag{8}$$

According to Miller and Blair (2009), this representation serves to answer questions such as the following:

> "If the demands of the exogenous sectors were forecast to be some specific amounts next year, how much output from each of the sectors would be necessary to supply these final demands?"

Other authors depict Input-Output tables differently, e.g. Hildenbrand and Hildenbrand in their book *Lineare ökonomische Modelle* (1975), where each column represents a so called production program or production plan. In its simplest form, the authors present the following exemplary table:

Table 1: Exemplary Input-Output table by Hildenbrand and Hildenbrand

	Agriculture	Industry
Food	1	0.6
Machines	-0.2	1
Labor	-1	-1

The production of 1 unit of food by the sector "agriculture" requires 0.2 units of machines and 1 unit of labor, whereas the production of 1 unit of machines by the sector "industry" needs 0.6 units of food and 1 unit of labor. The limiting factor in this depiction is the availability of labor, therefore, for different levels of labor availability, the most efficient compositions of production plans can be calculated (one plan for each sector). Hildenbrand and Hildenbrand's method also serves to evaluate whether an economy depicted in an Input-Output table is productive at all or not, i.e. whether an economy is even able to produce goods and services.

However, since I take already compiled Input-Output data representing past economic activities as a starting point for the analysis in this thesis, which is available in the format according to Miller and Blair (2009), I did not further enquire other Input-Output approaches such as the one introduced by Hildenbrand and Hildenbrand (1975).

2.2 The Commodity-by-Industry approach in Input-Output analysis

This section introduces an exemplary way of compiling Input-Output tables based on underlying Make and Use tables. All Commodity-by-Industry approaches, which can be found in Chapter 5 of *Input-Output Analysis* by Miller and Blair (2009), have in common that any industry can produce more than one commodity. Therefore, the fundamental concept is that *industries* use *commodities* to make *commodities*. In the Commodity-by-Industry approach, there are two underlying matrices, based on which the Input-Output tables are constructed, namely the *Use* matrix and the *Make* matrix.

The Use matrix $\boldsymbol{U} = [u_{ij}]$ shows each industry j's purchases (columns) of commodities i (rows) and, thereby, is the equivalent of *industries use commodities* from *industries use commodities to make commodities.* As in the previous section with a_{ij}, technical coefficients can be calculated for the Use matrix, where b_{ij} denotes the amount of commodity i in USD needed by industry j to produce one USD of output by industry j.

$$b_{ij} = \frac{u_{ij}}{x_j} \tag{9}$$

In matrix notation, this relationship can be rewritten as

$$\boldsymbol{B} = \boldsymbol{U}\boldsymbol{\hat{x}^{-1}} \tag{10}$$

where $\boldsymbol{B}$ has the dimensions *commodities-by-industries.* Other matrices in this section have different dimensions and, depending on the multiplication of such matrices, varying dimensions may result. Information on the final demand is commonly part of Use tables since all final demand categories use commodities just like industries, however, unlike industries, not to produce commodities. The column vector in the Use table containing total final demand from each industry is defined as $\boldsymbol{e}$.

The Make matrix $\boldsymbol{V} = [v_{ij}]$ represents the value of output in commodities j (columns) by each industry i (rows) and thereby quantifies the part of *industries make commodities* in *industries use commodities to make commodities.*

$\boldsymbol{x}$, which is used in Equation 10 can be computed by summing up each row of the Make matrix yielding the total industry outputs ($\boldsymbol{\hat{x}^{-1}}$ corresponds to dividing i, a column vector of ones, by $\boldsymbol{x}$ and transforming it into a diagonal matrix). Accordingly, when each row of the Use matrix is summed up, $\boldsymbol{q}$ is obtained, which denotes the total commodity outputs. Both of these relationships can be formally represented as follows, where $\boldsymbol{i}$ is a column vector of ones that is needed for the equations to be solvable.

$$\boldsymbol{x} = \boldsymbol{V}\boldsymbol{i} \tag{11}$$

$$\boldsymbol{q} = \boldsymbol{U}\boldsymbol{i} + \boldsymbol{e} \tag{12}$$

Rearranging Equation 10 and substituting into Equation 12 gives the parallel to Equation 8, however, a total requirements table cannot be calculated because the left-hand side of the equation contains commodity output $\boldsymbol{q}$ and the right-hand side of the equation contains industry output $\boldsymbol{x}$ (Miller & Blair, 2009).

$$\boldsymbol{q} = \boldsymbol{Bx} + \boldsymbol{e} \tag{13}$$

The solution to obtaining a total requirements matrix is to either transform industry output $\boldsymbol{x}$ into commodity output $\boldsymbol{q}$ or vice versa, which can be achieved in two alternative ways by using the Make matrix, whereby only one of said two ways is presented in the following.

d_{ij} can be calculated as follows, denoting the share of industry i in the total commodity output j. This relationship can also be represented in matrix notation.

$$d_{ij} = \frac{v_{ij}}{q_j} \tag{14}$$

$$\boldsymbol{D} = \boldsymbol{V}\boldsymbol{\hat{q}}^{\boldsymbol{-1}} \tag{15}$$

Rearranging Equation 15 thusly $\boldsymbol{D} = \boldsymbol{V}\boldsymbol{\hat{q}}^{\boldsymbol{-1}} \rightarrow \boldsymbol{D}\boldsymbol{\hat{q}} = \boldsymbol{V} \rightarrow \boldsymbol{D}\boldsymbol{\hat{q}}\boldsymbol{i} = \boldsymbol{V}\boldsymbol{i}$, and substituting into Equation 11, yields:

$$\boldsymbol{Dq} = \boldsymbol{x} \tag{16}$$

which, if $\boldsymbol{D}$ is square and non-singular, can be rewritten as:

$$\boldsymbol{q} = \boldsymbol{D}^{\boldsymbol{-1}}\boldsymbol{x} \tag{17}$$

Finally, Equation 17 can be substituted into Equation 13 in the following way, $\boldsymbol{q} = \boldsymbol{B}(\boldsymbol{Dq}) + \boldsymbol{e} = (\boldsymbol{BD})\boldsymbol{q} + \boldsymbol{e}$, which gives:

$$\boldsymbol{q} = (\boldsymbol{I} - \boldsymbol{BD})^{\boldsymbol{-1}}\boldsymbol{e} \tag{18}$$

Equation 18 is a calculated equivalent of Equation 8, where the inverse on the right-hand side of Equation 18 is called a *commodity-by-commodity total requirements matrix* due to the fact that commodity final demand is connected to commodity output.

The compilation of other total requirements matrices such as an *industry-by-commodity total requirements matrix* can be found in Chapter 5.3 of *Input-Output Analysis* by Miller and Blair (2009). The calculation of the total requirements table in Equation 18 shall exemplify how to get from Make and Use tables to an Input-Output table. Moreover, this particular approach served as a basis for the extended structural decomposition analysis in Section 3.3 .

2.3 Structural decomposition analysis

When Input-Output tables for more than one year are available, analysts are often interested in decomposing the total amount of change in any coefficient between the years under consideration, such as gross output, into various components. E.g. the total change in gross output could be disaggregated into changes in the production structure, as represented by the total requirements matrix, and into changes in final demand. The disaggregation could also be further reaching and thereby include more factors contributing to the total change: In the example of the disaggregation of gross output, the influence of final demand on the total change of gross output could be further decomposed into the final demand structure and the final demand volume. To obtain unbiased results, the data under consideration needs to be available in constant prices (Miller & Blair, 2009). To introduce the general concept of the structural decomposition analysis (SDA), Equation 8: $\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} = \boldsymbol{L}\boldsymbol{f}$, which is presented in the preceding section, serves as an example. Thereby the change in gross output $\boldsymbol{x}$ is decomposed into the part of the total requirements matrix or so called Leontief inverse $\boldsymbol{L}$, and the part of final demand $\boldsymbol{f}$. In the following the two time periods, between which the change is analyzed, are denoted with the superscripts 0 and 1. Thus, Equation 8 for the two time periods looks as follows:

$$\boldsymbol{x^0} = \boldsymbol{L^0 f^0} \tag{19}$$

$$\boldsymbol{x^1} = \boldsymbol{L^1 f^1} \tag{20}$$

The change in gross output is then defined as:

$$\boldsymbol{\Delta x} = \boldsymbol{x^1} - \boldsymbol{x^0} = \boldsymbol{L^1 f^1} - \boldsymbol{L^0 f^0} \tag{21}$$

The challenge posed is to transform Equation 21 in such a way that the change in the Leontief inverse and the change in final demand, as defined in the following, can be determined. This transformation is required since Equation 21 only yields the overall change in gross output and does not allow to deduce the influence of the Leontief inverse on the one hand and the influence of final demand on the other hand separately.

$$\boldsymbol{\Delta L} = \boldsymbol{L^1} - \boldsymbol{L^0} \tag{22}$$

$$\boldsymbol{\Delta f} = \boldsymbol{f^1} - \boldsymbol{f^0} \tag{23}$$

Equation 22 and 23 can be substituted into Equation 21 in numerous ways, e.g. $\boldsymbol{L^0}$ can be substituted with $\boldsymbol{(L^1 - \Delta L)}$ and $\boldsymbol{f^1}$ with $\boldsymbol{(f^0 + \Delta f)}$.

$$\boldsymbol{\Delta x} = \boldsymbol{L^1(f^0 + \Delta f)} - \boldsymbol{(L^1 - \Delta L)f^0} = \boldsymbol{(\Delta L)f^0} + \boldsymbol{L^1(\Delta f)} \tag{24}$$

This yields the influence of the production structure $\boldsymbol{\Delta L}$ weighted by the final demands in time period 0, $\boldsymbol{f^0}$, and the influence of final demand $\boldsymbol{\Delta f}$ weighted by the production structure in time period 1, $\boldsymbol{L^1}$. The so called weight can be interpreted as follows: E.g $\boldsymbol{(\Delta L)f^0} = \boldsymbol{L^1f^0} - \boldsymbol{L^0f^0}$, where $\boldsymbol{L^1f^0}$ is the amount of output needed to satisfy final demand in time period 0 with the production structure in time period 1, and $\boldsymbol{L^0f^0}$ is the amount of output needed to satisfy final demand in time period 0 with the production structure in time period 0. The same interpretation can be applied to $\boldsymbol{L^1(\Delta f)}$. Therefore, the weighted influences are appropriate coefficients to measure the contributing factors (Miller & Blair, 2009).

In the following, three more ways of substituting Equation 22 and 23 into Equation 21 are presented.

$$\boldsymbol{\Delta x} = \boldsymbol{(L^0 + \Delta L)f^1} - \boldsymbol{L^0(f^1 - \Delta f)} = \boldsymbol{(\Delta L)f^1} + \boldsymbol{L^0(\Delta f)} \tag{25}$$

$$\boldsymbol{\Delta x} = \boldsymbol{(L^0 + \Delta L)(f^0 + \Delta f)} - \boldsymbol{L^0f^0} = \boldsymbol{(\Delta L)f^0} + \boldsymbol{L^0(\Delta f)} + \boldsymbol{(\Delta L)(\Delta f)} \tag{26}$$

$$\boldsymbol{\Delta x} = \boldsymbol{L^1 f^1} - (\boldsymbol{L^1} - \boldsymbol{\Delta L})(\boldsymbol{f^1} - \boldsymbol{\Delta f}) = (\boldsymbol{\Delta L})\boldsymbol{f^1} + \boldsymbol{L^1}(\boldsymbol{\Delta f}) - (\boldsymbol{\Delta L})(\boldsymbol{\Delta f}) \tag{27}$$

All four Equations 24, 25, 26, and 27 are equally valid in terms of "mathematical correctness", they differ in the weights applied to the respective contributing factors and therefore, differing overall influences of the contributing factors occur. Extensive research has been conducted on the differences between the four approaches and their advantages and disadvantages (Miller & Blair, 2009).

In their article *Structural decomposition techniques: Sense and sensitivity*, Dietzenbacher and Los (1998) analyze 24 different decomposition forms in an empirical analysis for the Netherlands. They state that the problem of non-uniqueness of the structural decomposition technique has only been recognized and analyzed in detail for the case of solely two contributing factors, as in the afore-given example, by simply taking the average of the different approaches. However, they examined the implications of a larger number of contributing factors.
In an environment, where n influences are desired to be analyzed, the equation under consideration looks as follows.

$$\boldsymbol{y} = \boldsymbol{x_1 x_2 \dots x_n} \tag{28}$$

The goal is to establish $\boldsymbol{\Delta y}$ as the sum of all n weighted $\boldsymbol{\Delta x}$, whereby, in the case of Equation 8 presented before, n equals 2.
With the aim of deriving the additive decomposition, according to Equation 24 and 25, one can start using the time period weights at one or the other end, which yields the following two equations:

$$\begin{aligned}\boldsymbol{\Delta y} &= (\boldsymbol{\Delta x_1})\boldsymbol{x_2^0 x_3^0} \quad \dots \quad \boldsymbol{x_{n-1}^0 x_n^0} + \boldsymbol{x_1^1}(\boldsymbol{\Delta x_2})\boldsymbol{x_3^0} \quad \dots \quad \boldsymbol{x_{n-1}^0 x_n^0} + \\ &\vdots \\ &+ \boldsymbol{x_1^1 x_2^1 x_3^1} \quad \dots \quad (\boldsymbol{\Delta x_{n-1}})\boldsymbol{x_n^0} + \boldsymbol{x_1^1 x_2^1 x_3^1} \quad \dots \quad \boldsymbol{x_{n-1}^1}(\boldsymbol{\Delta x_n})\end{aligned} \tag{29}$$

$$\begin{aligned}\boldsymbol{\Delta y} = {} & (\boldsymbol{\Delta x_1})\boldsymbol{x_2^1 x_3^1} \quad \ldots \quad \boldsymbol{x_{n-1}^1 x_n^1} + \boldsymbol{x_1^0}(\boldsymbol{\Delta x_2})\boldsymbol{x_3^1} \quad \ldots \quad \boldsymbol{x_{n-1}^1 x_n^1} + \\ & \vdots \\ & + \boldsymbol{x_1^0 x_2^0 x_3^0} \quad \ldots \quad (\boldsymbol{\Delta x_{n-1}})\boldsymbol{x_n^1} + \boldsymbol{x_1^0 x_2^0 x_3^0} \quad \ldots \quad \boldsymbol{x_{n-1}^0}(\boldsymbol{\Delta x_n})\end{aligned} \tag{30}$$

These two equations are the so called *polar decompositions*, however, there is no apparent reason why one should start at either end. By changing the order of the terms $\boldsymbol{x_1, x_2}, \ldots, \boldsymbol{x_n}$ within each addend of either of the two equations, a new decomposition emerges. In the case of n contributing factors, there are hence $(n!)$ different kinds of decompositions.

Dietzenbacher and Los (1998) claim that most authors use one of the two "ad hoc" approaches of either taking the average of the two polar decompositions or using so called *mid-point weights*, which entails averaging the time period weights before applying them in the decomposition.
In a first step, to analyze the variability of all possible decomposition approaches, Dietzenbacher and Los (1998) performed all possible approaches for a SDA of four contributing factors, which gives 24 different decomposition approaches. They observed that the results are highly sensitive to the particular decomposition employed, e.g. the calculated influence of one contributing factor ranges from 50% to 70%. They elucidate that, even though the range might not seem extremely large, in the first case the other three contributing factors make up for 50% as well, which means that the first and the other three factors together are equally influential. However, in the second case, the three other factors only account for 30% of the total change, which implies that the first factor is more than twice as important than the other three factors combined.
In a second step, Dietzenbacher and Los (1998) conduct various further analyses, such as the afore-stated "ad hoc" approaches.They conclude that the average of the two polar decompositions and the mid-point weights approach yield similar results, which again closely resemble the results when averaging all $(n!)$ approaches. Nonetheless, with an increasing number of contributing factors, the results of the mid-points weights approach become less and less accurate.
All in all, Dietzenbacher and Los (1998) advocate the method of averaging all $(n!)$ approaches because, unlike solely averaging the two polar decompositions, the ranges of the measured influences between all possi-

ble decompositions may comprise valuable information. As a consequence, said method is used for the SDAs to follow in this thesis.

2.4 National accounts vs. energy statistics

To conduct a structural decomposition analysis all data inputs need to be structured in a corresponding manner. In this case, the economic actors (industries, households, etc.), their economic activites (monetary), and the thereby occuring energy use and the related CO2 emissions need to be circumscribed correspondingly.

Most environmental data such as data on energy use or CO2 emissions is not available in a framework compatible to national accounts, therefore most data needs to be transformed to be relatable to other data that corresponds to the national accounting framework, such as Input-Output tables. The following table, which is based on Table 2 by Genty, Arto, and Neuwahl (2012), depicts the main differences between energy statistics and national accounts.

Table 2: National accounts vs. energy statistics[1]

	National accounts	**Energy statistics**	**Transformation requirements**
Definition of country's boundaries	**Residence principle:** A resident is an institutional unit, such as a person or a company, whose economic activities take place in a territory. In the national accounting framework the entire energy use of a resident is attributed to that very resident, regardless of whether the energy was used in or out of the territory.	**Territory principle:** The energy use is attributed to the economic units, which are physically located in the territory, regardless of whether the energy is used by residents or non-residents.	**Add:** Energy use by residents abroad including notably: Road, Air, and Water transport **Subtract:** Energy use by non-residents on national territory including notably: Road, Air, and Water transport
Classification	**Industry classification systems:** E.g.: NACE (Nomenclature statistique des activités économiques dans la Communauté européenne), ISIC (International Standard Industrial Classification), or NAICS (North American Industry Classification System) Energy products are classified according to their purpose which allows the distinction of non-energy use of energy sources.	The energy use is assigned to sectors, e.g. all energy use for transport is assigned to the transportation sector, no matter if the transport is effected by a transportation company or a food manufacturer delivering his products.	The energy supply industries, e.g. extraction, conversion, or supply, as well as the energy using industries need to be defined uniformly.

[1] Based on Table 2 by Genty et al. (2012)

Genty et al. (2012) state that both the residence principle as well as the territory principle are widely used for various analysis approaches, and both have different advantages and disadvantages. Nonetheless, if one aims at accommodating one framework to the other, considerable effort is needed. The accommodation conducted in this thesis is fully documented in the subsequent methods section.

Furthermore, Genty et al. (2012) elucidate two concepts of energy accounting: First, they present the following equation, which depicts the *gross energy concept.*

$$\begin{gathered}\boldsymbol{Gross\ supply} : Domestic\ production + Imports + Inventory\ changes \\ = \\ \boldsymbol{Gross\ use} : Intermediate\ consumption + Final\ uses + Exports\end{gathered}$$

Second, they introduce the *net energy concept.*

$$\begin{gathered}\boldsymbol{Net\ supply} : Direct\ extraction + Imports + Inventory\ changes \\ = \\ \boldsymbol{Net\ use} : Final\ uses + Losses\ due\ to\ conversion\ uses + Exports\end{gathered}$$

The main difference between the two concepts is the presence of double counting: In the net energy concept, the energy use is never double counted since it is only measured at the final use level. Thereby the energy used for transformation processes is not included, e.g. crude oil inputs to refineries are not recorded. This implies that the information on the fuel mix is lost because various primary energy products, which are later transformed to secondary energy products, are neglected. Also, the information on the energy content of all primary energy products that are transformed to electricity and heat is only included in the form of energy and heat used by all industries and households but not in the form of the primary energy products' original energy content.

The gross energy concept entails double counting, however, it is fully compatible with national accounts. Regarding the afore-stated example, the crude oil inputs to refineries are fully recorded as well as the oil products, which likewise (partly) comprise the energy contained in the crude oil after the transformation process. As for electricity and heat, both the energy content of the primary energy products required to produce electricity and heat are recorded as well as the energy content of electricity and heat itself. The compatibility of the gross energy concept with national accounts in the case of Input-Output tables becomes apparent, when one considers that the monetary transactions between the oil extraction industry and the oil refinery industry are as much accounted for as the monetary transactions between the oil refinery industry and all the industries and households, which demand the refined oil products.

Contrary to the energy use data, CO2 emissions are not counted twice since various energy sources do not have directly related CO2 emissions, e.g. electricity and heat, where the potential emissions occur in the production process as long as the production is based on CO2 relevant primary energy products, as well as solar energy, hydro energy, and other renewable energy sources. In the case of primary energy products, which are both used for CO2 relevant transformations, e.g. coal to electricity, and for non CO2 relevant transformations, e.g. coal to coke, an additional layer to separate between the two transformations is required (Genty et al., 2012). In summary, it can be stated that the gross energy concept serves as a bridge between national accounts and energy statistics.

3 Methods

3.1 Extended data compilation

The data compilation I conducted includes Input-Output tables, CO2 emissions and energy use data. I assembled the Input-Output tables according to Miller and Blair (2009) within a commodity-demand driven model, under the industry technology assumption, and in the Commodity-by-Commodity format. The basis for the Input-Output tables are the Make and Use tables by the Bureau of Economic Analysis (BEA) (2016b, 2016c). I adjusted the obtained Input-Output tables from current prices to constant prices (base year 2009) on the basis of *Chain-Type Price Indexes for Gross Output by Industry* by the BEA (2016a) as follows. First, I applied the respective price index to each row (industry). For the two industries "Scrap, used and secondhand goods" and "Noncomparable imports and rest-of-the-world adjustment [1]", I used the unweighted average of the price indexes of all other industries. Second, I computed the total of each industry's value added by subtracting each industry's intermediate output (sum of each column without said value added) from each industry's commodity output (sum of each row). Finally, I divided the total value added of each industry onto the three value added categories by the BEA using the values of the Input-Output tables in current prices as the splitting key.

For the compilation of the energy use data, I followed the technical report on the compilation of the World Input-Output Database (WIOD) environmental data by Genty et al. (2012) whenever it was applicable. The authors of the report (Section 5.1.1) demonstrate in numerous steps how to get from energy balances to energy accounts that correspond to the national accounting framework, based on the *extended world energy balances* made available by the International Energy Agency (IEA) (2016c). Energy balances are identical in content to energy statistics with the sole difference that consistent energy units are used over all energy sources, which in this case are thousand tons of oil equivalent (ktoe). It should be noted that I did not include so called *flows* from the IEA data that did not use any energy, i.e. were not active over the entire time period observed, in the conversion of energy balances to energy accounts, e.g. "Autoproducer heat plants". The same applies to energy sources from the IEA data (so called *products*), which were not used over the entire time period under consideration, such as “Coal tar”. An exemplary excerpt of the unedited data file for the year 1997 can be found in the appendix (Figure A.1), where the rows depict the flows and the columns represent the products.

The report on the compilation of the World Input-Output Database environmental data by Genty et al. (2012) refers to industries in the NACE (Nomenclature statistique des activités économiques dans la Communauté européenne) format, revision 2, which is the industry classification system in the European Union and European implementation of the UN industry classification system ISIC (International Standard Industrial Classification), revision 4. The BEA Input-Output tables comprise 71 industries, which are based on the 2007 North American Industry Classification System (NAICS). Since I did not perform the steps defined by Genty et al. (2012) one-on-one due to a differing level of detail in the industry classification system at hand (71 BEA industries), I did not attach a NACE to BEA concordance table, but rather assigned the respective industries on a case-by-case basis, which is shown in the concordance tables for each step of the following data compilation.

3.1.1 Direct allocation of IEA flows

This first step follows Section 5.1.1.1 by Genty et al. (2012), which entails directly allocating the IEA flows to the industries used in the Input-Output tables, in this case the 71 BEA industries, whenever an IEA flow can be assigned to one of the 71 BEA industries as a whole. This is true for the IEA flows in the following concordance table, whereby “HH_dir” is not part of the BEA industries but rather a separate category denoting direct household consumption.

Table 3: IEA to BEA direct allocation concordance table

IEA flow	**BEA industry code**	**BEA industry label**
Main activity producer electricity plants	22	Utilities
Main activity producer CHP plants	22	Utilities
Main activity producer heat plants	22	Utilities
Blast furnaces	331	Primary metals
Gas works	324	Petroleum and coal products
Coke ovens	324	Petroleum and coal products

Patent fuel plants	324	Petroleum and coal products
Oil refineries	324	Petroleum and coal products
For blended natural gas	324	Petroleum and coal products
Coal mines[1]	212	Mining, except oil and gas
Oil and gas extraction[1]	211	Oil and gas extraction
Blast furnaces[1]	331	Primary metals
Coke ovens[1]	324	Petroleum and coal products
Oil refineries[1]	324	Oil refineries
Own use in electricity, CHP and heat plants[1]	22	Utilities
Pumped storage plants[1]	22	Utilities
Losses[2]	22	Utilities
Iron and steel	331	Primary metals
Chemical and petrochemical	325	Chemical products
Non-ferrous metals	331	Primary metals
Non-metallic minerals	327	Nonmetallic mineral products
Mining and quarrying	212	Mining, except coal and gas
Food and tobacco	311FT	Food and beverage and tobacco products
Wood and wood products	321	Wood products
Construction	23	Construction
Rail	482	Rail transportation
Pipeline transport	486	Pipeline transportation
Non-specified (transport)	487OS	Other transportation and support activities
Residential	HH_dir	Final demand by households
Non-specified (other)	GFGD	Federal general government (defense)

[1] Energy industry own use: energy consumed by energy industries for heating, pumping, traction and lighting purposes (IEA, 2015)

[2] Losses in gas energy distribution, transmission, and transport (IEA, 2015)

In a second step, Genty et al. (2012) adjust the inputs of coal to coking plants and the inputs of coke to blast furnaces, which are recorded separately in the IEA energy balances. This is necessary due to the fact that if a coking plant belongs to a blast furnace and is therefore not an independent reporting entity in terms of national accounts, the inputs of coal to the coking plant as well as the inputs of coke to the blast furnace do not appear as economic transactions in the Input-Output tables. Genty et al. suggest that the actual inputs of coal to coking plants and of coke to blast furnaces are adjusted based on their economic transactions, which can be

taken from the Input-Output tables.
However, the BEA industry containing coal, “Mining, except oil and gas”, also contains other commodities, which are traded between said industry and “Primary metals”, where blast furnaces are attributed to. Therefore, the economic transactions do not serve as reliable indicators within the BEA industry classification system and as a consequence, I did not implement the described second step by Genty et al. (2012) in my data compilation. This bears the risk that the use of coal as well as the use of coke from the IEA energy balances might not be fully represented in the Input-Output tables in monetary terms. Therefore, the energy intensity (energy use per economic output) for coal and coke might be overestimated.

3.1.2 Split allocation of IEA flows

This section involves splitting IEA flows into the respective BEA industries, where the input of energy commodities in monetary terms from the Use table serve as splitting key. Genty et al. (2012) suggest in Section 5.1.1.2 that each industry’s share of a more aggregate IEA flow is calculated individually for each IEA energy source.
The share of “Primary solid biofuels” is based on the input of agriculture and forestry to each industry using “Primary solid biofuels”, taken from the Use table. The shares of “Coking coal” and “Sub-bituminous coal” are based on the input of coal to each industry using said IEA energy sources, likewise gathered from the Use table. As in the preceding section, the same problem arises that there is neither an equivalent BEA industry for agriculture and forestry nor for coal to withdraw the respective inputs from the Use table. The BEA industries coming closest are “Farms” together with “Forestry, fishing, and related activities” in the case of agriculture and forestry, and “Mining, except oil and gas” in the case of coal. However, the first two BEA industries also include fishing, the latter includes mining other than coal, which overall could possibly bias the results. Therefore, I refrained from calculating each BEA industry’s share of a more aggregate IEA flow for each IEA energy source individually, instead I used the sum of the following BEA industries’ inputs from the Use table as a comprehensive energy indicator: “Oil and gas extraction”, “Utilities”, and “Petroleum and coal products”. This implies two assumptions: a) All BEA industries forming part of a more aggregate IEA flow pay the same price per energy unit of a particular IEA energy source, and b) all BEA industries form-

ing part of a more aggregate IEA flow have the same energy consumption structure in terms of shares of the different IEA energy sources (Genty et al., 2012). The following concordance table shows which IEA flows were split into which BEA industries according to the inputs of the described comprehensive energy indicator from the Use table.

Table 4: IEA to BEA split allocation concordance table

IEA flow	**BEA industry code**	**BEA industry label**
Non-specified (energy)[1]	211	Oil and gas extraction
	22	Utilities
	324	Petroleum and coal products
Transport equipment	3361MV	Motor vehicles, bodies and trailers, and parts
	3364OT	Other transportation equipment
Machinery	332	Fabricated metal products
	333	Machinery
	334	Computer and electronic products
	335	Electrical equipment, appliances, and components
Paper, pulp and print	332	Paper products
	323	Printing and related support activities
Textile and leather	313TT	Textile mills and textile product mills
	315AL	Apparel and leather and allied products
Non-specified (industry)	337	Furniture and related products
	339	Miscellaneous manufacturing
	326	Plastics and rubber products
Commercial and public services	42	Wholesale trade
	441	Motor vehicle and parts dealers
	445	Food and beverage stores
	452	General merchandise stores
	4A0	Other retail
	493	Warehousing and storage
	511	Publishing industries, except internet (includes software)
	512	Motion picture and sound recording industries
	513	Broadcasting and telecommunications
	514	Data processing, internet publishing, and other information services
	521CI	Federal Reserve banks, credit intermediation, and related activities
	523	Securities, commodity contracts, and investments

	524	Insurance carriers and related services
	525	Funds, trusts, and other financial vehicles
	HS	Housing
	ORE	Other real estate
	532RL	Rental and leasing services and lessors of intangible assets
	5411	Legal services
	5415	computer systems design and related services
	5412OP	Miscellaneous professional, scientific, and technical services
	55	Management of companies and enterprises
	561	Administrative and support services
	562	Waste management and remediation services
	61	Educational services
	621	Ambulatory health care services
	622	Hospitals
	623	Nursing and residential care facilities
	624	Social assistance
	711AS	Performing arts, spectator sports, museums, and related activities
	713	Amusements, gambling, and recreation industries
	721	Accommodation
	722	Food services and drinking places
	81	Other services, except government
	GFGN	Federal general government (nondefense)
	GFE	Federal government enterprises
	GSLG	State and local general government
	GSLE	State and local government enterprises
Agriculture/forestry **and** Fishing[2]	111CA	Farms
	113FF	Forestry, fishing, and related activities

[1] Energy industry own use: Represents own use in non-specified energy sector (IEA, 2015)

[2] Sum of IEA flows “Agriculture/forestry” and “Fishing” spilt into BEA industries “Farms” and “Forestry, fishing, and related activities” to account for the different allocation of forestry

3.1.3 Allocation of electricity and heat autoproduction

The following allocation conforms to section 5.1.1.3 by Genty et al. (2012). Entities, which mainly produce electricity and/or heat, are directly assigned to the BEA industry “Utilities” as shown in Table 3. Other entities (autoproduction), on the other hand, are assigned to various industries depending on the energy source that is being used. This applies to the three IEA flows “Autoproducer electricity plants”, “Autoproducer CHP plants”, and “Autoproducer heat plants”, whereat the latter did not use any energy over the entire time period under consideration, i.e. was not active, and is therefore neglected hereafter. The following table shows which IEA energy sources were assigned to which BEA industries.

Table 5: IEA to BEA energy autoproduction concordance table

IEA energy source	**BEA industry code**	**BEA industry label**
Coking coal Coke oven coke Blast furnace gas	331	Primary metals
Other bituminous coal Sub-bituminous coal Lignite Peat	212	Mining, except oil and gas
Gas works gas	22	Utilities
Coke oven gas Crude oil Refinery feedstocks Refinery gas Ethane Petroleum coke	324	Petroleum and coal products
Industrial waste Municipal waste (renewable) Municipal waste (non-renewable) Biogasoline Biodiesel Other liquid biofuels Biogases	562	Waste management and remediation services
Nuclear	GFGD	Federal general government (defense)
Primary solid biofuels [1]	113FF	Forestry, fishing, and related services
	321	Wood products
	322	Paper products

[1] See text below for splitting into three sectors

The IEA energy source “Primary solid biofuels” is split into three BEA industries, as shown in Table 5. The splitting key is the input of the BEA industry “Forestry, fishing, and related services” to each respective industry taken from the Use table. Genty et al. (2012) state that the majority of such inputs is non-energy related (wood used as raw material), therefore they apply a weighting factor to said inputs, which was computed based on Austrian data. Due to data availability, I did not use a weighting factor, which encompasses the assumption that all three industries use the same share of their respective input of “Forestry, fishing, and related services” for energy and non-energy purposes, respectively.

According to Genty et al. (2012), all IEA energy sources used by autoproducers that are not included in Table 5 are split amongst all BEA industries, which provide commodities of BEA industry “Utilities”. The splitting key is the respective amount provided that can be taken from the Make table, with the exception of BEA industry “Utilities”. Even if an electricity producing establishment that belongs to the same firm as the establishment consuming the electricity, the transfer ought to be recorded by the responsible statistical authority if the accounting conventions are applied correctly. However, according to Genty et al. (2012), it is common that such transfers remain unrecorded, therefore they suggest averaging the Make tables over the entire time period under consideration to avoid statistical volatility. This procedure reveals four BEA industries amongst which the energy use of the remaining energy sources is divided accordingly, namely “Federal general government (nondefense)”, “Feder government enterprises”, “State and local general government”, and “State and local government enterprises”.

3.1.4 Allocation of energy use in road transport

The gathering of the energy use data on road transport following Section 5.1.1.4 by Genty et al. (2012) involves several steps and can be divided into energy used directly by households in the afore-defined category “HH_dir” on the one hand, and energy used by all the industries in the economy on the other hand.

The first step of the data compilation on the energy use for road transport by households is to assign an IEA energy price from the IEA Energy Prices and Taxes Statistics: *End-use prices: Energy prices in national currency per toe* (IEA, 2016b) to all the IEA energy sources, which are used in the IEA flow “Road”. The assignment is shown in the following table, which also includes the assignment of IEA oil product spot prices (IEA, 2016d) to IEA energy sources. This information is required further below in the compilation of the energy use data for road transport by the BEA industries.

Table 6: IEA energy source to IEA energy price/IEA oil product spot price concordance table for the IEA flow "Road"

IEA energy source	**IEA energy price**	**IEA oil product spot price**
Biogasoline	Composite energy price[1]	Composite oil product spot price[2]
Biodiesel	Composite energy price[1]	Composite oil product spot price[2]
Natural gas	Natural gas	Composite oil product spot price[2]
Natural gas liquids	Composite energy price[1]	Composite oil product spot price[2]
Ethane	Composite energy price[1]	Composite oil product spot price[2]
Liquified petroleum gases (LPG)	Composite energy price[1]	Composite oil product spot price[2]
Electricity	Electricity	Composite oil product spot price[2]
Motor gasoline excl. biofuels	Regular unleaded gasoline	Gasoline
Gas/diesel oil excl. biofuels	Automotive diesel	Gasoil

[1] Composite energy price was used when no corresponding IEA energy price was available, see below for calculation

[2] Composite oil product spot price was used when no corresponding IEA oil product spot price was available, see below for calculation

The composite energy price is based on IEA energy prices (IEA, 2016b) as well as on the *Transportation Sector Energy Use by Fuel Type within Mode* published by the U.S. Energy Information Administration (EIA, 2015). In the latter, I calculated the average energy use of each fuel type for the years 2012, which is the first year available in the data, to 2014, which is the last year before the data was published. Subsequently, for the mode "Light-Duty Vehicle", I calculated the relative shares of the fuel types "Motor Gasoline excluding E85", "Propane", "Electricity", and "Distillate Fuel Oil (diesel)" while neglecting the other fuel types, and multiplied them

with the corresponding IEA energy prices for “Regular unleaded gasoline”, “Natural gas”, “Electricity”, and “Automotive diesel”, which in total adds up to the composite energy price. Thereby, the compiled composite energy price incorporates the shares of all fuel types and their respective prices, whereon information is available. The method of applying a composite energy price on any IEA energy source may distort the results, however, it should be noted that the IEA energy sources “Motor gasoline excl. biofuels” and “Gas/diesel oil excl. biofuels”, for which specific energy prices are available, account for over 94% of the entire energy use of the IEA flow “Road” for all the years under consideration.
Multiplying every IEA energy source with the corresponding IEA energy price (see Table 6) gives the entire IEA flow “Road” in monetary values based on IEA energy prices.

In the next step I calculated the share of direct household consumption (HH_dir) in the IEA flow “Road” based on the consumption from the BEA industry “Petroleum and coal products” that can be obtained from the Use table by taking the respective input to “Personal consumption expenditures”. This value, however, does not only include expenditures for transport fuels but also other refinery products, e.g. for heating (Genty et al., 2012). Therefore, I first subtracted the sum of all expenditures of the IEA flow “Residential” for IEA energy sources corresponding to the energy classes “Coal CO2 rel.”,“Coal non CO2 rel”, and “Oil Products” (see Table A.1) from said input taken from the Use table. Then, I divided the result by the sum of all expenditures of the IEA energy balance flow “Road” for IEA energy sources corresponding to the energy classes “Coal CO2 rel.”,“Coal non CO2 rel”, and “Oil Products”. This yields the share of direct household consumption of transport fuels in the economy-wide consumption of transport fuels specifically for coal and oil products. I finally applied said share to all IEA energy sources and not only to coal and oil products by multiplying the deduced share with the energy use of each single IEA energy source in the IEA flow “Road” yielding the direct household consumption of energy for road transport for all IEA energy sources. This implies the assumption that the share of direct household consumption of any transport fuel in the economy-wide consumption of transport fuels is equal to that very share for coal and oil products.
The expenditures for IEA energy sources of the IEA flow “Residential”

(monetary values) are generated based on the following concordance table. Genty et al. (2012) suggest that the IEA energy price for “Light fuel oil” is used for all IEA energy sources, where no corresponding IEA energy price is available. This bears the risk of distorting the results, however, the IEA energy sources “Natural gas” and “Electricity”, where corresponding energy prices exist, make up for over 82% for all the years observed.

Table 7: IEA energy source to IEA energy price concordance table for the IEA flow “Residential”

IEA energy source	**IEA energy price**
Other bituminous coal	Light fuel oil[1]
Sub-bituminous coal	Light fuel oil[1]
Biodiesels	Light fuel oil[1]
Natural gas	Natural gas
Natural gas liquids	Light fuel oil[1]
Liquefied petroleum gases (LPG)	Light fuel oil[1]
Other kerosene	Light fuel oil[1]
Geothermal	Light fuel oil[1]
Solar thermal	Light fuel oil[1]
Electricity	Electricity
Gas/diesel oil excl. biofuels	Light fuel oil[1]
Primary solid biofuels	Light fuel oil[1]

[1] The energy price for light fuel oil was used when no corresponding IEA energy price was available (Genty et al., 2012).

To compile the energy use in road transport by all BEA industries, I first computed the monetary values of all the IEA energy sources in the IEA flow “Road” by multiplying each IEA energy source with the corresponding IEA oil product spot price (see Table 6). Whenever a matching IEA oil product spot price was not available, a composite oil product spot price was used.

The IEA oil product spot prices are available in USD/bbl (Barrel) and need to be converted into USD/toe (ton of oil equivalent), which can be undertaken with the aid of heat contents found in the *Thermal Conversion Factor source Documentation* published by the EIA (2016d), as shown in the following table.

Table 8: IEA oil product spot price conversion table

IEA oil product spot price	**EIA Petroleum and Natural Gas Plant Liquids**	**M. Btu[1]per barrel**
Gasoil	Distillate Fuel Oil, 15 ppm Sulfur and Under	5.770 M. Btu/bbl
Gasoline	Motor Gasoline (Finished) Consumption	5.253 M. Btu/bbl
High sulphur fuel oil	Distillate Fuel Oil, Greater Than 500 ppm Sulfur	5.825 M. Btu/bbl
Jet kerosene[2]	Jet Fuel, Kerosene-Type	5.670 M. Btu/bbl

[1] 1 toe = 39.6832072 M. Btu (IEA, 2016e)

[2] Not used for compilation of road transport data, but for air and maritime transport data, see further below

The composite oil product spot price was calculated on the basis of the IEA oil product spot prices (IEA, 2016d) and the *Transportation Sector Energy Use by Fuel Type within Mode* (EIA, 2015). In the latter, as for the calculation of the composite energy price (see above), I averaged the energy use of each fuel type for the years 2012, the first year available in the data, to 2014, the last year before the publication of the data. Thereupon, for the modes “Light-Duty Vehicle”, “Commercial Light Trucks”, and “Freight Trucks”, I calculated the relative shares of the fuel types “Motor Gasoline excluding E85” together with “Motor Gasoline” and “Distillate Fuel Oil (diesel)” while neglecting the other fuel types. Finally, I multiplied them with the corresponding IEA oil product spot prices “Gasoline” as well as “Gasoil”, which in total adds up to the composite oil product spot price. Thus, the compiled composite oil product spot price combines the shares of all fuel types and their respective prices, if the corresponding price information is available. As for the composite energy price, applying a composite oil product spot price to any IEA energy source bears the risk of distortion, then again, the IEA energy sources, to which the composite oil product spot price was assigned, only account for less than 6% of the overall energy use of the IEA flow “Road” over the entire timespan under consideration.

Once the monetary values of the IEA energy sources for the IEA flow “Road” based on IEA oil product spot prices are calculated, the next step involves calculating the energy use for road transport of those BEA industries, where road transport is dominant enough to fully account for the respective input from the BEA industry "Petroleum and coal products" taken from the Use table. For this purpose, Genty et al. (2012) propose the equivalents of the BEA industries "Transit and ground passenger transportation", "Truck transportation", and "Other transportation and support activities", as well as the postal services industry, which in the BEA industry classification system is part of the industry "Federal government enterprises" along with federal electric utilities and other federal government enterprises. I neglected the postal services industry due to the fact that it cannot be singled out from the more aggregate BEA industry. For the afore-stated three BEA industries, I calculated the respective shares of each industry's coal and oil products' input from the Use table in the overall consumption of coal and oil products in the IEA flow "Road" in equal measure as for the direct household consumption. Finally, by multiplying each industry's share with the energy use of each respective IEA energy source, I obtained the total energy use for road transport of the three BEA industries.

The remaining energy use in the IEA energy balance flow "Road" is first adjusted correspondent to the residence principle and, thereafter, spilt among all remaining BEA industries, for which the energy use for road transport has not been calculated yet, as suggested by Genty et al. (2012). The adjustment corresponding to the residence principle is achieved by means of tourist data on inbound and outbound tourism expenditures by the World Tourism Organization (UNWTO, 2016). Since the structure of said tourism expenditures is not available but only the total value, Genty et al. (2012) propose the assumption that the share of fuel consumption in the total tourism expenditures is the same for residents regardless of whether they are at home or visiting other countries (outgoing tourism). Therefore, I divided the afore-calculated direct household consumption of energy for road transport (in monetary terms) by the total "Personal consumption expenditures" from the Use table to obtain the share of personal consumption expenditures on road transport. Then, I multiplied the share with the "Inbound tourism expenditures" and with the "Outbound tourism expenditures", respectively, which gives the monetary value of inbound as well as outbound tourist expenditures on road transport. I then subtracted the first figure from the total energy use of the IEA flow "Road" in monetary terms based on IEA energy prices and added the latter figure, which yields the total energy use for road transport adjusted for the residence principle. Last, I computed the share of the adjusted total energy use for road transport in the total energy use for road transport that was originally calculated based on IEA energy prices, and multiplied it with the remaining energy use of each single IEA energy source in the IEA flow “Road”.

To split the obtained residuals amongst the remnant BEA industries, I used each industry’s employees in full time equivalents as splitting key, as it is proposed by Genty, et al. (2012). This information is put at disposal by the BEA (2015), where the two BEA industries “Housing” and “Other real estate” are only available combined into one industry, namely “Real estate”. Consequently, in a first step, I split the residual of each IEA energy source among all BEA industries according to the respective number of full time equivalents, except those BEA industries, whose energy consumption for road transport I calculated already. In a second step, I split the energy consumption for road transport of the combined industry “Real estate” among the above-mentioned two BEA industries according to the respective input from “Petroleum and coal products” taken from the Use table, assuming that both industries use such products for transport and non-transport purposes equivalently. Hence, I compiled the energy use data for road transport for all BEA industries as well as for the direct household consumption.

3.1.5 Calculation of energy use in air and maritime transport

The following calculation is based on Section 5.1.1.5 by Genty et al. (2012). There are two separate IEA flows available for international air and maritime bunkering, however, they entail all fuel deliveries in the country, including fuels delivered to foreign carriers. Adjusting to the residence principle in this case means subtracting all domestic fuel deliveries to foreign carriers and adding all fuel deliveries to national carriers, which took place abroad. Since the gathering of such data is hardly feasible, Genty et al. (2012) suggest an alternative approach, which I adapted to my data.

For the energy use of the BEA industry “Air transportation”, I used the input of the industry “Petroleum and coal products” from the Use table and divided it by the IEA oil product spot price for Jet kerosene (2016d) as introduced in Table 8. As a result, I did not assign the IEA flow “Domestic aviation” to the BEA industry “Air transportation” as it is already

included due to the calculation based on the input from the Use table. I assigned the total calculated energy use to the IEA energy source “Kerosene type jet fuel excl. biofuels”.
Next, I calculated the energy use of the BEA industry “Water transportation” alike by, again, using the input of the BEA industry “Petroleum and coal products” from the Use table and dividing it by the IEA oil products sport price for High sulphur fuel oil (Table 8). As for air transport, I did not assign the IEA energy balance flow “Domestic navigation” to the BEA industry “Water transportation”. Finally, I allotted the total calculated energy use to the IEA energy source “Motor gasoline excl. biofuels”.

Genty et al. (2012) bring up the potentially problematic fact that large transport operators such as airlines are known to use hedge positions to be less vulnerable to price fluctuations. This implies that the spot price for a year might not necessarily correspond to the energy used in that same year. The authors suggest an alternative method to correct for this distortion, however, I refrained from adopting any further measures due to a lack of data availability.

3.1.6 Allocation of remaining energy use

According to Section 5.1.1.6 by Genty et al. (2012), most of the energy use related to military spending is covered by military secret. As laid down in the *World energy balances 2015 revised edition: database documentation* (IEA, 2015), the IEA flow “Non-specified (other)” includes military fuel use for all mobile and stationary consumption. However, if the military of another country buys said fuel, it is included in the IEA flow as well, whereas fuel use in military missions abroad is not captured, which is not conforming to the residence principle. Nonetheless, Genty et al. (2012) do not suggest an alternative way of gathering such data, since data shortages render such an undertaking impossible. Therefore, said IEA flow is fully assigned to the BEA industry “Federal general government (defense)” as shown in Table 3.
As explained in Section 5.1.1.7 by Genty et al. (2012), they did not compile data on the energy use of embassies as well as other extra-territorial organizations and bodies, which I neglected as well.

3.1.7 CO2 emissions

Genty et al. (2012) calculate the CO2 emissions corresponding to the energy use, among other, based on data from the default values by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC). In virtue of simplification, I adapted the *detailed CO2 emissions* (IEA 2016a) provided by the IEA according to the adjustments of the energy use data, assuming that the *extended world energy balances* (IEA 2016c) and the *detailed CO2 emissions* correspond with each other and can be modified uniformly.

CO2 emissions by IEA (2016a) distinguish 46 different kinds of energy sources, whereat the energy use data by IEA (2016c) entail 65 different energy sources. The reason for the differing number of energy sources lies in the fact that not all energy sources are CO2 relevant, such as hydro power or solar power, as well as electricity or heat where the CO2-emissions are allocated to the energy source, which is used to produce electricity or heat (secondary energy products), given such energy source is CO2 relevant (primary energy product). Beside the renewable energy sources as well as electricity and heat, the IEA energy source “Nuclear”, which does not emit CO2 directly related to energy production, is also not included in the IEA CO2 emissions. On the other hand, the IEA energy source “Orimulsion” is included in the IEA CO2 emissions but not in the IEA energy balances, however, since there are no CO2 emissions related to said energy source over the entire time period under consideration, I did not adopt any further measures to deal with it. As for the IEA energy balances, I neglected all IEA flows and IEA energy sources, where no CO2 emissions occurred, i.e. were not active over the years under consideration.

Regarding the IEA flows, the IEA CO2 emissions deviate from the IEA energy balances as well, namely the energy sector. The following IEA flows, which are available in the IEA energy balances, are missing in the IEA CO2 emissions: “Blast furnaces”, “Gas works”, “Coke ovens”, “Patent fuel plants”, “Oil refineries”, and “For blended natural gas”. This is due to the fact that they use a primary energy product and process it to a secondary energy product, where the CO2 emissions do not occur until the secondary energy product is consumed (CO2 relevant secondary energy product). E.g. An oil refinery uses crude oil and processes it to gasoline, then the CO2 emissions occur when the gasoline is combusted rather than in the refinery process. The energy used for such a process and its corre-

sponding CO2 emissions are allocated to the respective IEA flows under "Energy industry own use". On the contrary, IEA flows such as "Main activity producer electricity plants" can indeed be found in the IEA CO2 emissions since the primary energy products, e.g. coal, are processed to a secondary energy product, e.g. electricity, where the CO2 emissions occur during said process (non CO2 relevant secondary energy product).
As stated before, all IEA energy sources belonging to the energy classes "Nuclear", "Renewables", and "Electricity and heat" (see Table A.1) are not included in the IEA CO2 emissions. Furthermore, the energy classes "Coal non CO2 rel." and "Crude, NGL, refinery feedstocks non CO2 rel." do not have corresponding IEA CO2 emissions, due to the afore-described reason of CO2 relevant secondary energy products, and thereby serve as the additional layer described in Section 2.4. The reason why "Coal" and "Crude, NGL, refinery feedstocks" are both separated in CO2 relevant use and non CO2 relevant use, respectively, is that combining both uses bears the risk of biasing the resulting emission intensity (CO2 emissions per energy use) from one year to another if the shares of CO2 relevant use and non CO2 relevant use vary. E.g. If one were to analyze both uses combined and in the first year the overall coal use was the same as in the second year, but the share of coal used to produce coke relative to electricity, which is a CO2 relevant secondary energy product, was much higher in the second year, then the emission intensity of coal would be much lower in the second year. This is due to the fact that in the second year more CO2 emissions are allocated to the secondary energy product and not the primary energy product. Therefore, if one only looks at the emission intensity of the latter, it can vary drastically even though processing coal has not become more or less efficient, which the varied emission intensity might suggest.

As mentioned before, I adapted the IEA CO2 emissions according to the adjustments I applied to the IEA energy balances. In the following, I describe the adjustments briefly.
The direct allocation of IEA flows follows Section 3.1.1 except for the IEA flows missing in the IEA CO2 emissions described before. Moreover, the IEA flows of the category "Energy industry own use" are not documented as detailed in the IEA CO2 emissions as in the IEA energy balances, where the former only include the IEA flows "Own use in electricity, CHP and heat plants", which is assigned to the BEA industry "Utilities" conformable

to the IEA energy balances, and “Other energy industry own use”, which I split as follows: First, in the IEA energy balances I calculated the share of each BEA industry that forms part of the category “Energy industry own use” in the sum of all the IEA flows of the category “Energy industry own use” except “Own use in electricity, CHP and heat plants”, which is already accounted for. Second, I multiplied each respective share with the CO2 emissions from the IEA flow “Other energy industry own use” to obtain the CO2 emissions of the category “Energy industry own use” for all BEA industries concerned. I carried out this procedure for all IEA energy sources. The IEA flows, which are part of the category “Energy industry own use” and the corresponding BEA industries, for which I calculated the afore-described shares, are listed in the following table.

Table 9: Energy industry own use concordance table

BEA industry code	**BEA industry label**	**IEA flow**
211	Oil and gas extraction	Oil and gas extraction Non-specified (energy)[1]
212	Mining, except oil and gas	Coal mines
22	Utilities	Pumped storage plants Non-specified (energy)[1]
324	Petroleum and coal products	Coke ovens Oil refineries Non-specified (energy)[1]
331	Primary metals	Blast furnaces

[1] Respective partial IEA flow calculated in Section 3.1.2

The split allocation of IEA flows is in line with Section 3.1.2 apart from the IEA flow “Non-specified (energy)”, which has already been dealt with (see above). This means that I adjusted the IEA CO2 emissions concerned in the exact same manner as I adjusted the IEA energy balances.

The allocation of the CO2 emissions of electricity and heat autoproduction follows Section 3.1.3 except for the IEA energy sources that are not available in the IEA CO2 emissions, e.g. “Primary solid biofuels”, which are carbon-neutral.

The CO2 emissions for road transport as well as for air and maritime transport are based on the energy use of said transport sectors calculated in Section 3.1.4 and Section 3.1.5. First, for each IEA energy source I calculated the share of every BEA industry as well as of the direct household consumption "HH_dir", in the total energy use for road transport, i.e. the sum of all BEA industries and "HH_dir". Second, I computed the share of the calculated total energy use for road transport in the documented total energy use taken from the IEA flow "Road" for all IEA energy sources. Then, I used this share to adjust the CO2 emissions in the IEA flow "Road" accordingly. Last, I multiplied each BEA industry's share and the direct household consumption's share, respectively, with the adjusted CO2 emissions in IEA flow "Road" for each IEA energy source, which yields the CO2 emissions of road transport for all BEA industries and for direct household consumption.

For the CO2 emissions of air and maritime transport, I first calculated the share of the computed energy use of the IEA energy source "Kerosene type jet fuel excl. biofuels" by the BEA industry "Air transportation" in the corresponding documented energy use in the IEA flow "Domestic aviation", as well as the share of the computed energy use of the IEA energy source "Motor gasoline excl. biofuels" by the BEA industry "Water transportation" in the corresponding documented energy use in the IEA flow "Domestic navigation". Second, I multiplied the calculated shares with the CO2 emissions of the respective IEA energy sources of the IEA flows "Domestic aviation" and "Domestic navigation". Thereby, I obtained the total CO2 emissions for the BEA industries "Air transportation" and "Water transportation", which, according to the calculations in Section 3.1.5, both consist of only one IEA energy source each.

3.2 Replicated data compilation by Feng et al.

The data set compiled by Feng et al. (2015a) contains Input-Output tables, CO2 emissions and energy use data for the years 1997 to 2013. In the following, I describe the data compilation by Feng et al. according to the way I interpreted the description in their paper as well as to a number of further explanations in personal communication with Mr. Feng via email. However, it has to be noted that said communication has only occurred sporadically and some questions concerning the data compilation have not been answered by Mr. Feng as of this writing. Therefore, certain aspects of the data compilation by Feng et al. are based on assumptions that are declared as such.

The Input-Output tables are composed according to Miller and Blair (2009) within an industry-demand driven model, under the industry technology assumption, and in the Industry-by-Industry format. The Input-Output tables are based on the Make and Use tables put at disposal by the BEA (2016b, 2016c). The calculated Input-Output tables were then transformed from current prices to constant prices (base year 2009) on the basis of *Chain-Type Price Indexes for Gross Output by Industry* (BEA, 2016a), which I carried out in following three steps. First, I applied the respective price index to each row (industry). For the two industries "Scrap, used and secondhand goods" and "Noncomparable imports and rest-of-the-world adjustment [1]", I used the average of the price indexes of all other industries. Second, I computed the total of each industry's valued added by subtracting each industry's intermediate output (sum of each column without said value added) from each industry's commodity output (sum of each row). Third, I divided the total value added of each industry onto the three value added categories by the BEA using the values of the Input-Output tables in current prices as splitting key.

The obtained symmetric Input-Output tables comprising 71 industries are then aggregated to 35 industries according to a concordance table by Feng et al. (see table A.2) to match the industry classification system used by WIOD (Feng, personal communication, March 15, 2016).

The CO2 emissions and energy use data that Feng et al. used in their analysis consist of various data inputs: On the one hand, each industry's share of total CO2 emissions as well as total energy use was gathered from the respective data files provided by the WIOD database (2012a, 2012b). The WIOD database, however, only includes data up until the year 2009, therefore each industry's share of CO2 emissions and energy use for the years 2010 to 2013 needs to be computed otherwise as explained further below. On the other hand, the annual total values of CO2 emissions and energy use for the years 1997 to 2013 were retrieved from the U.S. Energy Information Administration (EIA) (2016a, 2016c). The total energy use is declared as "Primary Energy Consumption Total", whereas the total CO2 emissions need to be summed up from the different sectoral data files, i.e. residential, commercial, industrial, and transportation. The CO2 emissions by the electric power sector need to be omitted when calculating the total CO2 emissions over the entire economy, since they are already included in the other sectors' total CO2 emissions. Finally, each industry's share of total CO2 emissions and total energy use taken from the WIOD database is multiplied by the total CO2 emissions and the total energy use obtained from the EIA, which yields each industry's absolute value for said two categories (Feng, personal communication, March 15, 2016).

The calculation of the shares of CO2 emissions and energy use related to every WIOD industry for the years 2010 to 2013 remains partly unclear, as a consequence, the following steps entail some best guesses on my part based on the information that was available to me.
First, from the EIA energy use data and CO2 emissions (EIA, 2016a, 2016c), the categories "Primary Energy Consumed by the Electric Power Sector" and "Total Energy Electric Power Sector CO2 Emissions" are assigned to the WIOD industry "Electricity, Gas and Water Supply". Second, energy intensities as well as emission intensities are computed for all other WIOD industries (except for the final consumption expenditures by households) by dividing each industry's energy use and CO2 emissions, respectively, by each industry's corresponding commodity output from the Input-Ouput table (the rightmost column). At first, said intensities can only be calculated for the year 2009, which are then used to calculate each WIOD industry's share of total energy use and total CO2 emissions for the year 2010 (see further below). Once the shares for the year 2010 are calculated and multiplied with the total values of CO2 emissions and energy use from the EIA (2016a, 2016c), as described above for the years 1997 to 2009, the energy intensities and emission intensities can be calculated for the year 2010, and so forth. Third, each WIOD industry's afore-computed energy and emission intensity is multiplied with the corresponding commodity output of the following year to give a tentative value of each industry's energy use and CO2 emissions (tentative, because it serves as an intermediate step to calculate each industry's share in the total energy use and CO2 emissions).
The shares of energy use and CO2 emissions corresponding to the "direct household consumption expenditure by households" are compiled as follows: First, the "Personal consumption expenditures" on the WIOD industry "Coke, refined petroleum and nuclear fuel" are gathered from the Input-Output tables and the "Natural Gas Consumed by the Residential Sector (Excluding Supplemental Gaseous Fuels)" as well as the "Natu-

ral Gas, Excluding Supplemental Gaseous Fuels, Residential Sector CO2 Emissions" are collected from the EIA (2016b, 2016c). Second, I computed the share of "Natural Gas Consumed by the Residential Sector (Excluding Supplemental Gaseous Fuels)" and of "Natural Gas, Excluding Supplemental Gaseous Fuels, Residential Sector CO2 Emissions", respectively, in the total "direct household consumption expenditure by households", which, at first, can only be calculated for the year 2009, and later, once the share for the year 2010 is computed and multiplied with the total values of CO2 emissions and energy use from the EIA (2016b, 2016c) as for the years 1997 to 2009 (see further below), the shares for the following years can be calculated correspondingly. Third, I calculated growth rates for the "Personal consumption expenditures" on "Coke, refined petroleum and nuclear fuel" as well as for "Natural Gas Consumed by the Residential Sector (Excluding Supplemental Gaseous Fuels)" and "Natural Gas, Excluding Supplemental Gaseous Fuels, Residential Sector CO2 Emissions", respectively, from one year to the next. I then weighted the two respective growth rates according to the share of natural gas and the share of the remaining energy use or CO2 emissions from the previous year. In other words, I weighted the growth rate of "Natural Gas Consumed by the Residential Sector (Excluding Supplemental Gaseous Fuels)" correspondent to its share in the total energy use of "direct household consumption expenditure by households" and added the growth rate of "Personal consumption expenditures" on "Coke, refined petroleum and nuclear fuel" weighted by the share of the residual of said energy use. I carried out the same procedure for CO2 emissions, which yields an overall growth rate that I applied to the energy use and CO2 emissions of the "direct household consumption expenditure by households" from the previous year to obtain a tentative value of energy use and CO2 emissions.

Finally, I calculated the relative shares of all industries and "direct household consumption expenditure by households" in the tentative total of energy use and CO2 emissions, respectively, to multiply them with the total energy use and CO2 emissions by the EIA (2016a, 2016c) as carried out with the relative shares from the WIOD data for the years 1997 to 2009. It has to be noted that since a number of the afore-described calculations are based on the calculated energy use and CO2 emissions of the previous year, the data compilation for the years 2010 to 2013 needs to be achieved successively year by year.

3.3 Extended structural decomposition analysis

The extended structural decomposition analysis (SDA) involves seven different contributing factors, whose influences on the variations in the CO2 emissions from year to year are analyzed. In the following I elucidate the contributing factors of the SDA, which are, to a great extent, adopted from Feng et al. (2015a).

Equation 31 shows the relationship between the variables described in the following and the yearly total CO2 emissions, where the total of *direct household emissions* HH_dir is simply added to the otherwise purely multiplicative equation. The scalar denoting the direct household emissions entails the sum of all CO2 emissions assigned to the category "direct household consumption" in Section 3.1.7.

$$\boldsymbol{CO2} = \boldsymbol{cF\hat{E}Ly_s}y_v p + HH\_dir \tag{31}$$

The *emission intensity* $\boldsymbol{c}$ is represented by a 1 × 11 row vector, which comprises the CO2 emissions in Mt per energy use in ktoe for all eleven energy classes in Table A.1, to the exclusion of "Oil shale" since no energy use was recorded for that energy class over the entire time period under consideration. The *fuel mix* $\boldsymbol{F}$ is depicted by an 11 × 71 matrix where the rows stand for said eleven energy classes and the columns denote the 71 BEA industries. Each column representing a certain industry contains the relative shares of all energy classes in the total energy use of the respective industry, which results in each column summing up to 1. The *energy intensity* $\boldsymbol{\hat{E}}$ is represented by a 71 × 71 diagonal matrix, where the diagonal comprises the energy use in ktoe per total commodity output in USD for each of the 71 BEA industries.

The *production structure* $\boldsymbol{L}$ is depicted by the total requirements matrix, which entails all interindustry transactions and takes the shape of a 71×71 matrix. The *consumption patterns* $\boldsymbol{y_s}$ are represented by a 71 × 1 column vector that comprises the shares of total final demand in the 71 BEA industries, whereby the sum of the column vector equals 1. The shares are calculated on the basis of total final demand in USD, which covers all final demand categories from the Input-Output table. The *consumption volume* y_v and the *population* p are both scalars denoting the sum of total final demand based on all final demand categories per capita and the population size, respectively.

The variables are all based on the data, where the compilation is described in Section 3.1, with the exception of the data on the population size, which was gathered from the World Bank (2015).

As presented in Section 2.3, when an equation such as Equation 31 is decomposed, the influence of each variable is weighted by the remaining variables from either time period t or the previous time period $t-1$, between which the change of CO2 emissions is aimed to be decomposed. The weight of each variable w can hence be calculated in numerous different approaches, since the more remaining variables form part of a weight, the more constellations of the variables from either time period t or $t-1$ exist. As advocated by Dietzenbacher and Los (1998), the average of all possible approaches ($n!$) is used to compute the influences of each of the seven variables ($n = 7$), which, in this case, total up to $n! = 7! = 5040$ different decomposition approaches. Instead of calculating all 5040 approaches separately, Seibel (2003) proposes a method to calculate the repeated occurrence of the afore-stated remaining variables forming part of each respective weight (see below). In consequence, in the exemplary case of the influence of the emission intensity $\boldsymbol{c}$ along with the corresponding weight, the calculation looks as follows, where the term $w^c\boldsymbol{\Delta c}$ denotes the influence of the emission intensity on the change of CO2 emissions between $t-1$ and t weighted by the average of all decomposition approaches. $\boldsymbol{\Delta c}$ can simply be calculated by subtracting c_{t-1} from c_t. The equation at full length can be found in the appendix (Equation A.1), whereby both the abbreviated version in the following as well as the full version in the appendix are based on the *Supplemental information* corresponding to the article on the drivers of the US CO2 emissions by Feng et al. (2015b).

$$
\begin{aligned}
w^{c}\boldsymbol{\Delta c} = \frac{1}{5040}[& (720 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& \vdots \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+ \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+ \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& \vdots \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t})+ \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& (36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& \vdots \\
& (36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+ \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+ \\
& \vdots \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+ \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t})+ \\
& \vdots \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})+ \\
& (720 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})]
\end{aligned}
\tag{32}
$$

When denoting the entirety of all variables with either the subscript t or the subscript $t-1$ contained in each line in the foregoing Equation 32 as *weight coefficients*, Seibel (2003) proposes a method to calculate the number of different weight coefficients that are attached to the Δ of each respective variable whose influence is under consideration. In Equation 32, the number of different weight coefficients is represented by the number of lines of the entire equation.

If k stands for the number of $t-1$ subscripts, then, for each weight coefficient, k lies between 0 and $n-1$ since one of the n variables is the one whose influence is being computed. Consequently, the number of t subscripts equals $n-1-k$. Finally, the number of different weight coefficients for each k can be obtained as presented in the following equation.

$$\frac{(n-1)!}{(n-1-k)! \cdot k!} \tag{33}$$

In the case of this extended SDA, there are $n = 7$ variables, therefore according to Equation 33, for $k = 0$ or $k = 6$, there is merely one weight coefficient. For $k = 1$ or $k = 5$, there are six different weight coefficients, for $k = 2$ or $k = 4$, there are 15 different weight coefficients, etc. In a second step, the *occurrence rate*, which denotes the number of occurrences of each weight coefficient, is calculated by means of the following equation.

$$(n-1-k)! \cdot k! \tag{34}$$

This number can be found in the first position of each line in Equation 32, except for the first line (Feng et al., 2015b). E.g. for $k = 2$, according to Equation 33 and Equation 34, there are 15 different weight coefficients, which are all multiplied by the occurrence rate of 48. This means that there are 15 different constellations of assigning t twice and $t-1$ four times to the six above-named remaining variables forming part of each respective weight. Each constellation is then multiplied by 48, because it occurs 48 times in the total 5040 different decomposition approaches.

To calculate the influence of all other variables, e.g. the influence of the fuel mix $w^F \boldsymbol{\Delta F}$, on the change in CO2 emissions between $t-1$ and t, one needs to replace every $\boldsymbol{F_{t-1}}$ or $\boldsymbol{F_t}$ with $\boldsymbol{\Delta F}$, and every $\boldsymbol{\Delta c}$ with $\boldsymbol{c_{t-1}}$ or $\boldsymbol{F_t}$, respectively, in Equation 32. The entire procedure of calculating the influence of each variable on the change of CO2 emissions finally needs to be carried out for all years from the change between 1997 and 1998 up to the change between 2012 to 2013.

3.4 Structural decomposition analysis by Feng et al.

Feng et al. (2015a) decomposed the change in CO2 emissions into the following six contributing factors. The last five contributing factors are identical to the extended SDA presented in the previous section, with the sole difference that not the 71 BEA industries were used but rather the 35 WIOD industries. Moreover, the data compiled in Section 3.2 serves as a basis as opposed to the data compiled in Section 3.1, which was used in the previous section. The data on the population size was gathered from the World Bank (2015) and is the same as used in the foregoing section.

The *fuel mix* $\boldsymbol{f}$ is represented by a 1×35 row vector, which comprises the CO2 emissions in Mt per total energy use in ktoe for all 35 WIOD industries. The *energy intensity* $\boldsymbol{\hat{E}}$ is denoted by a 35×35 diagonal matrix, where the diagonal comprises the energy use in ktoe per total commodity output in USD for each of the 35 WIOD industries.

The *production structure* $\boldsymbol{L}$ is depicted by the total requirements matrix, which entails all interindustry transactions and takes the shape of a 35×35 matrix. The *consumption patterns* $\boldsymbol{y_s}$ are represented by a 35×1 column vector that comprises the shares of total final demand in the 35 WIOD industries, whereby the sum of the column vector equals 1. The shares are calculated on the basis of total final demand in USD, which covers all final demand categories from the Input-Output table. The *consumption volume* y_v and the *population* p are both scalars denoting the sum of total final demand based on all final demand categories per capita and the population size, respectively.

The following equation relates the defined variables to the CO2 emissions, whereby, it has to be noted that Feng et al. (2015a) positioned the variable for population size p at the beginning of the multiplicative term rather than at the end. This, however, does not influence the result since p is a scalar. As in the preceding chapter, the total of *direct household emissions* HH_dir are added at the end of the otherwise purely multiplicative equation.

$$\boldsymbol{CO2} = \boldsymbol{f}\boldsymbol{\hat{E}}\boldsymbol{L}\boldsymbol{y_s} y_v p + HH\_dir \tag{35}$$

As in the previous section, the average of all possible decomposition approaches ($n!$) according to Dietzenbacher and Los (1998) is used to compute the influences of each of the six variables ($n = 6$). In this case, the total of all possible approaches equals $n! = 6! = 720$. Corresponding to the method proposed by Seibel (2003), the exemplary calculation of the influence of the fuel mix $w^f \boldsymbol{\Delta f}$ on the change of CO2 emissions between $t-1$ and t weighted by the average of all decomposition approaches looks as follows, where $\boldsymbol{\Delta f}$ is calculated by subtracting f_{t-1} from f_t.The full equation can be found in the appendix (Equation A.2), where both the abbreviated version as well as the full version are based on the *Supplemental information* corresponding to the article on the drivers of the US CO2 emissions by Feng et al. (2015b).

$$
\begin{aligned}
w^f \boldsymbol{\Delta f} = \frac{1}{720}[& (720 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1}) + \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1}) + \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1}) + \\
& \vdots \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1}) + \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t}) + \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1}) + \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1}) + \\
& \vdots \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t}) + \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t}) + \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1}) + \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1}) + \\
& \vdots \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t}) + \\
& (12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t}) + \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1}) + \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t}) + \\
& \vdots \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t}) + \\
& (24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t}) + \\
& (120 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t})]
\end{aligned}
\tag{36}
$$

The description of the calculation method for Equation 36 can be found in the preceding chapter. The calculation of all variables' influences on the change of CO2 emissions, which are exemplified by the case of the fuel mix $\boldsymbol{f}$ as shown above, need to be carried out for all time intervals from the years 1997 to 1998 up to the years 2012 to 2013.

4 Results

4.1 Results of the extended structural decomposition analysis

Hereafter, the influences of the following contributing factors *emission intensity*, *fuel mix*, *energy intensity*, *production structure*, *consumption patterns*, *consumption volume*, and *population* are shown numerically in tabular form as well as graphically in various figures. Correspondent to Feng et al. (2015a) the contributing factor *consumption volume* also covers the influence of the *direct household emissions*.

Since the SDA Equation 31 involves various variables, which contain previously calculated coefficients, the calculated total CO2 emissions per year (according to Equation 31) might deviate slightly from the documented CO2 emissions (as compiled in Section 3.1). The deviation of each year is documented in the subsequent tables, whereby, in the following, the calculated total CO2 emissions are used, which correlate to the calculated influences.

Table 10: Results of the extended SDA in Mt CO2, 1997-2004

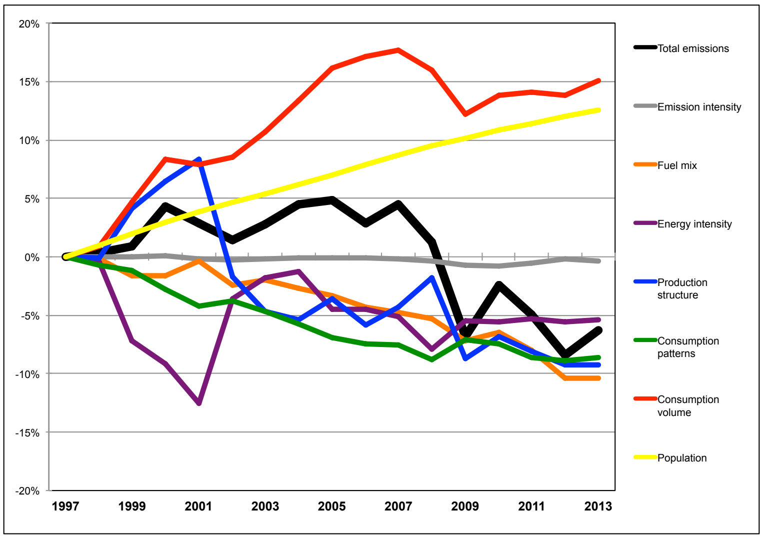
	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Emission intensity	-	-1	1	2	-10	-9	7	4
Fuel mix	-	-11	-77	1	66	-113	26	-38
Energy intensity	-	-26	-366	-109	-185	490	95	34
Production structure	-	-5	233	124	106	-549	-166	-36
Consumption patterns	-	-40	-25	-87	-77	21	-46	-61
Consumption volume	-	49	207	200	-22	33	120	145
Population	-	55	55	53	48	44	41	44
Total contributions	**-**	**21**	**28**	**185**	**-75**	**-82**	**77**	**92**
Calculated CO2 emissions (total)	**5474**	**5495**	**5523**	**5707**	**5632**	**5551**	**5628**	**5720**
Calculation deviation	-8	3	-6	-1	-3	-11	-9	-8
Calculation deviation in %	-0.15%	0.05%	-0.11%	-0.02%	-0.05%	-0.20%	-0.16%	-0.14%
Documented CO2 emissions (total)	**5428**	**5492**	**5529**	**5709**	**5635**	**5562**	**5637**	**5728**

Table 11: Results of the extended SDA in Mt CO2, 2005-2013

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Em. in.	1	0	-8	-11	-17	-4	13	19	-7
Fu. mi.	-36	-53	-26	-32	-100	38	-81	-133	1
En. in.	-178	-3	-32	-152	132	-2	14	-13	7
Pr. st.	96	-122	84	136	-378	104	-66	-65	-2
Co. pa.	-61	-29	-5	-70	93	-18	-66	-15	17
Co. vo.	150	57	28	-93	-206	86	17	-14	69
Po.	44	45	45	44	38	35	33	32	31
To. co.	**17**	**-105**	**86**	**-177**	**-438**	**239**	**-138**	**-190**	**116**
Ca. CO2 em. (to.)	**5737**	**5633**	**5718**	**5541**	**5103**	**5342**	**5204**	**5013**	**5129**
Ca. de.	-5	2	-9	-5	-6	-15	-7	-4	-2
Ca. de. in %	-0.09%	0.04%	-0.16%	-0.09%	-0.12%	-0.28%	-0.13%	-0.08%	-0.04%
Do. CO2 em. (to.)	**5742**	**5631**	**5727**	**5546**	**5109**	**5357**	**5211**	**5017**	**5131**

The results presented in Tables 10 and 11 are visualized in the following figure, which uses the same design as Figure 1 by Feng et al. (2015a).

Figure 2: Ext. SDA: Cumulative influences on the CO2 emissions in % (base year: 1997)

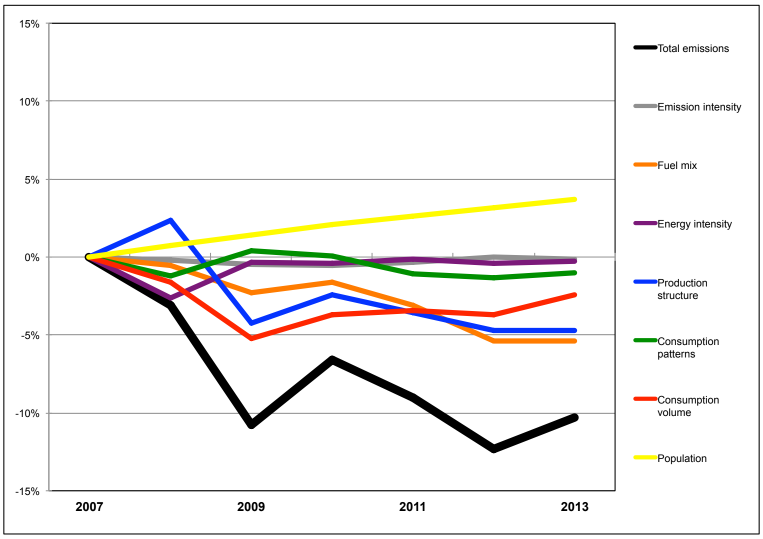


Between the years 1997 and 2008 the total CO2 emissions fluctuated between 0% and 5%, in the year 2009 they dropped by about 7% and then

remained fluctuating around -5% of the base year value in 1997. The influence of the emission intensity remained consistently around 0%, which implies that the CO2 emissions per energy unit consumed did not change over the time period under consideration. The fuel mix had a more or less continuously negative influence on the CO2 emissions, while the influence of the emission intensity, which denotes the amount of energy used to produce one USD of output, decreased vastly between the years 1997 and 2001 by over 12%, only to rise again in the year 2002 and fluctuate around -5% of the base year value in 1997 for the remainder of the time period considered.
The influence of the production structure shows a great rise between the years 1997 and 2001 working in opposite direction of the influence of the energy intensity. In the year 2002 the influence of the production structure dropped down to around -2% and decreased further ever so slightly in a volatile manner. The consumption patterns had a relatively consistent negative effect on the CO2 emissions, while the consumption volume's influence was strongly positive up until the year 2008 (over 17%), where it dropped by approximately 5% only to slowly rise again until the end of the time period under consideration. Finally, the influence of the population on the CO2 emissions is steadily positive and reflects the growth of population in the US between 1997 and 2013.
Over the entire time period under consideration, the consumption volume had the strongest positive influence on the total CO2 emissions, closely followed by the population size. The fuel mix on the other hand had the strongest negative effect, followed by the production structure and the consumption patterns.

To focus on the decline in total CO2 emissions between 2007 and 2013, in the following figure, which equates to Figure 2, only the years 2007 to 2010 are depicted, whereby the year 2007 serves as the base year.

Figure 3: Ext. SDA: Cumulative influences on the CO2 emissions in % (base year: 2007)



In relation to the base year 2007, the total CO2 emissions dropped by over 10% from 2007 to 2009 and remained fluctuating around that level until the year 2013. The effects of the emission intensity, the energy intensity, as well as the consumption patterns only experienced small fluctuations while remaining more or less uninfluential to the total CO2 emissions. The fuel mix shows a rather consistent negative effect on the total CO2 emissions from 2007 to 2013 and turns out to be the contributing factor with the strongest negative influence (approx. -5%) at the end of said time period. Both the production structure (approx. -4%) and the consumption volume (approx. -5%) exerted a strong negative effect on total CO2 emissions between the years 2008 and 2009, afterwards the former remained fluctuating around that level, where the latter slowly rose again to reach roughly -2% of the base year value in the year 2013. The population was the only contributing factor, where the influence on the CO2 emissions was positive throughout the years 2007 to 2013.

In the following figure, the fuel mix between the years 2007 and 2013 is illustrated on the basis of the use of the different energy classes over the years.

Figure 4: Ext. SDA: Fuel mix between 2007 and 2013 (Energy use by energy class in Mtoe)

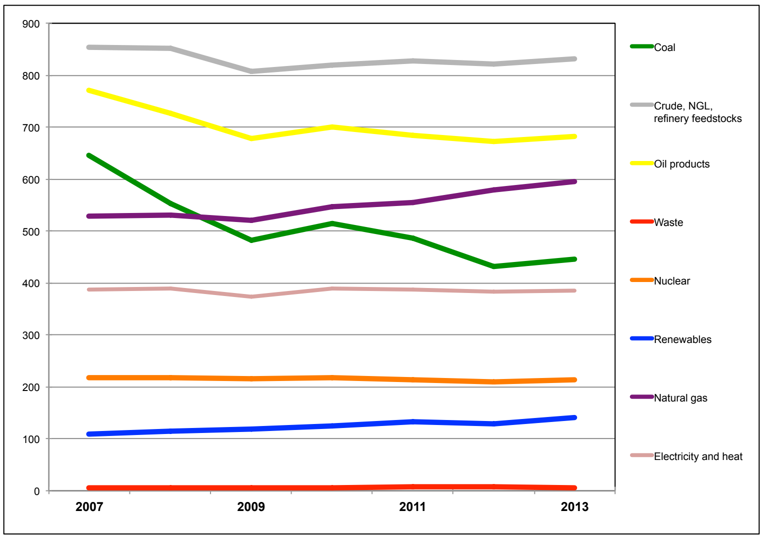
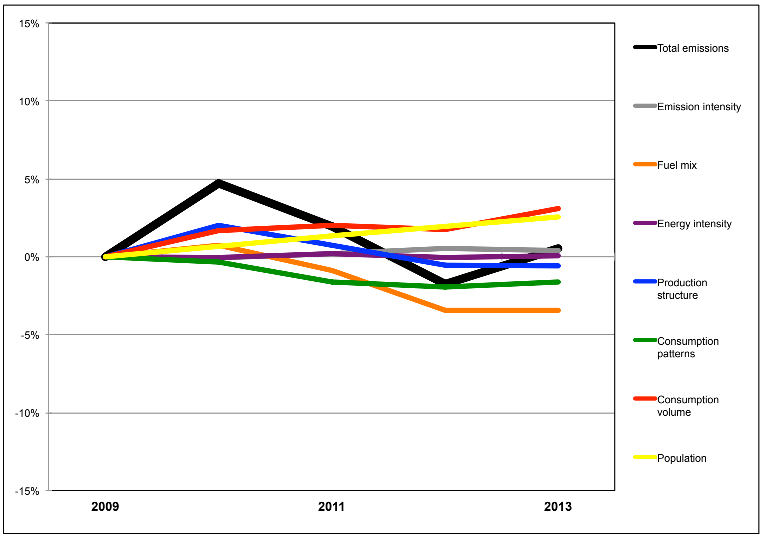


Figure 4 points out that the strongest changes in the fuel mix were a relatively strong decrease in the use of coal and a relatively distinct increase in the use of natural gas. A drop in the use of oil products as well as a slight growth in the use of renewable energy sources stand out as well. The use of the remaining energy classes stays relatively constant over the time period under consideration.

Finally, to elucidate the development of the CO2 emissions after the vast drop between 2007 and 2009, the following figure, which also corresponds to Figure 2, shows the total CO2 emissions as well as the contributing factors from 2009 to 2013.

Figure 5: Ext. SDA: Cumulative influences on the CO2 emissions in % (base year: 2009)



Over the time period under consideration, the total CO2 emissions fluctuated around the level they had amounted to in the year 2009. At the end of the time period in the year 2013, the influences of the emission intensity, the energy intensity, and the production structure remained within the limits of -1% and 1% of the base year value. The effect of the fuel mix amounts to approximately -3%, the effect of the consumption patterns to roughly -2%, and the effects of the consumption volume as well as the population each add up to approximately 3%. The fuel mix thus exerts the strongest negative influence on the total CO2 emissions, while the consumption volume is the strongest positive effect between the years 2009 and 2013.

4.2 Results of the replicated structural decomposition analysis by Feng et al.

In the replicated SDA by Feng et al. (2015a), I analyzed the influences of the following contributing factors *fuel mix*, *energy intensity*, *production structure*, *consumption patterns*, *consumption volume*, and *population*. The contributing factor *emission intensity* presented in the previous Section 4.1 is not included in this analysis, as the respective information is part of the variable *fuel mix*. As in the previous section and correspondent to Feng

et al. (2015a), the contributing factor *consumption volume* includes the influence of the *direct household emissions*.
The following tables show the results of the replicated SDA, which is based on the data compiled in Section 3.2.

Table 12: Results of the replicated SDA in Mt CO2, 1997-2004

	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Fuel mix	-	21	-73	50	73	33	37	-5
Energy intensity	-	-74	-313	-193	-276	519	21	12
Production structure	-	3	254	135	116	-564	-150	-44
Consumption patterns	-	-53	-40	-72	-61	-2	-55	-55
Consumption volume	-	96	167	204	-8	10	154	162
Population	-	57	57	56	50	47	43	47
Total contributions	**-**	**51**	**52**	**180**	**-107**	**43**	**49**	**117**
Calculated CO2 emissions (total)	**5584**	**5635**	**5688**	**5868**	**5761**	**5804**	**5853**	**5970**
Calculation deviation	0.00	0.00	0.00	0.01	-0.02	0.00	0.01	0.00
Calculation deviation in %	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Documented CO2 emissions (total)	**5584**	**5635**	**5688**	**5868**	**5761**	**5804**	**5853**	**5970**

Table 13: Results of the replicated SDA in Mt CO2, 2005-2013

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Fu. mi.	-27	-58	-62	-168	-101	-85	-63	-54	18
En. in.	-228	21	-40	8	208	139	29	-105	-37
Pr. st.	114	-133	92	111	-450	118	-63	-78	20
Co. pa.	-59	-11	3	-44	95	-12	-56	-11	8
Co. vo.	176	50	49	-146	-217	-8	-20	0	86
Po.	47	48	48	47	41	39	36	35	34
To. co.	**23**	**-83**	**91**	**-192**	**-423**	**191**	**-137**	**-213**	**129**
Ca. CO2 em. (to.)	**5993**	**5910**	**6001**	**5809**	**5386**	**5576**	**5439**	**5227**	**5355**
Ca. de.	-0.01	0.00	0.00	-0.01	-0.01	0.01	-0.01	0.02	0.01
Ca. de. in %	0.00%	0.00%	0.10%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Do. CO2 em. (to.)	**5993**	**5910**	**6001**	**5809**	**5386**	**5576**	**5439**	**5227**	**5355**

The tables show how total CO2 emissions rose from 5584 Mt CO2 in the year 1997 to 6001 Mt CO2 in the year 2007 in a slightly fluctuating manner. Afterwards, within two years the total CO2 emissions dropped down to 5386 Mt CO2, and ultimately remained around that emission level. To compare the results from the replicated SDA with the results by Feng et al. (2015a), Figure 7 by Feng et al. is contrasted with Figure 6, which is the same figure, however, constructed with the replicated data set as described in Section 3.2.

Figure 6: Rep. SDA: Cumulative influences on the CO2 emissions in % (base year: 1997)

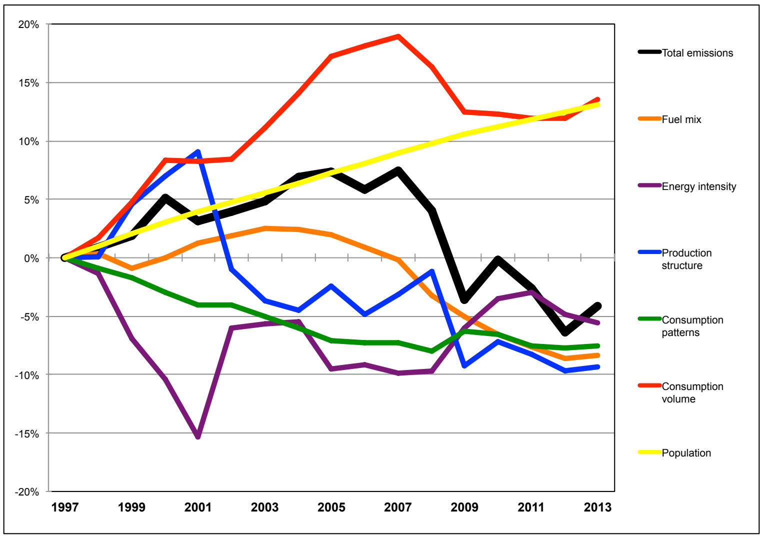


Figure 7: Contributions of different factors to changes in the US CO2 emissions between 1997 and 2013

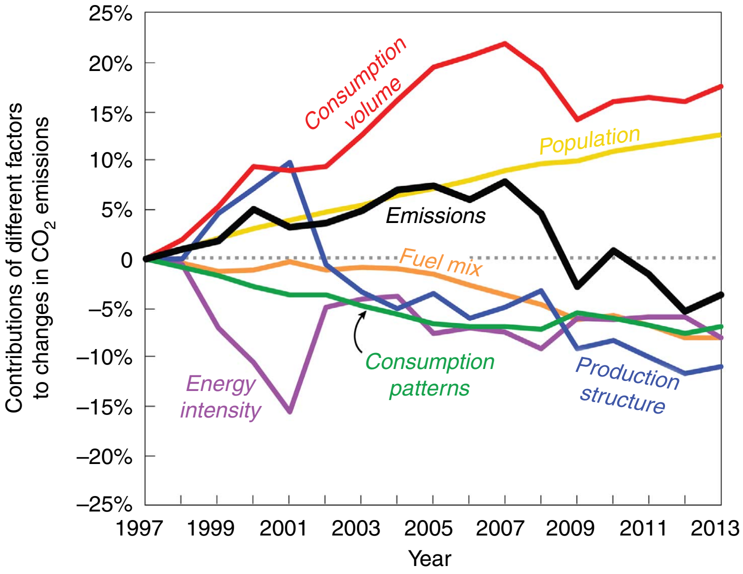


Figure 1 by Feng et al. (2015a)

The two figures show that the replicated data compilation was not fully successful in virtue of the differing results. E.g. while the influence of the consumption volume on the CO2 emissions in the SDA by Feng et al. reaches a maximum of well above 20% of the base year value in the year 2007, the same influence only amounts to approximately 19% in the replicated SDA. Furthermore, in the SDA by Feng et al. the effects of the consumption patterns, the fuel mix, as well as the energy intensity in the year 2013 are all roughly equal, each adding up to well below -5%, while the effect of the production structure amounted to approximately -10%. On the other hand, in the replicated SDA the effects of the consumption patterns, the fuel mix, and the production structure in the year 2013 are approximately equal at around -8% and -9%, whereas the energy intensity adds up to roughly -6%.

Due to the fact that the results of the replicated SDA do not match up well with the SDA conducted by Feng et al., I refrained from further assessing the results. Various shortcomings of the data compilation by Feng et al. (2015a) are addressed in the conclusion of this thesis.

4.3 Results of the extended SDA and results of the SDA by Feng et al. in comparison

When comparing the influences of the contributing factors between the years 2007 and 2013 from the extended SDA in Figure 8 on the one hand with the SDA by Feng et al. (2015a) on the other hand (see Figure 9 below), several observations stand out.

Figure 8: Ext. SDA: Influences on the CO2 emissions in % between 2007 and 2013

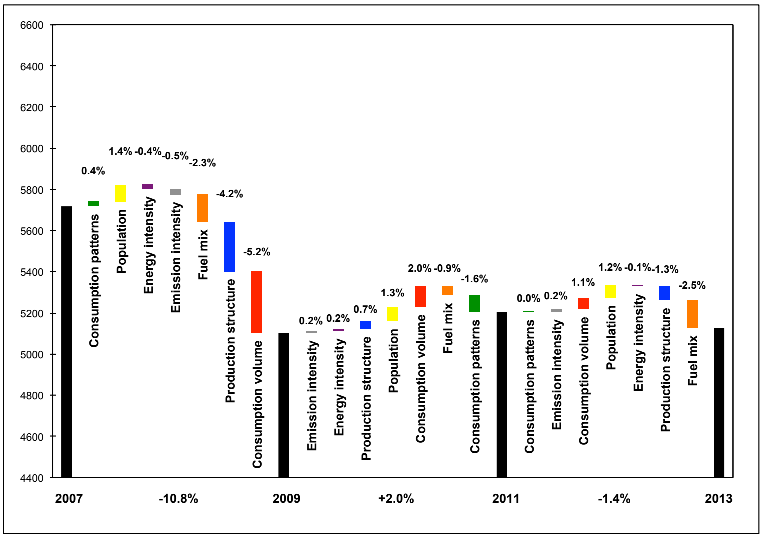


Figure 9: Contributions of different factors to the decline in US CO2 emissions 2007-2009 and 2009-2011 and 2011-2013

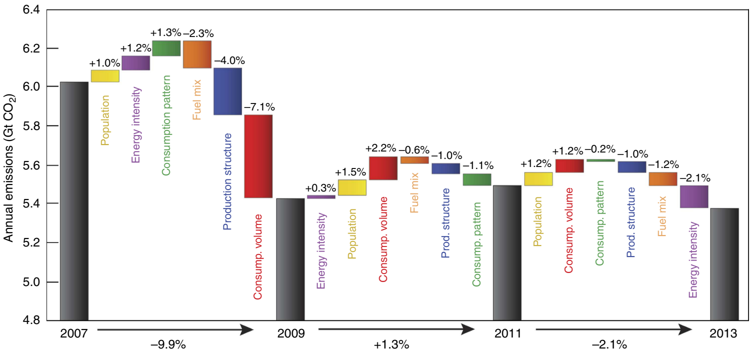


Figure 3 by Feng et al. (2015a)

While the total drop in CO2 emissions from 2007 to 2009 was higher in the extended SDA (-10.8%) than in the SDA by Feng et al. (-9.9%), the consumption volume played a much smaller role in the extended SDA (-5.2%) than in the SDA by Feng et al. (-7.1%). This applies to the following two timespans from 2009 to 2011 and from 2011 to 2013 as well, where the consumption volume in the extended SDA amounted to 2.0% and 1.1%, while in the SDA by Feng et al. the consumption volume added up to 2.2% and 1.2% in the respective timespans.

The influence of the production structure between 2007 and 2009 is stronger in the extended SDA (-4.2% vs. -4.0% in the SDA by Feng et al.), runs in the opposite direction between 2009 and 2011 (0.7% vs. -1.0%), and is again stronger in the last timespan between 2011 and 2013 (-1.3% vs. -1.0%).

Furthermore, the fuel mix played a more or less equally important role in the drop in CO2 emissions between the years 2007 and 2009. In the following two timespans from 2009 to 2011 and from 2011 to 2013, the negative effect of the fuel mix on the CO2 emissions was distinctly higher in the extended SDA compared to the SDA by Feng et al.

Regarding the total CO2 emissions, the total value in the year 2007 in the extended SDA was approximately 5700 Mt CO2, where the same value in the SDA by Feng et al. amounted to circa 6000 Mt CO2. In the year 2009, the total CO2 emissions in the extended SDA added up to circa 5100 Mt CO2, in the SDA by Feng et al. on the other hand, the same value is approximately 5400 Mt CO2. This difference in total CO2 emissions can also be observed for the years 2011 as well as 2013 and is due to the fact that Feng et al. used energy statistics (EIA, 2016a, 2016c), instead of energy accounts as a basis for the data compilation. The economy-wide energy use in the energy statistics is between approximately 5% and 9% higher than the very same energy use in the energy accounts depending on the year. Further shortcomings of the data compilation by Feng et al. (2015a) as well as other interpretations of the presented results can be found in the following section.

In summary, it can be stated that even though many aspects may seem almost identical at first glance, a closer look reveals rather extensive dissimilarities in the results of the two SDAs.

5 Discussion

The CO2 emissions in the US reached a turning point in the year 2007 after a period of continuous growth and decreased by roughly 10% until the year 2013. Feng et al. (2015a) concluded that the decreasing emissions resulted mainly from the economic recession and that the fuel mix only played a marginal role. More precisely they argue as follows:

> "Concurrent with the global economic recession, 83% of the decrease during 2007-2009 was due to decreased consumption and changes in the production structure of the US economy, with just 17% related to changes in the fuel mix."

The extended SDA shows similar results between 2007 and 2009 in that the consumption volume and the production structure accounted for 75% of the sum of all negative influences on the CO2 emissions, while the fuel mix only made out merely 18% (7% due to other contributing factors). Therefore, it can be confirmed that the economic recession had a predominant influence on the decrease in CO2 emissions between 2007 and 2009, however, no conclusions for the timespan from 2009 to 2013 can be derived based on the above-stated shares.

In this regard, Feng et al. (2015a) further state:

> "During the economic recovery, 2009-2013, the decrease in US emissions has been small ($< 1\%$), with nearly equal contributions from changes in the fuel mix, decreases in energy use per unit of GDP, changes in US production structure, and changes in consumption patterns."

As illustrated in Figure 5, the extended SDA shows different results as to the years 2009 to 2013. When considering the sum of all negative influences on the CO2 emissions in said time period, the fuel mix made out 61%, while the consumption patterns and the production structure accounted for 28% and 10%, respectively. In Mt CO2, the sum of all the contributing factors, whose influence on the CO2 emissions was negative, amounts to -288 Mt CO2, while all the positively affecting contributing factors add up to a total of 314 Mt CO2. Since the two kinds of effects compensate for each other the total effect between 2009 and 2013 amounts to 26 Mt CO2, which in relation to the base year 2009 is equivalent to an increase of approximately 0.5%.

When juxtaposing these results against the above-cited quote by Feng et al. (2015a) two differences stand out. First, Feng et al. mention a slight decrease in CO2 emissions between 2009 and 2013, whereas the extended SDA shows an ever so slight increase in CO2 emissions. However, since both changes are minuscule, this difference can be neglected. Second, the role of the fuel mix in the entirety of all negative effects on the CO2 emissions in the respective time period is distinctly underestimated by Feng et al. when compared to the extended SDA. . While Feng et al. quantify the effect of the fuel mix equally important as three other contributing factors, the extended SDA rates the fuel mix as more than twice as important as the consumption patterns and more than six times as influential as the production structure. Therefore, these results lead to the conclusion that the fuel mix did play an important role in the development of CO2 emissions between 2009 and 2013. Put another way, if the influence of the fuel mix between 2009 and 2013 was left aside, the increase in CO2 emissions would amount to 202 Mt CO2 (actual increase: 26 Mt CO2), which is equivalent to approximately 4% in relation to the base year 2009 (actual increase: 0.5%).

The differences in the results of the two analyses can be ascribed to shortcomings in the data compilation by Feng et al. (2015a). First, the absolute values of the yearly total energy use and the total CO2 emissions are in the form of energy statistics as explained in Section 2.4, while the rest of the data set corresponds to national accounts. Second, Feng et al. partly based the forward projection to obtain the data for the years 2010 to 2013 on the assumption that the energy intensity did not change from one year to another, i.e. the energy used per USD of gross output remained unchanged (Feng, personal communication, March 15, 2016). Since more detailed information on the exact forward projection was not provided, the aimed replication was not fully successful. However, it can be stated that keeping the energy intensity constant for a forward projection while later including that very energy intensity as a contributing factor in the SDA seems quite prone to potential biases in the results.

Another problematic aspect of the data compilation by Feng et al. is that they conducted a forward projection based on the last year available in the WIOD database, which is the year 2009. After the financial crisis the entire economy was in a rather unusual and exceptional environment, which might not indicate the next years developments in the energy sector well. Any rapid change in said sector could therefore invalidate a forward projection based on the previous year drastically.

Concerning the substitution of coal with natural gas, Feng et al. (2015a) conclude:

> "... that substitution of gas for coal has had a relatively minor role in the emissions reduction of US CO2 emissions since 2007."

Figure 4 elucidates the changes in the fuel mix by depicting the changes in the use of various energy classes, where the decline in the use of coal as well as the increase in the use of natural gas seem to be the predominant trends. Moreover, a decline in the use of oil products as well as a slight growth in the use of renewables can be observed as well.

The report on *the third national climate assessment* by the U.S. Global Change Research Program (Melillo et al., 2014) claims that a shift from coal to natural gas in the electricity production is mainly accountable for the decline in CO2 emissions in recent years. Trembath et al. (2013) argue along the same lines. On the contrary, McJeon et al. (2014) advocate that the increased use of natural gas in the future will not distinguishably affect the trajectory of greenhouse gas emissions. They find that even if the natural gas consumption increased by 170% until the year 2050, the impact on CO2 emissions would range between -2% and +11%.

All in all, the extended SDA shows that the fuel mix played a more important role in negatively affecting the CO2 emissions in recent years than estimated by Feng et al. (2015a). However, no finite conclusion can be drawn from the extended SDA on whether the shift from coal to natural gas formed the basis for the overall change in the fuel mix.

6 Conclusion

Various conclusions have been drawn regarding the decline in CO2 emissions in recent years reaching from mainly being caused by the economic recession (Feng et al., 2015a) to stemming from the shift from coal to natural gas in the electricity production (Melillo et al., 2014). The aim of this thesis was to put the former of the two argumentations under the microscope. The analysis showed that the economic recession indeed played a predominant role in the decline of CO2 emissions but merely between the years 2007 and 2009. Thereupon, from 2009 to 2013, the fuel mix had the strongest influence on the CO2 emissions, however, the exact shifts within the fuel mix have not been determined conclusively.

Little attention has been payed to the long-term effect of the fuel mix on the CO2 emissions. Even though the years of the financial crisis show quite interesting developments in the CO2 emissions, the long-term effects of all conceivable contributing factors in less exceptional time periods may provide much more meaningful information in terms of climate protection policies or economic as well as social changes affecting CO2 emissions. The analysis in this thesis showed that amongst all the considered influencing factors, the fuel mix exerted the strongest effect on the CO2 emissions over the entire time period under consideration, namely from 1997 to 2013.

The data set that was compiled in the context of this thesis could well be used for further research, whereby two issues seem the most prevalent to be further explored. First, the fuel mix and its respective energy sources such as natural gas, coal, renewables, etc. could be disaggregated and the role of each energy source on rising and falling CO2 emissions, respectively, could be further examined. Second, the conversion rates in electricity and heat production could be further analyzed. The relative importance of various energy sources varies vastly depending on whether the primary energy sources used to produce electricity and heat are measured in their original energy content or their potential secondary energy content (energy and heat).

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A Appendix

Table A.1: IEA energy sources to energy class concordance table

IEA energy source	Energy class
Hard coal (if no detail) Brown coal (if no detail) Anthracite[3] Other bituminous coal[3] Sub-bituminous coal Lignite[3] Patent fuel[3] Coke oven coke[3] Gas coke Coal tar BKB Coke oven gas Blast furnace gas Other recovered gases	Coal CO2 rel.[1]
Anthracite[3] Coking coal Other bituminous coal[3] Lignite[3] Patent fuel[3] Coke oven coke[3] Gas works gas	Coal non CO2 rel.[2]
Peat Peat products	Peat and peat products
Industrial waste Municipal waste (non-renewable)	Waste
Natural gas	Natural gas
Crude/NGL/feedstocks (if not detail) Crude oil[3] Natural gas liquids[3]	Crude, NGL, refinery feedstocks CO2 rel.[1]
Crude oil[3] Natural gas liquids[3] Refinery feedstocks Additives/blending components Other hydrocarbons	Crude, NGL, refinery feedstocks non CO2 rel.[2]
Refinery gas Ethane Liquefied petroleum gases (LPG) Aviation gasoline Gasoline type jet fuel	Oil products

Other kerosene Fuel oil Naphtha White spirit & SBP Lubricants Bitumen Paraffin waxes Petroleum coke Other oil products Motor gasoline excl. biofuels Kerosene type jet fuel excl. biofuels Gas/diesel oil excl. biofuels	
Nuclear	Nuclear
Municipal waste (renewable) Biogasoline Biodiesels Other liquid biofuels Non-specified primary biofuels and waste Charcoal Primary solid biofuels Biogases Hydro Geothermal Solar photovoltaics Solar thermal Tide, wave and ocean Wind	Renewables
Oil shale and oil sands	Oil shale
Electricity/heat output from non-specified manufactured gases Heat output from non-specified combustible fuels Electricity Heat Other sources	Electricity and heat

[1] Primary energy use for processing to secondary non CO2 relevant energy product, where CO2 emissions are assigned to **primary** product, e.g. Burning coal to produce electricity, see Section 3.1.7

[2] Primary energy use for processing into secondary CO2 relevant energy product, where CO2 emissions are assigned to **secondary** product, e.g. Crude oil is refined into gasoline, see Section 3.1.7

[3] The splitting key for CO2 relevant energy use and non CO2 relevant energy use can be found in Section 3.1.7

Table A.2: BEA to WIOD concordance table

BEA industry label	**BEA industry code**	**WIOD industry label**	**WIOD industry code**
Farms	111CA	Agriculture, Hunting, Forestry and Fishing	secAtB
Forestry, fishing, and related activities	113FF	Agriculture, Hunting, Forestry and Fishing	secAtB
Oil and gas extraction	211	Mining and Quarrying	secC
Mining, except oil and gas	212	Mining and Quarrying	secC
Support activities for mining	213	Mining and Quarrying	secC
Utilities	22	Electricity, Gas and Water Supply	secE
Construction	23	Construction	secF
Wood products	321	Wood and Products of Wood and Cork	sec20
Nonmetallic mineral products	327	Other Non-Metallic Mineral	sec26
Primary metals	331	Basic Metals and Fabricated Metal	sec27t28
Fabricated metal products	332	Basic Metals and Fabricated Metal	sec27t28
Machinery	333	Machinery, Nec	sec29
Computer and electronic products	334	Electrical and Optical Equipment	sec30t33
Electrical equipment, appliances, and components	335	Electrical and Optical Equipment	sec30t33
Motor vehicles, bodies and trailers, and parts	3361MV	Transport Equipment	sec34t35
Other transportation equipment	3364OT	Transport Equipment	sec34t35
Furniture and related products	337	Manufacturing, Nec; Recycling	sec36t37
Miscellaneous manufacturing	339	Manufacturing, Nec; Recycling	sec36t37
Food and beverage and tobacco products	311FT	Food, Beverages and Tobacco	sec15t16
Textile mills and textile product mills	313TT	Textiles and Textile Products	sec17t18

Apparel and leather and allied products	315AL	Leather, Leather and Footwear	sec19
Paper products	322	Pulp, Paper, Paper , Printing and Publishing	sec21t22
Printing and related support activities	323	Pulp, Paper, Paper , Printing and Publishing	sec21t22
Petroleum and coal products	324	Coke, Refined Petroleum and Nuclear Fuel	sec23
Chemical products	325	Chemicals and Chemical Products	sec24
Plastics and rubber products	326	Rubber and Plastics	sec25
Wholesale trade	42	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	sec51
Motor vehicle and parts dealers	441	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	sec50
Food and beverage stores	445	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	sec52
General merchandise stores	452	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	sec52
Other retail	4A0	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	sec52
Air transportation	481	Air Transport	sec62
Rail transportation	482	Inland Transport	sec60
Water transportation	483	Water Transport	sec61
Truck transportation	484	Inland Transport	sec60
Transit and ground passenger transportation	485	Inland Transport	sec60
Pipeline transportation	486	Inland Transport	sec60
Other transportation and support activities	487OS	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	sec63

Warehousing and storage	493	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	sec63
Publishing industries, except internet (includes software)	511	Pulp, Paper, Paper , Printing and Publishing	sec21t22
Motion picture and sound recording industries	512	Renting of M&Eq and Other Business Activities	sec71t74
Broadcasting and telecommunications	513	Post and Telecommunications	sec64
Data processing, internet publishing, and other information services	514	Post and Telecommunications	sec64
Federal Reserve banks, credit intermediation, and related activities	521CI	Financial Intermediation	secJ
Securities, commodity contracts, and investments	523	Financial Intermediation	secJ
Insurance carriers and related activities	524	Financial Intermediation	secJ
Funds, trusts, and other financial vehicles	525	Financial Intermediation	secJ
Housing	HS	Real Estate Activities	sec70
Other real estate	ORE	Real Estate Activities	sec70
Rental and leasing services and lessors of intangible assets	532RL	Renting of M&Eq and Other Business Activities	sec71t74
Legal services	5411	Renting of M&Eq and Other Business Activities	sec71t74
Computer systems design and related services	5415	Renting of M&Eq and Other Business Activities	sec71t74
Miscellaneous professional, scientific, and technical services	5412OP	Renting of M&Eq and Other Business Activities	sec71t74
Management of companies and enterprises	55	Renting of M&Eq and Other Business Activities	sec71t74
Administrative and support services	561	Public Admin and Defense; Compulsory Social Security	secL
Waste management and remediation services	562	Other Community, Social and Personal Services	secO

Educational services	61	Education	secM
Ambulatory health care services	621	Health and Social Work	secN
Hospitals	622	Health and Social Work	secN
Nursing and residential care facilities	623	Health and Social Work	secN
Social assistance	624	Private Households with Employed Persons	secP
Performing arts, spectator sports, museums, and related activities	711AS	Other Community, Social and Personal Services	secO
Amusements, gambling, and recreation industries	713	Other Community, Social and Personal Services	secO
Accommodation	721	Hotels and Restaurants	secH
Food services and drinking places	722	Hotels and Restaurants	secH
Other services, except government	81	Other Community, Social and Personal Services	secO
Federal general government (defense)	GFGD	Public Admin and Defense; Compulsory Social Security	secL
Federal general government (nondefense)	GFGN	Public Admin and Defense; Compulsory Social Security	secL
Federal government enterprises	GFE	Public Admin and Defense; Compulsory Social Security	secL
State and local general government	GSLG	Public Admin and Defense; Compulsory Social Security	secL
State and local government enterprises	GSLE	Public Admin and Defense; Compulsory Social Security	secL

Equation A.1: Calculation of the influence of the emission intensity

$$\begin{aligned}
w^c\boldsymbol{\Delta c} = \frac{1}{5040}[&(720 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t})+\\
&(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+
\end{aligned}$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(36 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(48 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+$$

$$(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+$$

$$(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+$$

$$(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+$$

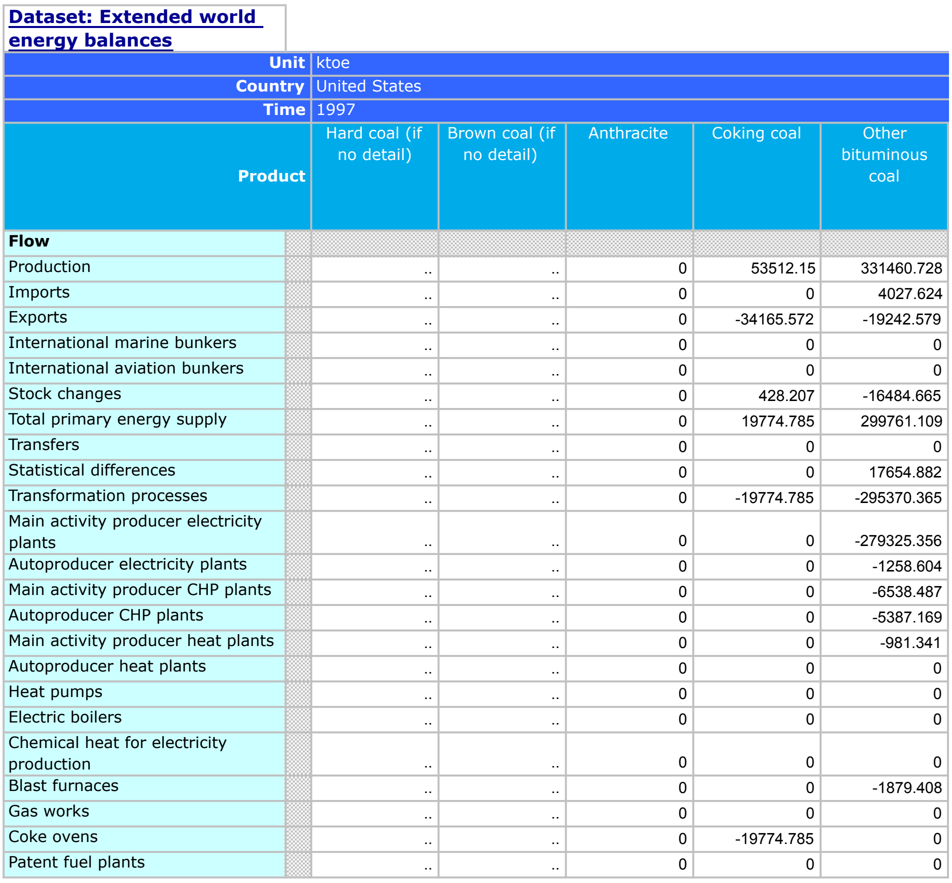
$$
\begin{aligned}
&(120 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_{t-1}} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+\\
&(720 \cdot \boldsymbol{\Delta c} \cdot \boldsymbol{F_t} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)]
\end{aligned}
$$

Equation A.2: Calculation of the influence of the fuel mix

$$
\begin{aligned}
w^f \boldsymbol{\Delta f} = \frac{1}{720}[&(720 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+\\
&(12 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+
\end{aligned}
$$

$$
\begin{aligned}
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_{t-1})+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t-1)} \cdot p_t)+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t-1)}} \cdot y_{v(t)} \cdot p_t)+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_{t-1}} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+\\
&(24 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_{t-1}} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)+\\
&(120 \cdot \boldsymbol{\Delta f} \cdot \boldsymbol{\hat{E}_t} \cdot \boldsymbol{L_t} \cdot \boldsymbol{y_{s(t)}} \cdot y_{v(t)} \cdot p_t)]
\end{aligned}
$$

Figure A.1: Excerpt from the data file *extended world energy balances*



Dataset: Extended world energy balances

Unit	ktoe				
Country	United States				
Time	1997				
Product	Hard coal (if no detail)	Brown coal (if no detail)	Anthracite	Coking coal	Other bituminous coal
Flow					
Production	..	..	0	53512.15	331460.728
Imports	..	..	0	0	4027.624
Exports	..	..	0	-34165.572	-19242.579
International marine bunkers	..	..	0	0	0
International aviation bunkers	..	..	0	0	0
Stock changes	..	..	0	428.207	-16484.665
Total primary energy supply	..	..	0	19774.785	299761.109
Transfers	..	..	0	0	0
Statistical differences	..	..	0	0	17654.882
Transformation processes	..	..	0	-19774.785	-295370.365
Main activity producer electricity plants	..	..	0	0	-279325.356
Autoproducer electricity plants	..	..	0	0	-1258.604
Main activity producer CHP plants	..	..	0	0	-6538.487
Autoproducer CHP plants	..	..	0	0	-5387.169
Main activity producer heat plants	..	..	0	0	-981.341
Autoproducer heat plants	..	..	0	0	0
Heat pumps	..	..	0	0	0
Electric boilers	..	..	0	0	0
Chemical heat for electricity production	..	..	0	0	0
Blast furnaces	..	..	0	0	-1879.408
Gas works	..	..	0	0	0
Coke ovens	..	..	0	-19774.785	0
Patent fuel plants	..	..	0	0	0

R Code A.1: Extended structural decomposition

```
# Equation: CO2 = ES * EM * E_hat * L * y_s * y_v * p + HH_dir

# Calculate w_ES

d_ES <- ES_t - ES_t_1

w_ES <- 1/5040 * (
  (720*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)

  + (120*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (120*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (120*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)

  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)

  + (36*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (36*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (36*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (36*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (36*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (36*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (36*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (36*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
  + (36*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
  + (36*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
  + (36*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (36*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (36*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (36*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
  + (36*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
  + (36*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
  + (36*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
  + (36*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
  + (36*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
  + (36*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
```

```
  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
  + (48*d_ES%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
  + (48*d_ES%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t)

  + (120*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
  + (120*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
  + (120*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
  + (120*d_ES%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
  + (120*d_ES%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t)
  + (120*d_ES%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t)

  + (720*d_ES%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t))

# Calculate w_EM

d_EM <- EM_t - EM_t_1

w_EM <- 1/5040 * (
  (720*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)

  + (120*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (120*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)

  + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)

  + (36*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
```

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    + (36*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
    + (36*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
    + (36*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
    + (36*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
    + (36*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
    + (36*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
    + (36*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
    + (36*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
    + (36*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
    + (36*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
    + (36*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
    + (36*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
    + (36*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
    + (36*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
    + (36*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
    + (36*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
    + (36*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
    + (36*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
    + (36*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)

    + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
    + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
    + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
    + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
    + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
    + (48*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
    + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
    + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
    + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
    + (48*ES_t%*%d_EM%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
    + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
    + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
    + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
    + (48*ES_t_1%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
    + (48*ES_t_1%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t)

    + (120*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
    + (120*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
    + (120*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
    + (120*ES_t%*%d_EM%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
    + (120*ES_t%*%d_EM%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%p_t)
    + (120*ES_t_1%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t)

    + (720*ES_t%*%d_EM%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%p_t))

# Calculate w_E_hat

d_E_hat <- E_hat_t - E_hat_t_1

w_E_hat <- 1/5040 * (
  (720*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)

    + (120*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
    + (120*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
    + (120*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
    + (120*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
```

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+ (120*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (120*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)

+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)

+ (36*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
+ (36*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (36*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (36*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (36*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (36*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (36*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (36*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
+ (36*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
+ (36*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
+ (36*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (36*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (36*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (36*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
+ (36*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
+ (36*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
+ (36*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
+ (36*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
+ (36*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
+ (36*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)

+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t_1)
+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t_1)
+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t_1%*%p_t)
+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t_1)
+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t_1%*%p_t)
+ (48*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t_1%*%y_v_t%*%p_t)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
+ (48*ES_t%*%EM_t_1%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
+ (48*ES_t_1%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t)
```

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  + (120*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t_1)
  + (120*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t_1%*%p_t)
  + (120*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t_1%*%y_v_t%*%p_t)
  + (120*ES_t%*%EM_t%*%d_E_hat%*%L_t_1%*%y_s_t%*%y_v_t%*%p_t)
  + (120*ES_t%*%EM_t_1%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t)
  + (120*ES_t_1%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t)

  + (720*ES_t%*%EM_t%*%d_E_hat%*%L_t%*%y_s_t%*%y_v_t%*%p_t))

# Calculate w_L

d_L <- L_t - L_t_1

w_L <- 1/5040 * (
  (720*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)

  + (120*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)

  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)

  + (36*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t_1)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
```

```
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t)

  + (48*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t_1%*%p_t)
  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t)

  + (120*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t_1)
  + (120*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t_1%*%p_t)
  + (120*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t_1%*%y_v_t%*%p_t)
  + (120*ES_t%*%EM_t%*%E_hat_t_1%*%d_L%*%y_s_t%*%y_v_t%*%p_t)
  + (120*ES_t%*%EM_t_1%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t)
  + (120*ES_t_1%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t)

  + (720*ES_t%*%EM_t%*%E_hat_t%*%d_L%*%y_s_t%*%y_v_t%*%p_t))

# Calculate w_y_s

d_y_s <- y_s_t - y_s_t_1

w_y_s <- 1/5040 * (
  (720*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)

  + (120*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)

  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
```

```
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)

  + (36*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (36*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t)

  + (48*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t_1)
  + (48*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t)

  + (120*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t_1)
  + (120*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t_1%*%p_t)
  + (120*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%d_y_s%*%y_v_t%*%p_t)
  + (120*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%d_y_s%*%y_v_t%*%p_t)
  + (120*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t)
  + (120*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t)

  + (720*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%d_y_s%*%y_v_t%*%p_t))

# Calculate w_y_v

d_y_v <- y_v_t - y_v_t_1

w_y_v <- 1/5040 * (
  (720*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
```

```
+ (120*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (120*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (120*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)

+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)

+ (36*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
+ (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
+ (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
+ (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t)

+ (48*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
+ (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t)
+ (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
+ (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
```

```
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t)

  + (120*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t_1)
  + (120*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%d_y_v%*%p_t)
  + (120*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%d_y_v%*%p_t)
  + (120*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%d_y_v%*%p_t)
  + (120*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t)
  + (120*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t)

  + (720*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%d_y_v%*%p_t))

# Calculate w_p

d_p <- p_t - p_t_1

w_p <- 1/5040 * (
  (720*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)

  + (120*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (120*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (120*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)

  + (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
  + (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
  + (48*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)

  + (36*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (36*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (36*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
  + (36*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
  + (36*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
```

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+ (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
+ (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
+ (36*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
+ (36*ES_t_1%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%d_p)

+ (48*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t_1%*%d_p)
+ (48*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t_1%*%d_p)
+ (48*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t_1%*%y_v_t%*%d_p)
+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
+ (48*ES_t%*%EM_t%*%E_hat_t_1%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
+ (48*ES_t%*%EM_t_1%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
+ (48*ES_t%*%EM_t_1%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%d_p)
+ (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
+ (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
+ (48*ES_t_1%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
+ (48*ES_t_1%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%d_p)
+ (48*ES_t_1%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%d_p)

+ (120*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t_1%*%d_p)
+ (120*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t_1%*%y_v_t%*%d_p)
+ (120*ES_t%*%EM_t%*%E_hat_t%*%L_t_1%*%y_s_t%*%y_v_t%*%d_p)
+ (120*ES_t%*%EM_t%*%E_hat_t_1%*%L_t%*%y_s_t%*%y_v_t%*%d_p)
+ (120*ES_t%*%EM_t_1%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%d_p)
+ (120*ES_t_1%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%d_p)

+ (720*ES_t%*%EM_t%*%E_hat_t%*%L_t%*%y_s_t%*%y_v_t%*%d_p))
```

Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Schneider Marius

Matriculation number: 07719552

Programme: Master of Science in Climate Sciences

Bachelor ☐ Master ☒ Dissertation ☐

Thesis title: Influences of various drivers of the CO2 emissions in the US with a special focus on the fuel mix

Thesis supervisor: Prof. Dr. Gunter Stephan

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise. I grant inspection of my thesis.

Zurich, 6.07.16

Place, date

M. Schneider

Signature