Distributional impacts of carbon taxing in the Netherlands: a 'flexible' input-output analysis

'Is the price really right?'

MSc Industrial Ecology

Laura Alexandra van Geene

TU Delft

Universiteit Leiden
The Netherlands

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Laura Alexandra van Geene

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Thesis committee:	Dr. Ranran Wang	Leiden University, first supervisor
	Dr. Enno Schröder	TU Delft, second supervisor
	Rosalie Hagenaars, MSc.	Leiden University, daily support

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Enquiries related to this thesis can be directed to lauravangeene@hotmail.nl.

Preface

Writing this preface symbolises both the end of my master thesis research as well as the end of my time as an Industrial Ecology student. After starting my journey into the environmental sciences at the University of Utrecht in 2018, I made the decision to switch universities and continue my education with the MSc Industrial Ecology in Leiden and Delft. A decision that seemed scary in the first few months, but these doubts were quick to disappear once I found my place in the IE-community. During the master, I took a great amount of interesting courses and learned skills that I would have never imagined learning (I can now code!) while making small contributions to a better world.

Yet, I have to admit that it were not only the courses that made my time at IE a huge success. In my first year at IE, I joined GreenTU's Research Committee and I spent the year learning and writing about TU Delft's sustainability plans. The following year, I joined Shift's Education Committee and organized a great number of interesting lectures and workshops for IE students. I combined both these skills in my final year and a half at Industrial Ecology when I joined GreenTPM as their Chair. Here, I got the opportunity to work on the sustainability of the TPM Faculty and to organize sustainability-related activities with an amazing team.

Being the Chair of a student team at the same time as writing your master thesis can be a bit intense, so a lot of thanks goes out to the people that have supported me during this research. First of all, I would like to thank my family (including our dog, Sjors) for their endless love and encouragement. Also, lots of love for my three roommates, Sophie, Eva, and Melle, for always letting me talk about about my thesis and helping me relax after long days of work. I would also like to thank all my friends who have supported and helped me along the way, including Lara, Luca, Kim, Daniek, Marissa, GreenTPM '23-'24 (Jula, Loes, and Adhvait) and in particular, Quan for our tea-and-cake meetings. A special thanks also goes out to my friends at EPA in The Hague for adopting this IE-student into the EPA community and for providing me with even more support (and many pots of tea).

A final thanks to my committee of supervisors. First of all, dr. Ranran Wang of CML (Universiteit Leiden) for her enthusiasm, supervision, and great input for my thesis. I would also like to thank dr. Enno Schröder of TPM for his insightful feedback and some much needed (and much appreciated) help with my economics. Endless thanks to Rosalie Hagenaars for always making time for me in her busy schedule to answer my many questions. I could not have completed this thesis research without my supervisors, but especially not without Rosalie.

Laura van Geene
Delft, April 2024

Summary

This thesis aimed to explore how the Leontief price model could be best used in carbon taxing research through a case study about carbon taxing impacts on the purchasing power of the elderly in the Netherlands. Previous studies highlighted the importance of preventing distributional impacts on the elderly to gain public support for carbon taxing. Previous research also suggested that the Leontief Price Model has the tendency to overestimate price impacts due to its inability to capture input substitutions in response to taxes. This thesis used two different input-output models: a conventional Leontief Price Model and a 'flexible' cost-push model developed by the Dutch National Bank that can incorporate additional price impacts of input-substitution. The Consumer Price Index was calculated to estimate the tax impacts on the purchasing power of elderly in the Netherlands.

It was discovered that the overall effects on the purchasing power of Dutch elderly remained marginal in the case of both an economy-wide Dutch carbon tax and a tax on the Dutch electricity sector. The inflation rates for the elderly ranged from 0.9% to 4.5% for the Dutch tax and 0.4% and 2% in the case of the electricity tax.

Yet, compared to other age groups in the Netherlands, carbon taxes could still pose a risk to the purchasing power of the elderly, particularly to their ability to afford essential expenses such as electricity. All scenarios resulted in striking increases in electricity prices. The most ambitious scenarios, a Dutch carbon tax of €250 per tCO_2, could result in a 25% increase in electricity prices. Given the limited disposable income and already weak purchasing power of Dutch elderly, carbon taxing could, thus, potentially worsen energy poverty among this group. Due to difference in consumption patterns and total income between age groups of main earners, elderly above 75 are more vulnerable to the tax compared to other age groups, including the elderly between 65 and 75.

In addition, the case study highlighted the limitations of domestic forms of carbon taxing for a trade-oriented economy such as the Netherlands, since the displacement of emissions is disregarded here. Furthermore, this thesis confirms the conventional Leontief price model's tendency to overestimate price impacts, as the flexible cost-push showed systematically lower outcomes. Although the flexible cost-push model improves on the conventional model through the inclusion of input-substitution, the results also showed that the flexible model is still somewhat limited in its ability to capture input-substitution. This thesis, therefore, also identified several opportunities for refining the flexible cost-push model to enhance its value in future research.

This thesis is an important contribution to the limited recent research on flexible input-output models by suggesting improvements to the flexible input-output model developed by the Dutch National Bank, which to the best of our knowledge had not been empirically tested since its development. This thesis also builds on existing literature by showing that the consumption pattern is not only vital in determining vulnerability to carbon taxing between income groups and countries, but also between different age groups of main earners. All in all, the findings once again emphasize the importance of explicitly considering both environmental effectiveness as well as social sustainability in carbon taxing design to not further exacerbate existing inequalities.

Keywords: Carbon Taxing, Environmentally-Extended Input-Output Analysis, Leontief Price Model, Input-Substitution, Distributional Impacts, Energy Poverty

Contents

Nomenclature

Table of Abbreviations

Abbreviation	Definition
CBS	Central Statistical Office of the Netherlands (Centraal Bureau voor de Statistiek)
CGE	Computable general equilibrium
CPB	Netherlands Bureau for Economic Policy Analysis (Centraal Planbureau)
CPI	Consumer Price Index
DNB	Dutch National Bank (De Nederlandse Bank)
EEIOA	Environmentally extended input–output analysis
ETS	Emission Trading System
FIGARO	Full International and Global Accounts for Research in input-Output analysis
IO	Input-Output
kt	Thousand tonnes
LPM	Leontief Price Model
MRIO	Multi-regional input-output analysis
SPA	Structural Path Analysis
tCO_2	tonne CO_2

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Introduction

Limiting global warming to 1.5 °C will become increasingly difficult without more ambitious climate policies (Bednar et al., 2021; Carattini et al., 2018). Carbon pricing has been proposed as an effective instrument to combat greenhouse gas emissions. In carbon pricing schemes, a price is placed on the costs of the environmental damage caused by emissions (Sumner et al., 2011). In 2023, approximately 23% of the global emissions were covered by carbon pricing schemes (World Bank, 2023). The majority of these emissions were covered by Emission Trading Schemes (ETS) (World Bank, 2023), which are market-based systems in which a limited number of emissions can be 'traded' on a carbon market (European Commission, n.d.-b). However, these complex systems are most suitable to cover large emissions from heavy industries, but cannot be scaled up to include all emissions (Carattini et al., 2018). Carbon taxes are commonly perceived as a low-invasive policy option (Best et al., 2020). The taxes are relatively simple to implement and do not burden government budgets (Carattini et al., 2018), making them a suitable alternative for the more commonly used ETS (Baranzini et al., 2017; Carattini et al., 2018).

Questions have been raised about the fairness of carbon taxes (Baranzini et al., 2017; Fremstad & Paul, 2019; Klenert & Mattauch, 2016). Fair climate policies should have the biggest repercussions for the largest contributors to climate change (Dreyer & Walker, 2013). However, carbon taxes in their current forms often become the biggest burden for those with a lower-income, as these people pay a large share of their income to the carbon tax (Baranzini et al., 2017; Beck et al., 2015; Klenert & Mattauch, 2016). Potential disproportionate impacts on low-income households also decrease public approval of carbon taxing, particularly if these impacts are mostly felt by the elderly (Maestre-Andrés et al., 2019). In the Netherlands, the purchasing power of the elderly has already been stagnating due to rising costs of living (Hasekamp, 2023) without the potential added pressure of carbon taxing. At the same time, distributive fairness is becoming more important in Dutch climate policy (Hulscher et al., 2023).

Sustainable carbon taxes, therefore, not only need to be effective but must also not contribute to further income inequality. To fully understand this dynamic, proper economic and social assessment is necessary. The field of Industrial Ecology studies ways in which society's material, energy and economic metabolism can be changed to decrease environmental damage while generating technological, social, and economic progress (Graedel, 1996). Environmentally-Extended Input-Output Analysis (EEIOA) is a key tool for Industrial Ecologists, as it allows for analysis of environmental effects and economic linkages hidden behind the production and trade of goods and services (Daniels et al., 2011). Because of this, it is an important tool to research potential economic benefits and disadvantages of making changes in society's metabolism (Duchin & Lange, 1995), such as the implementation of carbon taxes.

Previous research has already used EEIOA to research potential impacts of carbon taxing. For example, Nabernegg et al. (2019) combined EEIOA with other modelling approaches to explore the effects of national policies, such as carbon taxes, on the international supply chain and global emission reductions. Within EEIOA, the Leontief price model has been applied to explore the outcomes of tax introduction for the final consumer (Miller & Blair, 2009). However, the Leontief price model has been used in only a small number of studies on carbon taxing. These studies also demonstrated the potential for unequal impacts on those with a lower income, such as Gemechu et al. (2014) for Spain and Mardones and Mena (2020) for Chile. As far as could be found, no studies have used to the Leontief price model to research carbon taxing impacts in the Netherlands nor impacts on the (Dutch) elderly.

Due to their high sectoral detail compared to other macro-economic models (de Koning, 2018), an input-output model, such as the Leontief price model, can contribute to a more detailed understanding about the specific impacts of carbon taxing. Combining the need to put climate justice at the center of Dutch climate policy and the stagnating purchasing power of the Dutch elderly, the Leontief price model can also potentially reveal new insights about this dynamic. Yet, the Leontief price model is not without its limitations (Llop, 2008; Mardones & Mena, 2020) that influence its capacity to properly estimate price impacts (Koks et al., 2016). To combat these limitations, several improvements to the model have been proposed in recent years (e.g., Bun, 2018; Choi et al., 2016; Vats et al., 2021).

This thesis, therefore, aims to answer the question: *How can the Leontief price model be applied in multi-regional EEIOA to assess the impacts of carbon taxing on the purchasing power of the elderly in the Netherlands?*

This study used both a conventional Leontief price model as well as an improved version of the model, a 'flexible' cost-push model that can capture additional price impacts of substitution of expensive inputs after the tax. Even though the overall effects on the purchasing power of the elderly were limited in the case of an economy-wide tax or an energy tax in the Netherlands, carbon taxing could still become a danger to the elderly's purchasing power through large price increases for essential expenditures like electricity. Given both the low disposable income of Dutch elderly and their already limited purchasing power, carbon taxing could, therefore, potentially contribute to energy poverty under elderly in the Netherlands. A comparison between the two models also showed that the conventional Leontief price model has the potential to exaggerate price impacts, since it excludes possibilities of substituting expensive inputs following the carbon tax. However, due to its underlying assumptions, the flexible cost-push model proved to be limited to some extent in its ability to simulate the effects of input-substitution. Hence, several improvements for the model were also identified.

The rest of this thesis is structured as follows: Section 2 of this thesis reviews previous research and further outlines the research gap. Section 3 explains the methods used in this thesis, after which the results are discussed in Section 4. The last two sections cover the discussion and conclusion of this research, respectively. The Conclusion can be found on page 40.

2

Literature Review

2.1. Carbon taxing

Carbon taxes internalize (part of) the costs of environmental damage by placing a price on the emissions that induce environmental pressures (Sumner et al., 2011). The precise effect of a carbon tax depends on its tax base and tax rate. The tax base is the item that is taxed, which can be a specific product, emission source, or a part of the supply chain. The tax rate indicates the emission intensity and the price of carbon, for example €25 per tonne CO_2 (Sumner et al., 2011). There are several different forms of carbon taxing, which are further explained in Appendix A.

2.1.1. Distributive impacts of carbon taxing

Socially just carbon taxes would target those that have the biggest responsibility for carbon emissions the most (Zheng et al., 2023). Those with little means use less carbon-intensive products and their lifestyles are associated with significantly lower GHG emissions (Gore, 2015). Chancel (2022) estimated that the global top 10% incomes emitted almost half of the global GHG emissions in 2019, whereas the bottom 50% incomes emitted only 12%. The wealthy, therefore, also hold more responsibility for the emissions that caused the global climate crisis (Zheng et al., 2023) and should feel the impacts of carbon taxes the most. This approach would make carbon taxing progressive, meaning that the tax would take a larger fraction of income from those with a high-income (and larger responsibility for climate change) (Klenert & Mattauch, 2016). However, multiple studies warn that carbon taxes in their current forms are often a particularly large burden on the spendable income of low-income households (Baranzini et al., 2017; Beck et al., 2015; Povitkina et al., 2021), making the taxes regressive. This regressive effect is caused by the fact that households with a lower-income often spend larger shares of their income on products from sectors that are especially affected by the carbon tax than households with more means (Mardones & Mena, 2020).

These potentially unjust outcomes also undermine public support of carbon taxes. Policies that have direct monetary impacts generally have lower public support (Drews & van den Bergh, 2016). This is one of the main reasons why existing carbon taxes often only implement a low carbon price (Maestre-Andrés et al., 2019). Moreover, when these policies are seen as unfair, their potential for public support falls even more (Drews & van den Bergh, 2016). Lamb et al. (2020) even argue that socially harmful policies indirectly support the fossil fuel industry, since these industries will use the failing policy as an example to support their agenda. Distributive fairness is, thus, extremely important in the design of carbon taxing policies (Drews & van den Bergh, 2016; Lamb et al., 2020).

Maestre-Andrés et al. (2019) found that potential impacts on the elderly are one of the key concerns when it comes to the distributive impacts of carbon taxes. Elderly people are especially vulnerable to carbon taxing, because they spend a relatively large portion of their incomes on heating costs for their homes (Maestre-Andrés et al., 2019). This can also be seen in the Netherlands, where elderly both have a relatively small disposable income and already spend a relatively large fraction of that income. In 2015, elderly between 65 and 75 had an average income of €35,500, of which they spent €32,000. Approximately 35 to 40% of their expenditure (around €11,000) is used for covering costs of utilities and household, which is about 10 to 15% more than other age groups (CBS, 2017).

Throughout Europe, the costs of living have been rapidly rising and have become a major political concern (European Parliament, 2023). In the Netherlands, 'bestaanszekerheid' (livelihood security) became one of the most important topics in the 2023 elections (Koole & Hankel, 2023). The CPB (Netherlands Bureau for Economic Policy Analysis) speaks of a structural problem with the cost of living in the Netherlands, as these costs keep rising but the purchasing power of many does not. While the purchasing power in the Netherlands had been rising up until 2022, the purchasing power of the elderly had already been stagnating for several year (Hasekamp, 2023). Given this stagnating purchasing power and the existing burden of the costs of utilities on the spendable income of elderly in the Netherlands, this group could be particularly vulnerable to the impacts of carbon taxes.

2.2. Carbon taxing & input-output analysis

Carbon taxing has been researched from multiple angles using input-output models in recent years. For example, Feindt et al. (2021) compare the burden of European carbon taxing between and within different EU member states. Dorband et al. (2022) researched ways to potentially recycle revenue of carbon taxing in Nigeria to public infrastructure to stimulate inclusive development. Both studies emphasized the importance of compensating the households (or countries) with the lowest incomes. Another approach was taken by Ward et al. (2019) who researched how of a global carbon price could influence competitiveness. They found that a global carbon price would improve the economic position of the more developed and industrialized economies, but would likely cause adverse effects for the upcoming Asian and Eastern European economies (Ward et al., 2019).

Lastly, Steckel et al. (2021) used multi-regional input-output (MRIO) to determine how carbon taxing could be effective and equitable in developing nations in Asia. They combined input-output analysis with household survey data about consumption to determine the final effect on expenditure of consumers. Conversely to other studies, they found that for their selected countries the differences in impact of the tax were bigger within income groups than between income groups (Steckel et al., 2021). For example, the lower end of the highest income group might consists of "the rural rich", while the "urban rich" dominate the upper end of this group. The living standards and consumption patterns of these two groups might still be significantly different, making them each in a different way vulnerable to carbon taxing (Steckel et al., 2021).

2.2.1. Previous research using the Leontief price model

Within input-output analysis, the Leontief price model (LPM) has been often used to explore the effects of taxes imposed by governments (Miller & Blair, 2009). The LPM describes the relationship between the prices of primary inputs for products and the value-added of the product. The model can investigate both direct and indirect effects of price changes on an economy (Dietzenbacher, 1997; Leontief, 1949). It can be used in a wide-range of contexts, such as price changes in industries following rising costs (Kwak et al., 2005) or the impacts on prices in an economy following an earthquake (Yagi et al., 2020). The LPM model has also been applied to research potential impacts of carbon taxing, albeit less than in other contexts. Gemechu et al. (2014) found that carbon taxation in Spain endangers economic sustainability goals if the revenues are not used to compensate low-income households. Mardones and Mena (2020) took this a step further and investigated the environmental and economic consequences of internalizing social costs of carbon in the existing Chilean carbon tax. Both studies emphasized the risk of disproportionate burden for low-income households.

Limitations of and alternatives for the Leontief price model

Llop (2008), Gemechu et al. (2014), and Mardones and Mena (2020) point to one important limitation of the Leontief price model: the assumption of a complete pass through of the costs of the tax and the lack of input-substitution. This limitation is caused by the fixed input coefficients upon which IO models are built. This means "*that each additional unit of production in sector* j *requires the same fixed amount of input from sector* i" (Dietzenbacher, 1997, p. 629). In the LPM, this leads to the assumption that firms directly transfer the costs of environmental taxes to their prices (Mardones & Mena, 2020). This could be correct in the short-term. In the long term, however, the increased costs would result in input substitutions and changes to supply chains, meaning that the more expensive inputs are replaced by cheaper ones or by less emission-intensive inputs. These input substitutions can happen in the supply chain, but also at final consumption (Mardones & Mena, 2020). Due to this lack of input-substitution, it is argued that input-output (IO) models overestimate economic impacts (Koks et al., 2016).

Over the years, several authors have argued for the importance of considering these potential substitution effects by including elasticities in the price model (Kratena, 2005; Truchon, 1984). For example, Yagi et al. (2020) introduced a price elasticity of demand to model a supply constraint following an earthquake in Japan. In the context of carbon taxing research, only one study and one technical report were found in which an elasticity was incorporated in the price model. Choi et al. (2016) used an elasticity of demand in combination with both physical and monetary IO tables to explore the impacts of a fuel tax and bio-fuel subsidy on the US economy. Using the price elasticity of demand, they quantified the potential changes to final demand of (bio-)fuel (Choi et al., 2016). More specifically, only one model could be found during this research that used an 'improved' version of the Leontief price model in the context of a carbon tax. In their research about about carbon taxing impacts on Dutch industries, De Nederlandse Bank (Dutch National

Bank (DNB)) introduced an elasticity of substitution to the LPM to calculate potential additional price-effects of input-substitution (Bun, 2018; Hebbink et al., 2018). Another approach worth mentioning here is that of Vats et al. (2021), who employ a flexible input-output model similar to that of Bun (2018) and Hebbink et al. (2018) but with a focus on the impacts of climate policies on the water-energy-food nexus.

An important barrier for the inclusion of elasticities in the LPM is the lack of quantified elasticities, since each elasticity needs to be exogenously specified for all products/sectors upon which it applies (Gemechu et al., 2014; Mardones & Mena, 2020). These precise quantifications are not always available (Gemechu et al., 2014). To deal with this, Truchon (1984) recommends to only focus on certain key sectors instead of all possible sectors, similar to the research by Choi et al. (2016) that only focused fuel-related sectors in their study.

As an alternative to including substitution in IO models, there is a large body of research using computable general equilibrium (CGE) models for carbon taxing research (e.g., Lin & Jia, 2018). CGE models are dynamic, macro-economic models that assume economic equilibrium (Donati et al., 2021). CGE models include input-substitution by default and because of this, they provide a somewhat more nuanced estimate of potential price effects (Koks et al., 2016). IO models, on the other hand, usually have more sectoral detail than CGE models, as the latter type of model has a more complex, black box, and dynamic structure and provide more aggregated results because of this (Koks et al., 2016). Both CGE and IO models are preferable for different kinds of analysis. For example, the inclusion of substitutions in CGE models makes them preferable for short-term analysis, such as short-term predictions (de Koning, 2018). In IO models, on the other hand, parameters are more easily identifiable and adaptable, and outcomes more detailed, making them preferable for long-term scenario analysis (de Koning, 2018).

2.3. Research gap & main research question

To synthesize the above, there is a need to develop carbon taxing schemes that are effective and fair. The perceived fairness for lower-income households is closely linked with public support of carbon taxes, especially when it comes to disproportionate impacts on the elderly (Maestre-Andrés et al., 2019). The purchasing power of the elderly is already being threatened in the Netherlands (Hasekamp, 2023) without the additional potential burden of carbon taxes. Design of carbon taxing for the Netherlands should, therefore, explicitly consider the distributive impacts for the elderly, especially in the face of growing demands for fair climate policy in the Netherlands (Hulscher et al., 2023).

IO models can be used to shed light on these purchasing power impacts by specifying the impacts per industry or product as well as under different scenarios. While the Leontief price model is a well-established method for researching price impacts following taxes (Miller & Blair, 2009), the price model is not widely used for carbon taxing research specifically. Moreover, the Leontief price model is also not without its limitations and several attempts have been made to account for these limitations (e.g., Bun, 2018; Hebbink et al., 2018 or Vats et al., 2021). Compared to the approach by Vats et al. (2021), the model by Bun (2018) and Hebbink et al. (2018) was specifically developed for carbon taxing research in the Netherlands, making it very suitable for a case study about the Netherlands. Due to its inclusion of input-substitution, the model could show additional insights about purchasing power impacts on the elderly following a carbon tax. Yet, to the best of our knowledge, the model has not been empirically tested since its development.

The aim of this thesis is two-fold: research the potential distributional impacts of carbon taxing on the purchasing power of the Dutch elderly, while also comparing the benefits of using the improved version of the Leontief price model by Bun (2018) and Hebbink et al. (2018) with the conventional approach. This thesis, therefore, aims to answer the research question: *How can the Leontief price model be applied in multi-regional EEIOA to assess the impacts of carbon taxing on the purchasing power of the elderly in the Netherlands?*

3
Methods

To answer the research question, two consecutive analyses[1] were done. First, an environmentally-extended input-output analysis was done to determine the economy-wide price impacts of carbon taxing. Second, the outcomes were combined with Dutch household consumption data to calculate the Consumer Price Index to discover the impacts on the purchasing power of the elderly in the Netherlands.

3.1. Environmentally-Extended Input-Output Analysis

The main input-output (IO) model used in this thesis is the Leontief price model. As discussed in Section 2.2.1, there are several limitations to the Leontief price model, with the lack of input-substitution being one of its most well-known restrictions. Input-substitution is especially relevant to consider in the context of carbon taxing. After tax implementation, industries are likely to replace more expensive fossil-fuel inputs with cheaper ones, which could mitigate the price effects of the tax (Bun, 2018).

Two input-output analyses were done in this research. First, the conventional Leontief price model was used to calculate the direct sectoral price changes under different carbon tax scenarios. These price changes were then used to calculate the sectoral price changes in a situation with input-substitution using a 'flexible cost-push model'. These two price changes were then compared. The following two sections explain the Leontief price model and the flexible cost-push model used in this research.

3.1.1. The Leontief price model

The Leontief price model is based on one central equitation as shown in Equation 3.1. The introduction of a tax is commonly modelled by changing the value-added vector. The Leontief price model is also known as a cost-push model (Dietzenbacher, 1997; Miller & Blair, 2009). The logic of the model is that changes in prices of primary inputs (e.g. due to rising costs) "push" the output prices of sectors to change, which then ripple through the supply chain via trade (Dietzenbacher, 1997; Miller & Blair, 2009).

$$\boldsymbol{p}_{\text{tax}} = (\mathsf{I} - \mathsf{A}')^{-1} * \boldsymbol{v'}_{\text{tax}} \tag{3.1}$$

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[1] Please consult Appendix B.1 for additional material. All visualisations in the thesis were made following recommendations by Tol (2021) for colourblindness.

where:

$\boldsymbol{p}_{tax}$ are the price indexes for the sectors in the economy following the carbon tax;

$\boldsymbol{I}$ is the identity matrix;

$\boldsymbol{A'}$ is the transposed technical coefficient matrix, where element a_{ji} shows the direct requirements from sector *j* per million euro of output from sector *i* (million €/million €);

$(\boldsymbol{I}\text{-}\boldsymbol{A'})^{-1}$ is the transposed Leontief inverse, $\boldsymbol{L'}$ (million €/million €);

$\boldsymbol{v'}_{tax}$ is the transposed value-added vector adapted to include the carbon tax (million €/million €).

Depending on the specific taxing scenario (see Section 3.4), the carbon tax was added to the value-added coefficients of different sectors. The value of the tax was based on a common carbon price (€ per tonne CO_2) and the emission intensity of each sector (in thousand tonne CO_2). In this way, the value of the carbon tax grows proportionally to the CO_2 emissions of each sector. Using Equations 3.2 and 3.3, the tax value was calculated and added element-wise to the original value-added vector.

$$\boldsymbol{v}_{\text{tax}} = \boldsymbol{v}_0 + \boldsymbol{t} \tag{3.2}$$

where:

$\boldsymbol{v}_0$ is the value-added vector before taxing obtained from the IO database, where each element represents the value-added of each sector (million €/million €);

$\boldsymbol{t}$ is tax value vector, where each element is the carbon tax that is levied on a sector (million €/million €).

$$\boldsymbol{t} = \phi * \boldsymbol{f}_{\text{CO}_2} \tag{3.3}$$

where:

ϕ is the carbon price (€) per tonne CO_2;

$\boldsymbol{f}_{CO_2}$ is the direct impact vector, where each element represents the CO_2 emissions of a sector in a specific country (thousand tonne CO_2/million €).

3.1.2. The flexible cost-push model

In a flexible input-output model, sometimes also referred to as a variable IO model, changes in input costs affect the industrial production structure (Liew, 1984; Miller & Blair, 2009). The technical coefficients of the A-matrix are not solely dependent on the production recipe of the sectors, but also on potential price changes in those sectors (Liew, 1984; Miller & Blair, 2009). There are also flexible variations of the Leontief price model available, so-called 'flexible cost-push models'. This thesis uses a flexible cost-push model developed by Bun (2018) and Hebbink et al. (2018) for the Dutch National Bank. This model was chosen since it was specifically developed to investigate potential effects of carbon taxing on Dutch industries. The documentation of this model, therefore, included the necessary information and parameters to do a case study about the Netherlands.

In the model by Bun (2018) and Hebbink et al. (2018), input-substitution is incorporated by recalculating the A-matrix after tax implementation. The assumption is that input-substitution will make the technical coefficients of certain sectors decrease, whereas those of other sectors increase as inputs are shifted in the supply chain (Bun, 2018). In the technical appendix of Hebbink et al. (2018), they propose two ways in which input substitution can occur following a carbon tax:

1. **Substitution from energy inputs to capital/labour inputs**
   This is based on the assumption that businesses will tackle the largest sources of emissions first: their energy-use. The model, therefore, assumes that the carbon tax will lead to investments in energy-saving measures. For example, investing in energy-efficient machinery or renovating real-estate to improve insulation (Hebbink et al., 2018). This leads to substitution from energy-inputs to capital/labour, i.e. business spend less on energy due to capital investments in energy-efficiency (Bun, 2018).
2. **Technological progress**
   This version of the model assumes that carbon taxing encourages innovation. This technological progress leads to lower energy inputs (Bun, 2018). While this model is an extension of the conventional Leontief price model, the assumption of technological progress means that there is no real input-substitution in this model, since energy-inputs are lowered, but not substituted.

Since the focus of this thesis is to explore possibilities to incorporate input-substitution in IO models, the 'Technological progress' scenario proposed by Bun (2018) will not be taken into account. Additionally, this scenario assumes that technological progress follows directly after the carbon tax. This is also the case in the energy-capital/labour substitution proposed by Bun (2018) and Hebbink et al. (2018), where investments are said to follow shortly after the tax. Both scenarios proposed by Bun (2018) and Hebbink et al. (2018) are oversimplifications to some degree. However, energy-efficiency measures that industries are assumed to take in the 'Energy-capital/labour substitution' scenario are more easily achieved than innovation of industrial processes in the 'Technological progress' scenario. The latter involves a long-term process in which the technologies first face multiple barriers before they are implemented (Geels et al., 2008).

Incorporating the elasticity of substitution

To quantify the potential for substitution from energy inputs to capital/labour inputs in their flexible cost-push model, Bun (2018) uses an elasticity of substitution. Elasticities show the economic responsiveness between two variables (Greenlaw et al., 2023). Specifically, the elasticity of substitution is used in situations where changing input prices of certain products may result in replacement of those products with another (Debertin, 2012).

The elasticity of substitution estimates the potential with which can be switched between different factors of production (Debertin, 2012; McKenzie, 2020). For example, if an industry only has a few employees available to operate its machinery, it is hard to cut costs on employees to buy additional machinery (i.e., substitute labour with machinery) while also keeping all the machinery operational (McKenzie, 2020). To give an example in the context of energy-capital/labour substitution: if an industry already requires large investments to be operational, this money cannot be so easily moved to invest in energy-efficiency measures while staying operational (Hebbink et al., 2018). Thus, depending on the specific conditions in an industry, these switches of inputs can be made more easily (Debertin, 2012). The potential for substitution is reflected in the value of the elasticity of substitution, which ranges between 0 and infinity. A substitution elasticity near zero indicates very little potential for substitution between the two inputs in question, wheres a large elasticity represents great potential for input substitution in the production process (Debertin, 2012; McKenzie, 2020). For example, an elasticity of substitution of 0.2 for the energy-capital/labour substitution shows that a 1% increase in price in energy results in 0.2% more capital use.

In the case of energy-capital/labour substitution, the new technical coefficients are calculated using Equation 3.4 (Bun, 2018).

$$a_{\mathrm{ji}}^{1} = \frac{a_{\mathrm{ji}}^{0} + v_{\mathrm{j}}}{a_{\mathrm{ji}}^{0} + v_{\mathrm{j}}(1 + \sigma_{\mathrm{j}} \Delta p_{\mathrm{j}}^{\mathrm{tax}})} \tag{3.4}$$

where:

$\mathrm{a_{ji}}^0$ is the old technical coefficient indicating the direct requirements from sector *j* per million euro of output from sector *i* (million €/million €);

$\mathrm{a_{ji}}^1$ is the new technical coefficient indicating the new direct requirements from sector *j* per million euro of output from sector *i* after input-substitution (million €/million €);

$\mathrm{v_j}$ is the capital/labour coefficient for sector *j* (million €/million €). Following Bun (2018), the value-added coefficient of sector *j* is imputed here to represent the capital/labour investments, since investments are also included in the value-added vector;

σ_{j} is the elasticity of substitution from energy to capital/labour for sector *j*;

$\Delta \mathrm{p_j}^{\mathrm{tax}}$ is the relative sectoral price change (%) of sector *j* following the implementation of the carbon tax that is computed using Equation 3.1.

The degree of substitution from energy inputs to capital/labour in sector *j* is indicated by $\sigma_{\mathrm{j}}\Delta p_{\mathrm{tax}}$ in Equation 3.4, which is driven by the potential for substitution following in sector *j* (σ_{j}) and the relative price change ($\Delta p_{\mathrm{j}}^{\mathrm{tax}}$). The larger the relative price change, the larger $\sigma_{\mathrm{j}}\Delta p_{\mathrm{j}}^{\mathrm{tax}}$ becomes and a higher degree of energy-capital/labour substitution is modelled. If an industry is faced with a larger price increase, they are more likely to invest in their energy-efficiency, resulting in more input-substitution.

However, if input-substitution is not possible, the elasticity of substitution will be zero. This means that $1+\sigma_{\mathrm{j}}\Delta p_{\mathrm{j}}^{\mathrm{tax}}$ is equal to 1, making that a_{ji}^{1} does not change. If substitution is impossible for all sectors, the technical coefficients of the A-matrix will not change and the outcomes of the flexible cost-push model would, thus, be equal to those of the conventional Leontief price model. Leontief price models are known to assume elasticities of substitution of zero for all sectors, which excludes possibilities for input-substitution (Miller & Blair, 2009).

The larger the degree of energy-capital/labour substitution, the larger the denominator of Equation 3.4 becomes, meaning that the new technical coefficient, a_{ji}^{1}, also becomes smaller. This is in line with the hypothesis that capital/labour substitution reduces energy inputs, especially since the capital/labour substitution represents investments in energy-efficiency (Bun, 2018; Hebbink et al., 2018).

Recalculating the sectoral price changes

For the final step of this input-output analysis, this research deviates from the methodology proposed by Bun (2018). In their original model, the author compose a ΔA-vector from the adapted technical coefficients to calculate the price effect of substitution. They do not, however, use the technical coefficients to recalculate the Leontief Inverse and, therefore, they do not fully capture the potential effects of the input-substitution on the supply chain. In this research, Equation 3.5 was used to calculate the sectoral price changes following input-substitution. The Leontief Inverse shows the total requirements of an economy per unit of final demand (Miller & Blair, 2009) and by using the adapted A-matrix to calculate the Leontief Inverse, it is aimed to also show the effects of the carbon tax and input-substitution on the total supply chain. Equation 3.5 is similar to Equation 3.1 of the conventional Leontief price model.

$$\boldsymbol{p}_{\text{substitution}} = (\mathsf{I} - \mathsf{A}^{*})^{-1} * \boldsymbol{v'}_{\text{tax}} \tag{3.5}$$

where:

$\mathbf{p}_{\text{substitution}}$ are price indexes for the different sectors following the carbon tax if substitution occurs;

$\mathbf{A}^{*}$ is the new A-matrix composed of the recalculated technical coefficients (million €/ million €);

$(\mathbf{I} - \mathbf{A}^{*})^{-1}$ is the new Leontief Inverse, L^{*} (million €/ million €);

$\mathbf{v'}_{\text{tax}}$ is the transposed value-added vector adapted to include the carbon tax (million €/million €).

3.2. The Consumer Price Index

To evaluate the impacts on the purchasing power of the final consumer, the change in the Consumer Price Index was calculated. The Consumer Price Index measures change in the price of goods and services bought/used by households. The CPI is a well-known statistic to measure inflation and is usually calculated on national level using a standardized set of goods/services (International Monetary Fund, n.d.). In this study, the CPI is, thus, used as a proxy for measuring the purchasing power impacts. The CPI was also used in previous studies to translate the results of the Leontief price model into purchasing power effects (e.g., Gemechu et al., 2014; Mardones & Mena, 2020). The CPI is calculated following Mardones and Mena (2020):

$$\Delta\mathrm{CPI} = \frac{\sum_{j=1}^{n} p_{\mathrm{j}}^{\mathrm{tax}}\alpha_{\mathrm{j}} - \sum_{j=1}^{n} p_{\mathrm{j}}^{\mathrm{old}}\alpha_{\mathrm{j}}}{\sum_{j=1}^{n} p_{\mathrm{j}}^{\mathrm{old}}\alpha_{\mathrm{j}}} \tag{3.6}$$

where:

ΔCPI is change in the Consumer Price Index, i.e. the degree of inflation or deflation for a certain income group after implementation of the carbon tax;

$\boldsymbol{p_{j_{old}}}$ is the price index of production for sector j before introducing the carbon tax;

$\boldsymbol{p_{j_{tax}}}$ is the price index of production for sector j after implementation of the carbon tax (modelled with the Leontief price model);

α_{j} indicates the share of output from sector j as a percentage (%) of the total basket of consumer goods, which was obtained from CBS.

3.3. Data requirements

3.3.1. Consumption data

The Consumer Price Index requires information about consumption patterns. Since the focus of this research is on the elderly, data was obtained about the expenditure of different age groups in the Netherlands. This dataset, obtained from CBS (the Central Statistical Office of the Netherlands) specifies expenditure (in percentage of the total disposable income) according to the age of the main earner of that household (CBS, 2023). This data is only available for 2015 and 2020. Due to the large impact of the COVID-19 pandemic on national and global economies and consumer behaviour (Verschuur et al., 2021), it was chosen to use consumption data from 2015, since the 2020 data could give an distorted representation of the consumption patterns. The dataset from CBS contained information about approx. 400 expenditure categories, some of which are aggregates of other categories. In total, the dataset has three levels of aggregation:

1. Main categories of expenditure, such as 'Food and alcoholic drinks' or 'Taxes' or 'Healthcare';
2. Sub-categories of expenditure, such as 'Food', 'Alcoholic drinks', 'Non-alcoholic drinks';
3. Detailed expenditures, such as 'Bread and wheat', 'Rice', etc.

For this research, the sub-categories of expenditure were used, which included 48 different expenditures. This selection was made for the sake of time. As will be explained below, a bridge matrix needed to be made, since the FIGARO data and the CBS data do not have the same granularity. This proved to be a time-intensive exercise and it was not feasible to make a bridge matrix for the more than 200 detailed expenditures in the CBS dataset. To further interpret the consumption patterns in Section 4.3, additional information from CBS about the expenditure of elderly was also used (CBS, 2017). The consumption table can be found in Table B.1 in Appendix B.

3.3.2. Input-output data

The input-output data and CO_2-data used for the input-output analysis were obtained from the FIGARO (Full International and Global Accounts for Research in input-Output analysis) database of Eurostat and the European Commission. FIGARO has high quality input-output data on European Member states as well as detailed CO_2-accounts (Eurostat, 2021), which can be used to calculate the value of the carbon tax for the different industries. While other databases have higher sectoral detail, such as EXIOBASE (Stadler et al., 2018), or include more countries, as in the ICIO database by OECD (2021), the quality of the economic data heavily influences the outcomes of price model. Additionally, due to its focus on the European Union, FIGARO is also very applicable for a case-study about the Netherlands. FIGARO's input-output data is in million € and the unit of the CO_2-accounts is thousand tonne CO_2. Household emissions were excluded from the CO_2-accounts, since the carbon taxes are applied at the industry level, meaning that the tax value is based on the industrial emissions. Additionally, there was complexity in assigning the indirect household emissions to the appropriate sector, since there is much unknown about the exact driving forces of household emissions (Wang et al., 2015).

3.3.3. Bridge matrix

A bridge matrix was made to match the 64 FIGARO sectors with the 48 goods and services in the consumption data. This table was largely based on an existing bridge matrix for combining Eurostat consumption data with EXIOBASE (Ivanova & Steen-Olsen, 2021). Eurostat data and CBS are classified using the same system: the COICOP (Classification Of Individual COnsumption by Purpose). EXIOBASE and FIGARO both use the NACE Rev. 2 classification for their sectoral divisions (Eurostat, 2021; Stadler et al., 2018). This means that the two databases contain information for the same sectors, albeit more aggregated in the case of FIGARO. Therefore, in the bridge matrix several of the detailed sectors available in the original bridge matrix for EXIOBASE had to be allocated to their higher-level class using the NACE Rev. 2 classification system (Eurostat, 2008) as a guide. Following the example of Johne et al. (2023) for Germany, values in the matrix were changed to reflect the Dutch context in 2015 more accurately. This was done for the expenditure category 'Transport Services', where the division of the different transport sectors (e.g. *Air Transport, Land Transport, Rail Transport*) was based on the Dutch mobility division in 2015 (Kennisinstituut voor Mobiliteitsbeleid, 2018). The expenditure category 'Narcotics' had to be omitted due to complexity in matching it to the FIGARO sectors. 'Narcotics' was also not present in the existing tables by Ivanova and Steen-Olsen (2021) and Johne et al. (2023). The bridge matrix can be found in Appendix B.1.

3.3.4. Elasticities of substitution

The flexible cost-push model requires information about the elasticities of substitution of different sectors. As part of the development of the flexible cost-push model, the DNB researched the elasticities of substitution for energy and capital/labour substitution for the Dutch economy in 2015. Bun et al. (2018) quantified the elasticities for energy-capital/labour substitution for each of the sectors in their input-output model. The IO model used in this thesis has a higher sectoral detail than the elasticities reported by Bun et al. (2018). Because of this, another matching needed to be done and not all sectors have specifically quantified elasticities of substitution. Futhermore, Bun et al. (2018) also included negative elasticities of substitution in their original model. These negative values are due to the estimation method that the authors used (which is further explained in Bun et al. (2018) but will not be covered in detail in this thesis). Negative elasticities of substitution are, however, theoretically impossible (Debertin, 2012; McKenzie, 2020). Therefore, all negative elasticities proposed by Bun et al. (2018) were changed to 0. In essence, this indicates the same about the possibility of substitution in those sectors as a negative elasticity, namely that substitution from energy inputs to capital/labour cannot happen. A full overview of the elasticities can be found in Table B.2.

3.4. Carbon taxing scenarios

In this research several different carbon taxing scenarios were modelled with differing carbon prices and target industries. Two different taxes were modelled:

1. **Economy-wide carbon tax in the Netherlands**
   In this scenario, a carbon tax is levied on all sectors in the Netherlands. Currently, only a limited number of industries in the Netherlands is subjected to a carbon tax (Nederlandse Emissieauthoriteit, 2022). Potential expansion of the tax could have large repercussions for the Dutch economy and the price level of final consumers.
2. **Carbon tax for Dutch energy sector**
   The CO_2-data from FIGARO shows that the Dutch energy sector is one of the most emission-intensive sectors of the Netherlands. Additionally, many other sectors in the economy require inputs from this sector. Levying a carbon tax on specifically the energy sector could, therefore, have large impacts, which can also trickle down the supply chain to other sectors. Moreover, the flexible cost-push model was originally developed to research an energy-tax (Hebbink et al., 2018). This scenario can also help further explore the assumptions beneath the model. In the FIGARO IO data, the energy sector is aggregated into *'Electricity, gas, steam and air conditioning supply'*.

For each of the taxes above, three different carbon prices[2] were modelled.

- **€50 per tCO_2.** Carbon prices of €50 per tCO2 are often considered as the necessary carbon price for limiting global warming to 2°C (High-level Commission on Carbon Pricing and Competitiveness, 2017). A carbon price of €50 per tCO_2 is also used in other studies about carbon taxing, such as Ward et al. (2019);
- **€150 per tCO_2.** First estimations indicate that carbon prices for limiting global warming to 1.5 °C scenarios are two to at least three times higher than current policies aimed at limiting warming to 2°C (Duan et al., 2021; Guivarch & Rogelj, 2017). This carbon price was included to give an indication of the potential impacts of a more ambitious climate policy;
- **€250 per tCO_2.** This carbon price is rather ambitious. This tax might not obtain the required political or societal support to be implemented in practice. The societal resistance for this carbon tax would be most likely be based on the belief the tax would increase inflation (Drews & van den Bergh, 2016). By including this 'extreme' policy, it can be explored if this would actually be the case.

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[2] Some of these carbon prices were originally reported in US Dollar. To streamline with the IO data, the prices were directly converted to Euros without accounting for the exchange rate.

A scenario with a global carbon tax is also shortly discussed in Chapter 4. The impacts of the global tax were explored to put the results more into context, since a trade-oriented economy such as the Netherlands is largely dependent on foreign trade and production (CBS, 2022). However, the global tax could be not be modelled with the flexible cost-push model, since data about the elasticities of substitution for other countries than the Netherlands was unavailable. The estimates by Bun et al. (2018) for the Netherlands already showed large differences in substitution potential for different sectors in the Netherlands. Moreover, the estimates are also based on the specific conditions of each sector (Bun et al., 2018). Alternative sources were also unavailable. In general, the outcomes of macro-economic models using substitution elasticities, such as the flexible cost-push model, are very sensitive to the values of the elasticities (Jacoby et al., 2006; Lazkano & Pham, 2016). Making assumptions about the substitution potential for such a large number of sectors would, therefore, not have produced reliable model outcomes. Therefore, it was decided to only use the results of the global tax as illustration in Section 4.1.

4

Results

First, the effects on the purchasing power of the elderly will be explored through changes in the Consumer Price Index. This chapter will then discuss the price changes per expenditure and the consumption patterns of the elderly to determine the vulnerability of the Dutch elderly to carbon taxing. Finally, the results of the conventional Leontief price model will be compared with those of the flexible cost-push model.

4.1. Impacts on purchasing power

In both scenarios, the impacts of the carbon taxes on the purchasing power of the elderly in the Netherlands appear to be relatively marginal. In the Dutch carbon tax scenario, the lowest carbon price of €50 per tCO_2 results in approx. 0.8% inflation. The consequences of the tax becomes more severe if a carbon price of €250 per tCO_2 is used (Figure 4.1). This scenario results in 4% inflation. The impacts on the Consumer Price Index (CPI) also grow almost proportionally to the increase in carbon price, which is due to the linearity of the IO model and the linear increase of carbon prices.

Similar trends can be observed about the energy tax in Figure 4.2. Here, the overall impact on the purchasing power is even lower. With a carbon price of €50 per tCO_2, there is a minimal effect on the purchasing power. Comparing Figures 4.1 and 4.2 shows that taxing just the *'Electricity, gas, steam and air conditioning supply'* sector already results in relatively large changes to the CPI. Around 40% of the changes in Consumer Price Index following the Dutch carbon tax (Figure 4.1) can be traced back to price increases in the energy sector.

In both scenarios, the elderly are not significantly more affected by the tax than other age groups of main earners. The elderly of 75 years or older are always the most affected, yet the difference with the other age groups is almost neglectable under all carbon prices. Noticeably, under the Dutch carbon tax, the youth under 25 are slightly more affected by the tax than the elderly between 65 and 75. Figure 4.2 shows that the differences between main earners becomes slightly more pronounced when the energy tax is levied with higher carbon prices. In this case, the youth up to 25 years also becomes more affected by the tax than the elderly. Yet, the overall difference between the age groups of main earners remains limited at most tax rates. This difference will be further discussed in Section 4.3.

The results above give the impression that the Dutch economy is not particularly vulnerable to carbon taxation. However, the scenarios only tax domestically-made products

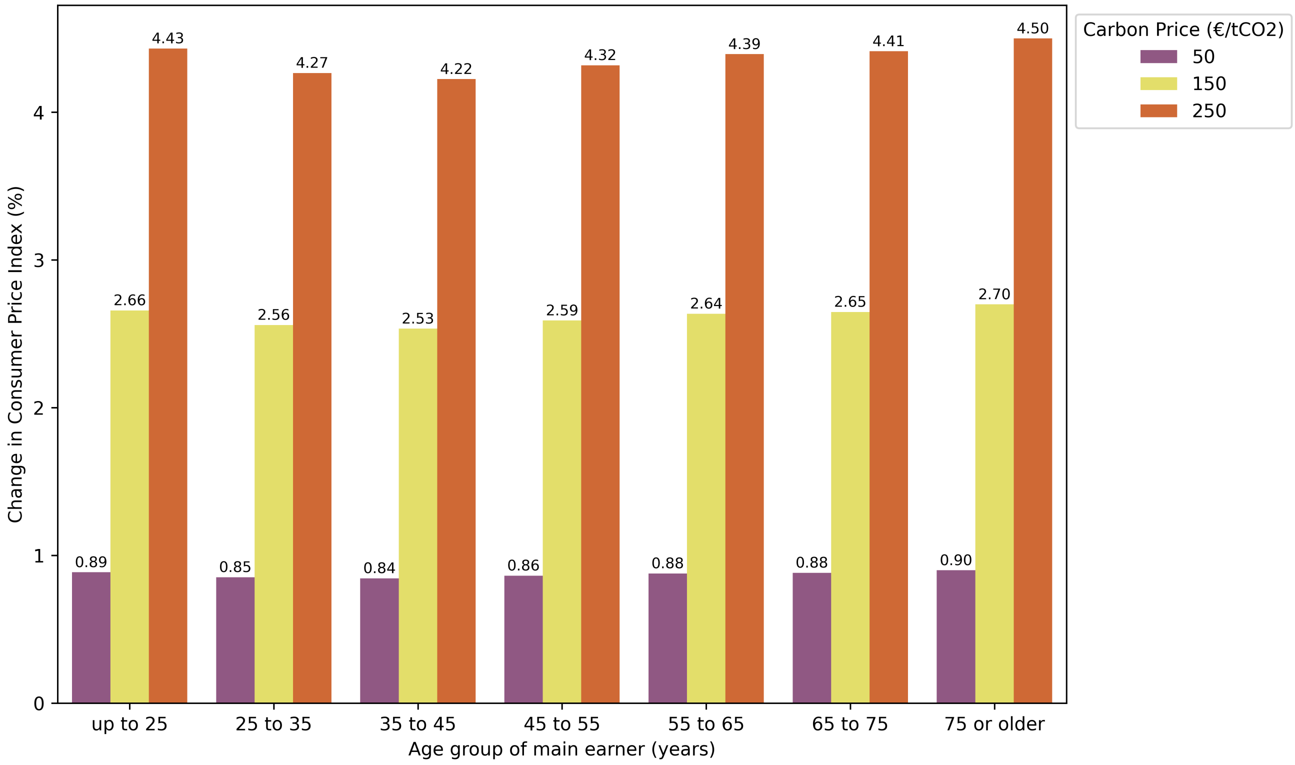

Figure 4.1: Changes to the Consumer Price Index (%) following an economy-wide Dutch carbon tax with different carbon prices.

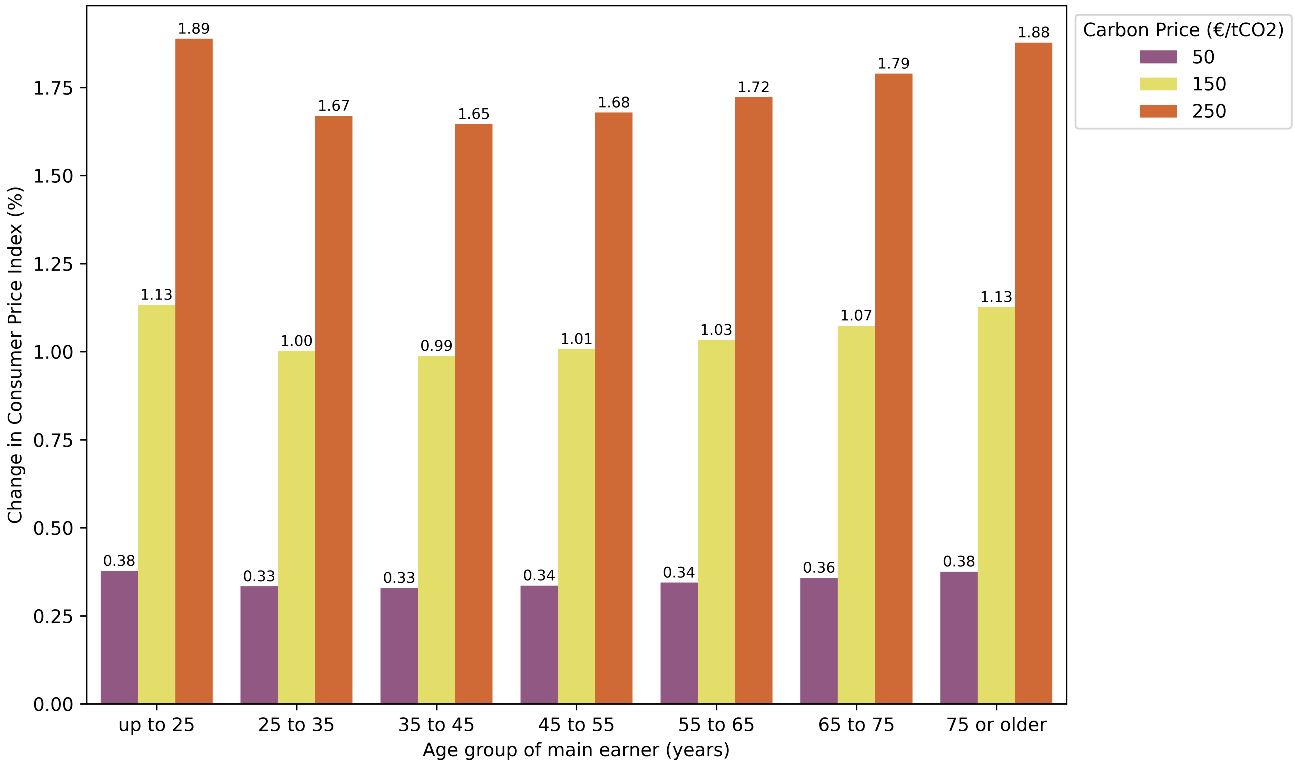

Figure 4.2: Changes to the Consumer Price Index (%) following a tax on the Dutch energy sector with different carbon prices.

and not the imported goods/services, meaning that the price of emission-intensive imports remains unchanged. For example, the Dutch food sectors relies on foreign sectors for the import of foods that cannot be grown in the Netherlands (CBS, 2022). Another example is the Dutch mining and quarrying sector, which imports critical raw materials such as lithium from abroad, since these products cannot be mined in the Netherlands or other European countries (Gemechu et al., 2016). These products are used in the Dutch economy, but their emissions are, for instance, not covered under the Dutch carbon tax scenario. Figure 4.3 shows the inflation rates if a global carbon tax would be implemented. The change in Consumer Price Index becomes twice as high compared to the Dutch carbon tax and five times higher than the energy tax. This suggests that a more nuanced taxing scenario, which takes the inter-industry relations and export/import pattern of the Netherlands into account, might be more effective to combat the emissions of Dutch consumption. At the same time, this would also affect the purchasing power of the Dutch population more.

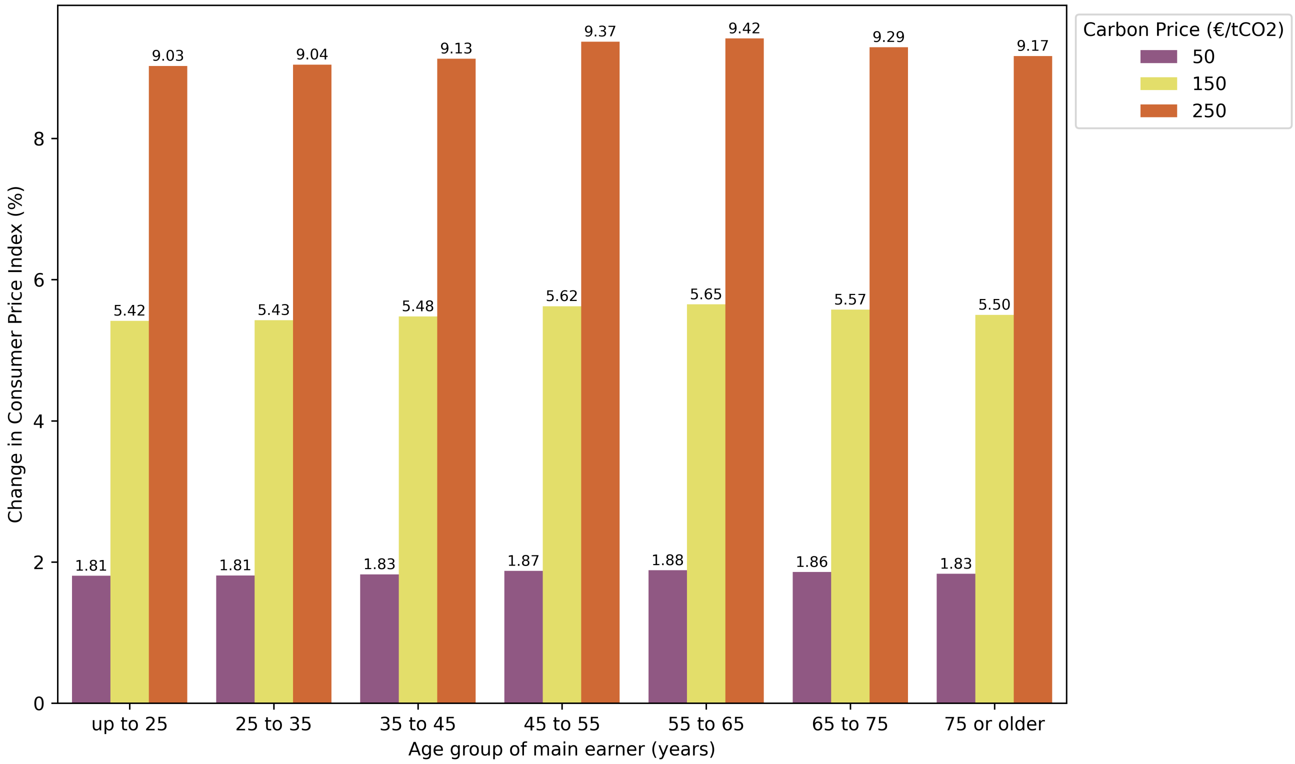

Figure 4.3: Changes to the Consumer Price Index (%) following a global carbon tax with different carbon prices.

4.2. Drivers of inflation

Changes in Consumer Prince Index are driven by price changes of specific expenditures. The influence of those expenditures on the inflation for a certain age group of main earner is dependent on their contribution to the total expenditure specified in the consumption data. To further understand the outcomes above, this section will zoom into the price changes per expenditure and the sectoral price changes that drive those.

4.2.1. Impacts on essential expenditures

While the cumulative impacts of the Dutch carbon tax on inflation seem contained in Figure 4.1, the tax forms a risk for several essential expenditures. As can be seen in Figure 4.4, inflation is mainly driven by price increases in expenditure on electricity, transport, medicines and household maintenance. This Figure also show that the lowest carbon price of €50 per tCo_2 results in only limited price increases for the majority of the expenditure categories. This makes that the cumulative effects on the CPI are also limited, since the large number of marginal price increases balances out the few large increases. However, in the case of higher tax rates, the carbon tax has big consequences for several essential expenditures, such as a price surge of 25% for expenditure on electricity, 15% for medicines, and 13% for transport.

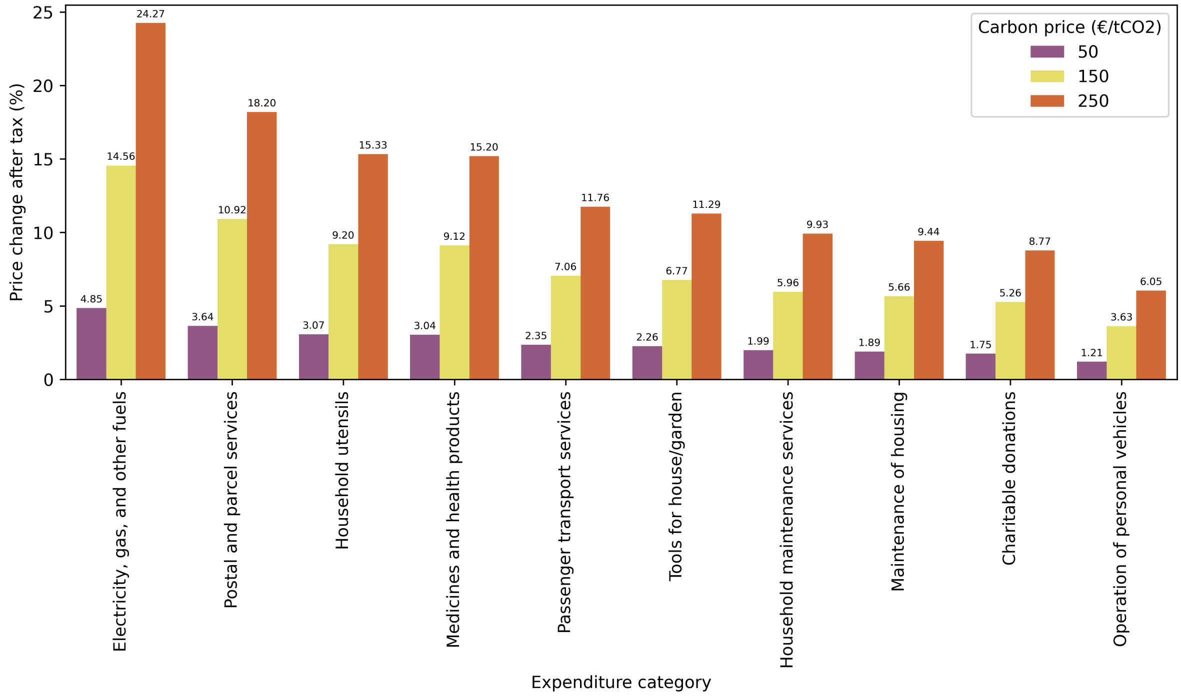

Figure 4.4: Overview of the ten largest price changes (%) per expenditure category following the economy-wide Dutch carbon tax with different carbon prices.

The energy tax, on the other hand, primarily results in price increases for expenditure on 'Electricity, gas, and other fuels'. Table 4.1 also shows that the spillover effects of the tax are contained. The only other expenditure categories with noticeable price increases in this scenario were 'Maintenance of housing' and 'Charitable donations', which also stood out in Figure 4.4. Explanations for the susceptibility of these expenditure categories to carbon taxing lie in the sectoral price changes and the way in which these are aggregated in the bridge matrix, which will be explained in the next two sections.

Table 4.1: The three expenditure categories with the largest price change (%) following the energy tax.

Sector	Price change (%)		
	€50 per tCO_2	**€150 per tCO_2**	**€250 per tCO_2**
Electricity, gas, and other fuels	4.7	14.1	23.5
Maintenance of housing	1.1	3.4	5.6
Charitable donations	0.4	1.1	1.9

4.2.2. Sectoral price changes

The emission-intensive industry in the Netherlands experiences the most effects of economy-wide Dutch carbon tax. The heavy industries, such as *'Manufacture of basic metals'*, *'Manufacture of chemicals and chemical products'*, and *'Electricity, gas, steam and air conditioning supply'*, dominate Table 4.3. These sectors face significant price increases with carbon taxes of €150 and €250 per tCO_2, such a 50% increase for the basic metals sector in the €250 per tCo_2 scenario. Interesting about Table 4.3 is that the emission-intensity of the sector (Table 4.2) does not necessarily indicate its vulnerability to the tax. For example, *'Postal and courier activities'* is the fourth most affected sector, but the sixth most emission-intensive sector of the Netherlands. Another example is *'Other professional, scientific and technical activities; veterinary activities'*, which is not among the most emission-intensive sectors, but which is among the most affected industries by the tax. For these sectors, their vulnerability is not solely caused by their emissions (which lead to a higher tax rate), but also by their inter-industry linkages. The A-matrix showed that both sectors are heavily reliant on emission-intensive sectors: transport- and fuel-related sectors in the case of *'Postal and courier activities'*, as packages and post are transported over large distances. Energy use makes up an important part of the carbon footprint of laboratory research (Farley & Nicolet, 2023) and veterinary medicine (Koytcheva et al., 2021). The *'Other professional, scientific and technical activities; veterinary activities'* is, therefore, for a large part reliant on inputs from the *'Electricity, gas, steam and air conditioning supply'* sector.

Table 4.2: The six most emission-intensive sectors of the Netherlands (Source: Eurostat, 2021).

Sector	CO2-emissions (kt)
Manufacture of basic metals	1.97
Manufacture of other non-metallic mineral products	1.07
Manufacture of chemicals and chemical products	0.57
Electricity, gas, steam and air conditioning supply	0.54
Manufacture of coke and petroleum products	0.50
Postal and courier activities	0.49

Where Table 4.3 primarily included the heavy industry, the energy tax also poses a risk to several Dutch services (Table 4.4). The '*Electricity, gas, steam and air conditioning*

Table 4.3: Ten largest sectoral price changes (%) following the economy-wide Dutch carbon tax with different carbon prices.

Sector	Price change (%)		
	€50 per tCO_2	€150 per tCO_2	€250 per tCO_2
Manufacture of basic metals	10.7	32.2	53.6
Manufacture of other non-metallic mineral products	6.3	19.0	31.7
Electricity, gas, steam and air conditioning supply	4.9	14.6	24.3
Postal and courier activities	3.6	10.9	18.2
Manufacture of chemicals and chemical products	3.4	10.1	16.8
Manufacture of coke and refined petroleum products	2.7	8.2	13.7
Air transport	2.7	8.1	13.5
Manufacture of fabricated metal products	2.3	6.8	11.3
Land transport and transport via pipelines	2.2	6.6	11.0
Other professional, scientific and veterinary activities	2.2	6.5	10.9

Table 4.4: The five biggest sectoral price change (%) following the Dutch energy tax with different carbon prices.

Sector	Price change (%)		
	€50 per tCO_2	€150 per tCO_2	€250 per tCO_2
Electricity, gas, steam and air conditioning supply	4.7	14.1	23.5
Other professional, scientific and veterinary activities	1.9	5.8	9.7
Security, service and landscape, office support	0.4	1.3	2.1
Manufacture of basic metals	0.4	1.2	2.0
Activities of membership organisations	0.4	1.1	1.8

supply' sector experiences the largest price increase as a result of the direct carbon tax applied to this sector. The other price changes in Table 4.4 are indirect effects of the tax, where the direct price increase for electricity has spilled over to other sectors via inter-industry linkages. These sectors also experience lower to almost insignificant price effects (hence, only five are included in Table 4.4). Some of these spillover effects were already visible in Table 4.3, where *'Other professional, scientific and technical activities; veterinary activities'* was also included due to its reliance on the electricity-sector. This becomes even clearer if an energy tax is levied, as this sector is the third most affected sector.

4.2.3. The bridge matrix

The price changes per expenditure category in Figure 4.4 and Table 4.1 are the result of aggregating the sectoral price changes with the bridge matrix. Several of these expenditures stand out. For example, in the Dutch tax scenario, there is a prominent increase for expenditures on 'Medicines and health services' (Figure 4.4). Via the bridge matrix, the price for this expenditure category is for 90% based on the sectoral price changes in '*Manufacture of chemicals and chemical products*'. In their original bridge matrix, Ivanova and Steen-Olsen (2021) based 'Medicines and health services' on inputs from 'Chemicals n.e.c.', which is a subcategory of the '*Manufacture of chemicals and chemical products*' sector available in FIGARO. Healthcare is one of the most emission-intensive industries (McAlister et al., 2020) (see also Table 4.2), making that the '*Manufacture of chemicals and chemical products*' sector, and in turn the expenditure category 'Medicines and health products', is particularly affected by the carbon tax.

The bridge matrix also explains the origins of the price increase for expenditure on 'Maintenance of housing', which can be traced back to the allocation of *'Electricitiy'* (22%) and *'Construction activities'* (28%) that represent the maintenance work, and rubber and plastic (18%), which indicate some of the materials used to do small maintenance. All three of these sectors are emission-intensive sectors, making 'Maintenance of housing' highly affected by carbon taxing. Two other housing-related categories in Figure 4.4, 'Household utensils' and 'Tools for house and garden', are allocated significant percentages of *'Non-metallic mineral'* inputs, which is the second most emission-intensive sector of the Netherlands. For 'Household maintenance services', the increase is most likely due to the allocation of inputs from '*Manufacture of chemicals and chemical products'*. Both of these allocations are plausible. Household utensils include glassware and ceramics such as plates, which both fall under the non-metallic minerals (European Commission, n.d.-c). An important part of 'Household maintenance services' include domestic tasks such as cleaning, which requires chemical cleaning products. 'Operation of personal vehicles' becomes more expensive due to the rising price for the petroleum industry following the Dutch carbon tax. 'Passenger transport services' receives large inputs from *'Land transport'* (70%) and *'Air transport'* (30%), which are both emission-intensive sectors in itself, but are also dependent on the petroleum industry for their fuels.

The unexpected price increase for 'Charitable donations' seen in both Figure 4.4 and Table 4.1 is due to its allocation to the *'Activities of membership organisations'* sector in the bridge matrix. Using the NACE Rev. 2 manual, this expenditure category was allocated to this sector, since membership organisations can also include charities (Eurostat, 2008).

'Activities of membership organisations' is the second most emission-intensive service sector of the Dutch economy in 2015, due its reliance on inputs from the electricity sector. This sector includes many large-scale corporations, such as trade unions and political organisations (Eurostat, 2008). Offices are big electricity consumers, since they often require airconditioning as well as electricity for their appliances and lighting (Tjandra et al., 2016).

4.3. Consumption pattern drives vulnerability

Figures 4.1 and 4.2 suggest that there is not one age group of main earner that is the most vulnerable to the impacts of carbon taxing. The change in CPI for the two groups of elderly was not significantly higher. However, a further investigation of their consumption pattern shows that the tax could still present risks to the purchasing power of the Dutch elderly. The consumption pattern is, thus, key in determining vulnerability to the tax.

Figure 4.5 highlights that, compared to the average expenditure among the age groups of main earners, elderly above 75 spend particularly large shares of their income on electricity, medicines, household maintenance services, and charitable donations. These four expenditure categories also showed up in the top ten expenditure categories with a particularly high price change following the Dutch tax (Figure 4.4) and the electricity tax (Table 4.1). In total, elderly above 75 spend more than average on seven of the ten most affected expenditures in Figure 4.5, although this difference is not as pronounced for all expenses. To illustrate, this particular age group of elderly spends almost 6% of their total income on electricity costs, 2% on medicines and household maintenance services, and 1% on charitable donations. For these latter categories, this is about twice as much as average. Where households with younger main earners might be able to do some of the household maintenance themselves, elderly quite often have to outsource this work, making this a more expensive activity. Additionally, medical expenses increase with age, as health issues become more prevalent. These marginal differences between the expenses of the elderly above 75 and the average expenditure could cause the slightly increased inflation seen in Figure 4.1.

The purchasing power of the elderly between 65 and 75 is a little less affected than that of elderly above 75 in the two taxing scenarios (Figure 4.1 and 4.2). For the ten expenditure categories below, this specific group of elderly only spends an above average percentage of their income on four of these expenditure categories. In general, this group of elderly spent a smaller part of their total disposable income of the ten most affected expenditures than the elderly above 75, making them slightly less vulnerable to price increases for these expenditure categories than elderly above 75.

The vulnerability of the two groups of elderly is also determined by their total disposable income and their total expenditure (Table 4.5). The elderly between 65 and 75 have a larger disposable income than the other group of elderly. Households with a main earner above 75 already spent 96% of their total income in 2015, of which they spent 40% on expenses related to housing, electricity, and utilities. This is the largest share of all age groups of main earners (CBS, 2017). At the same time, electricity becomes particularly expensive in all carbon taxing scenarios. Thus, given their relatively small disposable income and their already large expenditure on electricity, housing, and utilities, the elderly above 75 have little financial means to respond to these price changes, making them, at the level of specific expenditures, more vulnerable to carbon tax impacts than other age groups.

Section 4.1 also showed a slight increase in vulnerability to the carbon tax for youth up to 25 compared to other age groups. Similarly to the elderly, the youth spend a relatively large fraction of their total disposable income on expenditure categories that are especially affected by the tax, such as electricity and transport services. The youth below 25 spend about three times as much as other age groups on transport services. Those below 25 often do not own a car yet, meaning that they have to pay for transport services. This is also reflected in their below average expenditure on 'Operation of personal vehicles'. Moreover, the youth also spend about 35% of their income on electricity, and utility and housing costs. In addition, the youth up to 25 also have an especially limited disposable income (Table 4.5). This means that they already have a very limited purchasing power to start with, which is also seen in the fact that they tend to spend more than they earn (CBS, 2017).

In general, the differences in consumption pattern between different age groups of main earner remain relatively small. As discussed above, there are certain expenses on which specific age groups spend a particularly large fraction of their income. If there would have been more widespread differences in the consumption patterns, the cumulative difference between age groups would have grown. The similarity in consumption pattern is, thus, the root cause of the small differences in changes in Consumer Price Index between age groups observed in Figures 4.1 and 4.2.

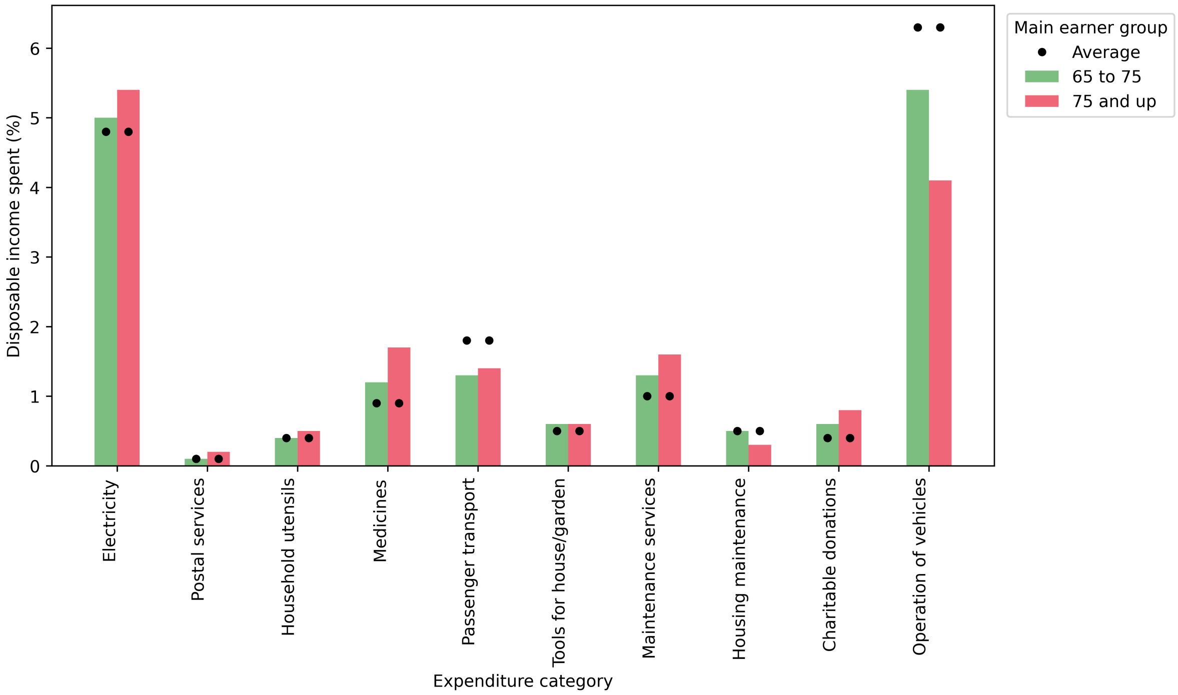

Figure 4.5: Percentage disposable income spend by the elderly on the ten most affected expenditures by the Dutch carbon tax.

Table 4.5: Statistics about expenditure of Dutch elderly and youth in 2015 (Source: CBS, 2017).

	Between 65 and 75	75 years and older	Youth up to 25
Total disposable income (thousand €)	35,5	27,2	13,8
Total expenditure (thousand €)	32,2	26,1	21,3
Expenditure on utilities (thousand €)	11,1	10,6	4,7
Total disposable income spent (%)	92	96	158
Income spent on utilities & housing (%)	35	40	34

4.4. Incorporating input-substitution

Thus far, this chapter has paid little attention to the outcomes of the flexible cost-push model. This section will first compare the outcomes of the flexible cost-push model with the conventional model, before delving deeper into the results to determine the influence of the elasticities of substitution.

4.4.1. The influence of the carbon price

The flexible cost-push model showed systematically lower outcomes than the conventional model. As can be seen in Figures 4.6 and 4.7, the difference between the two models seems only marginal at €50 per tCO_2, but this becomes quite significant when a carbon tax of €250 per tCO_2 is levied. Yet, further exploration of the results showed that while the absolute influence of input-substitution grows with increasing carbon prices, the relative mitigating influence of substitution is always approximately 17% for all carbon prices, taxing scenarios, and age groups (Table 4.6 and Table C.2) .

Thus, in absolute terms, input-substitution plays a more prominent role at higher carbon prices when the tax impacts are larger. This is in line with the literature, which suggests that input-substitution can decrease the price effect of carbon taxes (Bun, 2018; Hebbink et al., 2018; Mardones & Mena, 2020). This effect grows with growing carbon prices, since industries are more likely to replace the more expensive inputs to reduce costs if they are more affected by the carbon taxes. At the same, the industries will save more costs through input-substitution if they replace very expensive inputs with cheaper ones. This makes input-substitution more influential at higher carbon prices.

On the other hand, the relative mitigating influence of input-substitution on the change in Consumer Price Index remains 17% for all scenarios, even in the most ambitious scenarios that have large monetary effects. As mentioned above and in Equation 3.4, the influence of substitution is for an important part determined by the price effect, hence it was expected that the relative influence of input-substitution would also grow if the carbon tax scenario would become more ambitious. This means that the flexible cost-push model potentially underestimates the relative influence of input-substitution at higher carbon prices in its current form. Since the absolute effect of input-substitution does grow with increasing carbon prices, the exact cause of this effect is not immediately clear. This might, nonetheless, lie with Equation 3.4 or might stem from an issue in the Python modelling. Unfortunately, within the time frame of this research, the exact cause of this

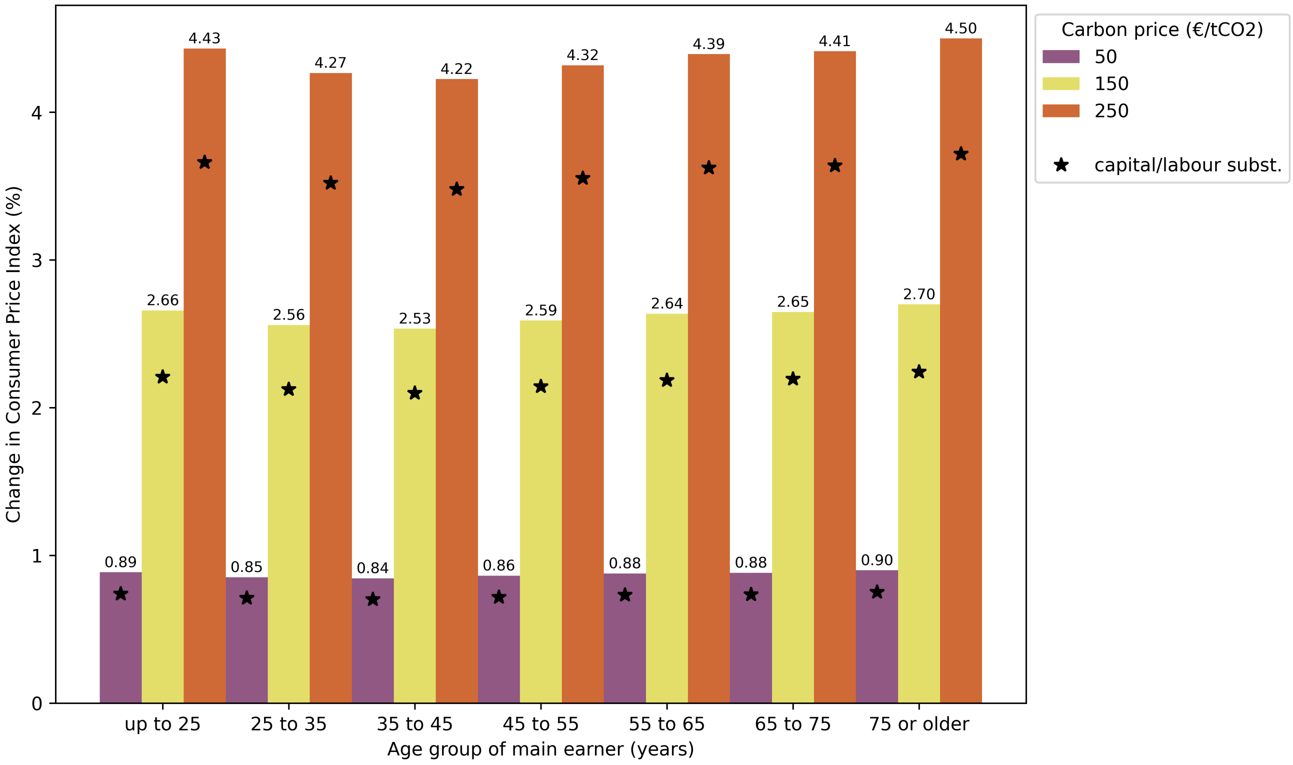

Figure 4.6: Changes to the Consumer Price Index (%) for an economy-wide Dutch carbon tax under different carbon prices and substitution scenarios.

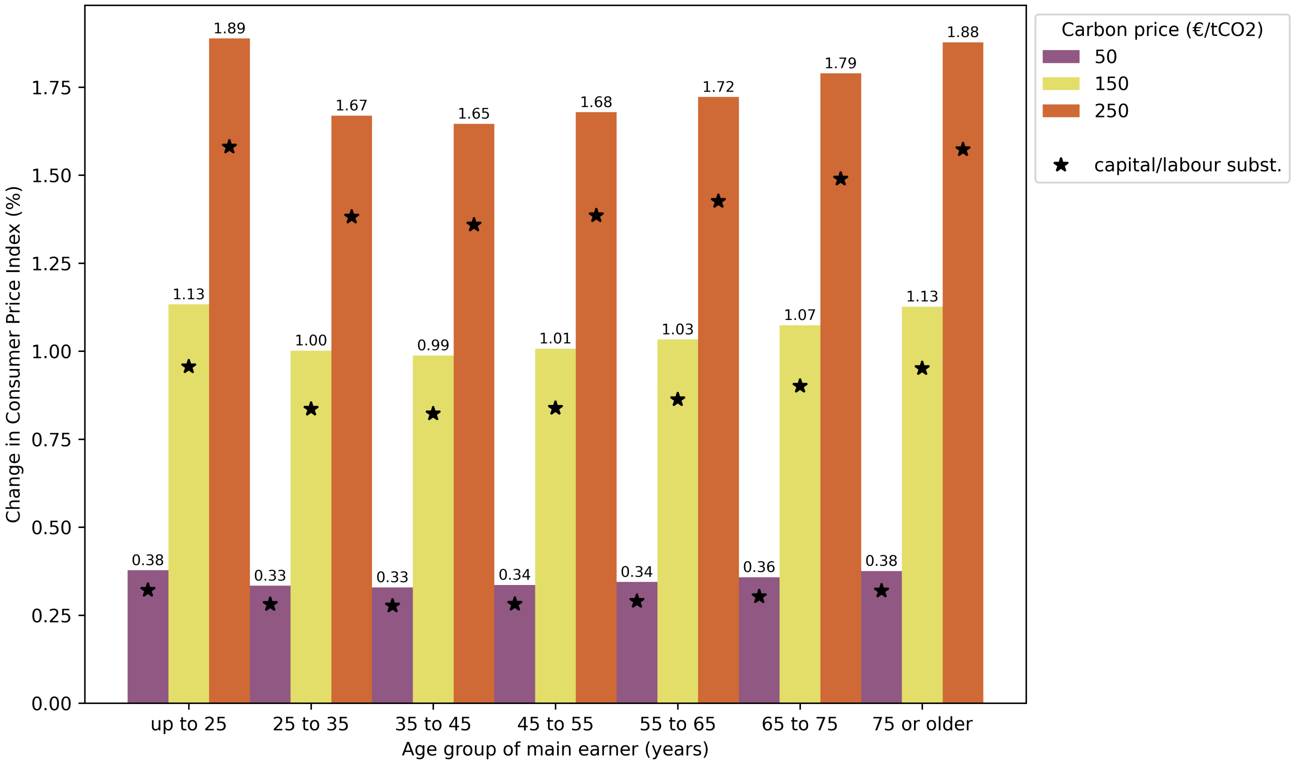

Figure 4.7: Changes to the Consumer Price Index (%) for a Dutch energy tax under different carbon prices and substitution scenarios.

issue could also not be found.

Table 4.6: The relative influence of input-substitution on the changes in Consumer Price Index (%) for the Dutch carbon tax under different carbon prices.

Carbon price		Between 35 and 45	Between 65 and 75	75 years and older
€50/tCO2	CPI *(no substitution)*	0.84	0.88	0.90
	CPI *(with substitution)*	0.70	0.74	0.75
	Relative influence (%)	-17	-16	-17
€150/tCO2	CPI *(no substitution)*	2.53	2.65	2.70
	CPI *(with substitution)*	2.10	2.19	2.24
	Relative influence (%)	-17	-17	-17
€250/tCO2	CPI *(no substitution)*	4.22	4.41	4.50
	CPI *(with substitution)*	3.48	3.64	3.72
	Relative influence (%)	-18	-17	-17

4.4.2. The influence of the substitution elasticity

The results of the flexible cost-push model are dependent on the value of the elasticity of substitution. For this thesis, elasticities quantified by the DNB were used, which differed per sector (Bun et al., 2018). To gain a better understanding of the influence of the elasticity of substitution, a sensitivity analysis was done. The analysis zoomed in on the change in CPI for the two groups of elderly and sectoral price changes in the energy tax scenario with a carbon price of €150 per tCO_2. Elasticities of substitution between 0.0 and 1.0 were explored for the *'Electricity, gas, steam and air conditioning supply'* sector, with 0.0 indicating no possibilities for substitution between energy and capital and 1.0 indicating a high potential for substitution. Bun et al. (2018) quantified a substitution elasticity of 0.16 for the electricity sector, which is used as the default in this thesis.

Table 4.7 shows that the change in CPI, i.e. the inflation, decreases with growing elasticities of substitution. Following the logic of Hebbink et al. (2018), this indicates the ease with which industries can invest in energy saving measures, whereas a lower elasticity represents barriers to investing for a particular sector. In the case of the energy tax, higher elasticities also indicate that sectors are better able to mitigate the tax. With an energy tax of €150 per tCO_2, increasing elasticities can mitigate the tax-induced price change by an additional four percent (Figure 4.8). Previous results showed that the energy tax also has spillover effects on energy-intensive sectors, such as *"Other professional, scientific and technical activities; veterinary activities"*. Due to these inter-industry linkages, this sector also experiences less impacts if the electricity sector is better able to mitigate the tax impacts (Figure 4.8).

Table 4.7: Change in Consumer Price Index (%) for the two groups elderly under different elasticities of substitution following an energy tax with a carbon price of €150 per tCO2.

Elasticity	65 to 75	75 and older
0.0	1.07	1.13
0.16	0.99	1.04
0.3	0.81	0.86
0.5	0.69	0.74
0.7	0.58	0.62
1.0	0.42	0.46

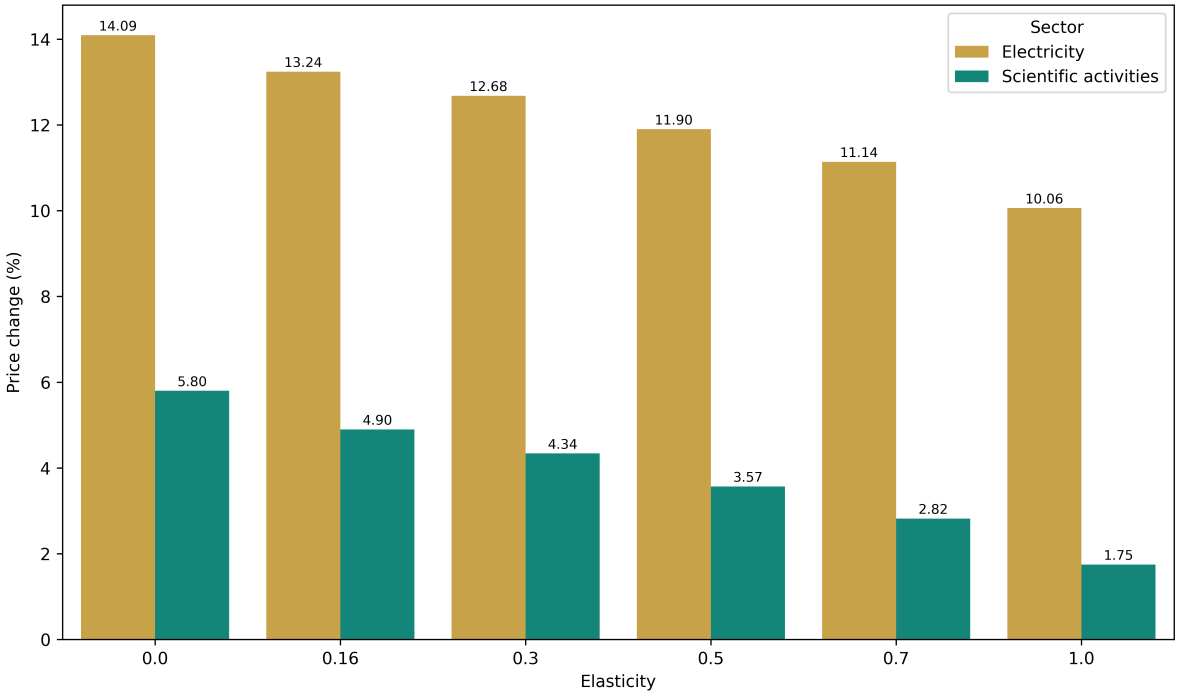

Figure 4.8: Sectoral price changes for the electricity and scientific activities sectors under different substitution elasticities following an energy tax of €150 per tCO_2.

5
Discussion

Potential impacts of different carbon taxing scenarios on the purchasing power of the eldery in the Netherlands were researched using a conventional Leontief price model and a flexible cost-push model. The main results of this thesis and future possibilities for research will be discussed below.

5.1. Synthesis

5.1.1. Purchasing power of the elderly

The overall impacts on the purchasing power of the elderly in the Netherlands seem to suggest that the Dutch elderly are not particularly vulnerable to both an economy-wide carbon tax as to an electricity tax. In the scenario with an economy-wide Dutch carbon tax, the inflation rates ranged from approx. 1% at a carbon price of €50 per tCO_2 to 4.5% in a €250 per tCO_2 scenario. In the case of a tax on the Dutch *'Electricity, gas, steam and air conditioning supply'* sector, the impacts on the purchasing power became even lower, 0.4% and 1.9% for the same carbon prices, respectively. Section 4.1 showed that the elderly are only slightly more susceptible to the effects of carbon taxing than other age groups. There are no significant differences visible at this general level between the age groups of main earner.

Section 4.3 proved the importance of the consumption pattern in determining this vulnerability. The elderly above 75 spend an above average percentage of their income on expenses that would be especially affected by a carbon tax. These expenses included electricity, utility, and housing costs. For example, the Dutch tax can result in a five to 25 % increase in costs of electricity. The elderly above 75 already spend 40% of their total disposable income on these expenses, which is the largest percentage of all age groups and also 5% higher than the elderly between 65 and 75. This other group of elderly spends less on these expenditure categories, making them somewhat less susceptible to the most extreme impacts of the carbon taxes than the elderly above 75.

Thus, the true impacts of the carbon tax are more complex than shown by the Consumer Price Index and should also be considered in the larger socio-economic context of elderly in the Netherlands. The elderly above 75 have a relatively small disposable income, which they already almost entirely spend. Moreover, the purchasing power of the elderly in the Netherlands has stagnated in recent years, while the costs of living in the Netherlands are only rising (Hasekamp, 2023). Elderly in the Netherlands, thus, already have a limited purchasing power to start with. This also means that the elderly above 75 have little buffer that they can use to compensate for the rising prices. This could make carbon taxing particularly regressive for the Dutch elderly.

Research has also shown that the elderly are already one of the key groups at risk of energy poverty in the Netherlands (Straver et al., 2020). Households that are 'energy poor' do not have access to energy services, due to, for example, financial reasons (Karpinska & Śmiech, 2021). It should also be taken into account that elderly generally face more insecurities when it comes to their health, housing, and income (Franken et al., 2022). This makes the potentially large increases for electricity and housing costs an even larger risk for Dutch elderly. Taking all of this into account, carbon taxing can become one economic burden too many for the elderly in the Netherlands.

5.1.2. Effective carbon taxing design

This study also explored two different carbon taxing scenarios: one in which an economy-wide carbon tax was levied on all industries of the Dutch economy, and a second tax on the Dutch electricity sector. The economy-wide tax resulted in the largest price effects, particularly for the emissions-intensive industries. The energy tax primarily affected the energy-intensive sectors in the Netherlands, which are both manufacturing and service sectors. Comparing the two taxes showed that the energy tax already resulted in relatively large price effects, due to its importance in the supply chain. However, a short exploration of a potential global carbon tax showed the importance of considering the import and export pattern of the Netherlands (Figure 4.3 and Table A.1). The Dutch economy is trade-oriented (CBS, 2022) and because of this, the Netherlands displaces an important part of its environmental impacts to other countries. These emissions are not covered by domestically-focused carbon taxing scenarios.

Therefore, a more nuanced approach that includes both the emission-intensity of the Dutch production and the Dutch import/export behaviour would be more effective to combat the emissions of Dutch consumption. To achieve this, widespread taxing in the Netherlands can be combined with specific taxes on emission-intensive imports. The EU is working on implementing such a system. In 2026, a similar system will be put permanently into place at European scale through the 'Carbon Border Adjustment Mechanism' (CBAM), where a price needs to be paid for the hidden emissions of certain heavy industries (European Commission, n.d.-a). The aim is to use CBAM to also cover the displaced emissions of European production/consumption (European Commission, n.d.-a).

Lastly, there is an important trade-off that needs to be considered here. The more effective a carbon taxing scheme, the more emissions it will cover. This will result in higher taxes imposed om more sectors, which in turn results in price increases for final consumers. Gemechu et al. (2014) concluded *"that there is an unavoidable trade-off among society, the environment and the economy"* (p. 764) when it comes to carbon taxing. The design of carbon taxes requires an integrated approach that also gives explicit place to the distributional impacts of carbon taxing (Gemechu et al., 2014). This trade-off also became clear from the results of this study, where scenarios with higher carbon prices would result in larger emission reductions, but also in larger purchasing power impacts.

5.1.3. On the flexible cost-push model

Lastly, this study also explored the influence of including input-substitution in the Leontief price model by using a flexible cost-push model designed by the Dutch National Bank. This model showed systematically lower price effects than the conventional Leontief price model. The outcomes affirm the hypothesis that input-substitution can mitigate the price changes of carbon taxes. From that perspective, it can be argued that the conventional Leontief price model overestimates the price changes, due to its lack of input-substitution.

The case study also showed that with increasing carbon prices, the absolute mitigating effect of input-substitution grows, leading to larger monetary savings for industries (Figures 4.6 and 4.7). This absolute growth of the effect of input-substitution is due to the specific form in which the flexible cost-push model is used in this research, which goes back to Equation 3.4. In this equation, the change in technical coefficient for a specific sector is for a large part dependent on the relative price change in that sector following the carbon tax. The relative sectoral price increases grow with more ambitious scenarios, meaning that the technical coefficients in the A-matrix increasingly change, leading to increasingly different outcomes following Equation 3.5.

Yet, the relative effect of input-substitution does not grow with increasing carbon prices and tax effects. The change to the Consumer Price Index was approx. 17% lower for all taxing scenarios, carbon prices, and age groups (Tables 4.6 and C.2). It was expected that the relative influence of input-substitution would also increase in more ambitious scenarios, since industries gain more from input-substitutions in these scenarios. Since the relative influence of input-substitution remains the same, the substitutions are not influential as they could have been. Further investigation is needed to discover if this effect is due to the structure of the flexible cost-push model (i.e., Equation 3.4) or if the cause lies somewhere else, since the exact cause of this effect could not be pinpointed in this research. Thus, in its current form the flexible cost-push model could potentially underestimate the relative influence of input-substitution in more ambitious scenarios.

In addition, there are several other assumptions that limited the potential outcomes of the flexible cost-push model. First, the model disregards other possibilities for input-substitution beyond substitution from energy inputs to capital/labour inputs. This is also one of the main limitations pointed out by Hebbink et al. (2018) themselves. For example, the results show that petroleum and transport prices will rise following a carbon tax, which might trigger businesses to upgrade vehicles instead of investing in energy efficiency. Furthermore, the model disregards the possibility of substitution between energy types, e.g., the replacement of fossil fuel energy with renewable forms of energy to combat the price increases by the carbon tax. Third, the assumption to only model energy-capital/labour substitution also influenced the elasticities of substitution, which in turn again affected the outcomes of the flexible cost-push model. The average elasticity estimated by Bun et al. (2018) was 0.249, which is symbolize a low potential for this specific type of substitution in the Dutch industries. There might be larger potential for substitution for other substitution types, such as substitution between energy types. The focus on energy-capital/labour substitution, therefore, restricted the outcomes of the flexible cost-push model in multiple ways.

Thus, the potential of the flexible cost-model is restricted by its underlying assumptions and econometric structure. Nonetheless, Section 4.4 did show that the conventional model has the tendency to overestimate price impacts. The flexible model, therefore, has added-value compared to the common Leontief price-model. However, this thesis also showed that further development of the flexible cost-push model by Bun (2018) and Hebbink et al. (2018) is required on multiple levels before this specific model would be recommended as a viable alternative to the Leontief price model in all scenarios.

To conclude, the outcomes of the flexible cost-push model used in this research highlight the limitations of the conventional approach, yet the model is still restricted to some extent in its ability to model input-substitution and further development of the model is necessary to increase the empirical value of the model. This study also showed that even though the overall impacts on the purchasing power of the elderly in the Netherlands could be only marginal, the carbon tax could still present risks to the welfare of Dutch elderly. Their stagnating purchasing power and consumption pattern make Dutch elderly especially susceptible to energy poverty due rising electricity prices following carbon taxing. Additionally, this thesis also showed that designing effective carbon taxing schemes is complex for trade-oriented economies like the Netherlands. Domestic carbon taxing cannot incorporate the displaced emissions of trade. This thesis, therefore, also underlines the importance of considering both the effectiveness of carbon taxing scheme (emissions covered and displacement of impacts) and explicitly accounting for distributional impacts for carbon taxing to be truly sustainable.

5.2. Comparing to existing literature

As far as could be found during this research, Hebbink et al. (2018) were the only ones that used a flexible IO model to investigate carbon taxing impacts in the Netherlands. Hebbink et al. (2018) also concluded that a Dutch carbon tax of €50 per tCO_2 does not harm the Dutch industries significantly. This thesis goes beyond that by proposing an improvement to the method by Bun (2018) and Hebbink et al. (2018) and by showing that higher carbon prices could, in fact, present a risk to Dutch industries. Hebbink et al. (2018) did not consider how sectoral price changes following carbon taxing translate to prices for the final consumer. No other studies were found that researched this for the Netherlands.

There are, however, several other studies that used an input-output approach to research carbon taxing impacts in other countries. Mardones and Mena (2020) found that a carbon tax of €50 per tCO_2 results in almost 2% of inflation for low-income households. Gemechu et al. (2014) modelled an energy tax of €20 per tonne CO_2 in Spain, which resulted in 0.19% inflation, which would be approx. 0.48% inflation at €50 per tCO_2. Both studies found higher inflation rates than those found in this study. There could be multiple explanations for this.

First, the consumption patterns of the three countries mentioned could differ. Consumption patterns do not only differ within countries, but also per countries (Clements et al., 2006). Chile, Spain, and the Netherlands are countries with significantly different cultures and socioeconomic systems, with can both, for example, drive result in differences in energy consumption (Lutzenhiser, 1997). Chilean and Spanish consumers might consume more emission-intensive products than Dutch consumers, making them more vulnerable to the tax. The importance of the consumption pattern in the vulnerability of certain groups to carbon taxes was also pointed out by Johne et al. (2023), who discovered that nitrogen taxing in Germany would result in a relatively small monetary impact, yet rising prices in certain sectors would affect certain income groups more than others.

This thesis also did not explicitly take difference in income into account, as done by Mardones and Mena (2020). Difference in income is shortly discussed in Section 4.3, but is not systematically included in the consumption dataset and the calculation of the Consumer Price Index. From Section 4.3, it already becomes clear that this is an important perspective that should not be completely neglected. Elderly in the Netherlands generally have a lower disposable income than other age groups. They consume less than other age groups in absolute terms, yet they use up a larger fraction of their income than other age groups (CBS, 2017). Moreover, Steckel et al. (2021) also pointed out that there could also be large differences in tax impacts within income groups. Income inequality is also present under elderly in the Netherlands. Not all elderly are entitled to a supplementary pension and these also differ in height per person (Skugor et al., 2017). There are, thus, multiple socioeconomic dimensions that were not taken into account in this research that could have shown more nuanced outcomes and potentially also more extreme outcomes for the Dutch elderly.

The higher inflation rates found by Gemechu et al. (2014) and Mardones and Mena (2020) might also be driven by potentially higher emissions of the industries in Chile and Spain. Countries with more heavy industry are also more vulnerable to carbon taxing. This was also pointed out by Ward et al. (2019), who concluded that a global carbon tax would disproportionately affect the competitiveness of emerging economies, since these economies are more reliant on heavy industry than Western countries.

Thus, literature about carbon taxing in the Netherlands is limited and previous research found that the taxes could have larger impacts in other countries than the Netherlands. At the same time, the body of literature comes to a similar conclusion as this thesis: that vulnerability to carbon taxes should not only be determined at the macroeconomic level, but should also take the specific socioeconomic conditions of the age group, the country, or the income group into account. Conditions like the consumption pattern, existing income inequality, or the industrialization of the economy can play an important role in determining the vulnerability to carbon taxing.

5.3. Limitations & Recommendations

There are several limitations to this research that open up opportunities for future research. On the one hand, there are possibilities for further analysis about carbon taxing impacts in the Netherlands. On the other hand, future research is necessary to improve the methods used in this thesis.

5.3.1. Additional analyses

First of all, analysis with more recent data is necessary to better understand the influence of carbon taxing on the purchasing power in the Netherlands. The current analysis uses data about the Dutch economy and CO_2-emissions in 2015. Since then, both the Dutch economy (CBS, n.d.) and the consumption patterns in the Netherlands have changed significantly (Compendium voor de Leefomgeving, 2024). Expenditure in the Netherlands has increased annually since 2015 and consumption patterns also change depending on the socioeconomic conditions of that year (Compendium voor de Leefomgeving, 2024). For instance, energy-related expenditure has grown in recent years (Compendium voor de Leefomgeving, 2024), making the elderly potentially even more vulnerable to carbon taxes. Analysis with more recent data could, thus, yield different results.

Additionally, future research could also more explicitly explore the difference in income between the age groups of main earners. A more systematic inclusion of differences in total disposable income than done in this thesis can help quantify the impacts of the carbon tax for the elderly more precisely. As a first step, a dataset could be used that specifies expenditure per income quintile, similar to Mardones and Mena (2020). In that way, it could be explored if the tax also potentially contributes to other forms of income equality, as suggested by multiple authors (e.g., Baranzini et al., 2017; Beck et al., 2015; Mardones & Mena, 2020). It could also be insightful to explore differences in taxing impacts within the different age groups of main earner, similarly to Steckel et al. (2021).

Several authors also went beyond the scope of this thesis to research tax revenue recycling schemes to combat the unfair impacts of carbon taxes. This research already showed the potential of distributional effects on the elderly, which only highlights the importance of researching measures to prevent these. Tax revenues could, for example, be directly paid to the most affected groups (Zhang et al., 2019; Zhao et al., 2022) or can be invested in infrastructure that particularly benefits these groups (Dorband et al., 2022). Future analysis should, thus, not only investigate the potential impacts of carbon taxing in the Netherlands, but also research opportunities to prevent or alleviate these burdens.

Future research can explore how final consumers might respond to price increases caused by the carbon taxes. The model used in this thesis only considers input-substitution by industries, not by final consumers. This is a general limitation of macro-economic models, such as IO models, and measures like the CPI. The CPI cannot fully capture a dynamic economy where products are constantly introduced and price levels continuously vary, leading to an oversimplification of the economy (Boskin, 2005). To capture the lower scale impacts of climate policies, such as carbon taxes, Niamir et al. (2020) suggest to combine macro-economics models with an agent-based model. Agent-based models are able to mimic behaviour of agents, e.g. final consumers in the supermarket, responding to different climate policies (Niamir et al., 2020).

The more bottom-up approach of an agent-based model can also combat another limitation of macro-economic modelling: the homogenization of a diverse population into one numerical indicator score (Mügge, 2016). The CPI results suggested a limited risk of carbon taxing for the elderly, but a more detailed look at their consumption pattern revealed otherwise. Additionally, the CPI analysis in this thesis could not account for difference in income level between or within age groups. This underlines that macro-economic indicators should not be seen as accurate representations of the economic situation of entire populations (Mügge, 2016), but rather as aggregated estimations and that additional, more lower scale economic analysis is often necessary.

Lastly, sceptics could say that carbon taxing scenarios resulting in large input-substitutions are not particularly effective, since the monetary effect of the tax is limited by industries. In that way, the financial burden of their CO_2-emissions is decreased. Yet, it is important to remember that input-substitutions represent investments in energy efficiency in the model by Bun (2018) and Hebbink et al. (2018). Large scale energy efficiency upgrades could lead in large reductions of emissions. In that sense, a carbon scenario inducing widespread input-substitutions could also be viewed as particularly effective. Future research could explore the emissions that would be saved by carbon taxes and compare the effect of input-substitution on the emissions saved, since this was not investigated in this thesis.

5.3.2. Model and method development

All the above also indicates several possibilities for the improvement of the methods used in this thesis, starting with the bridge matrix. At the time of this research, there was no bridge matrix publicly available to aggregate the sectoral price changes from the FIGARO model into the COICOP expenditure categories. Section 4.2.3 highlighted the influence of the aggregations in the bridge matrix on the price changes per expenditure, and indirectly on the changes in CPI per age group of main earner. The bridge matrix by Ivanova and Steen-Olsen (2021) was used as a base to develop this research's bridge matrix. The documentation of Ivanova and Steen-Olsen (2021), however, contains little information about the assumptions beneath the matrix. These assumptions were not explored in detail during this research due to reasons of time. For the same reason not all products of the COICOP classification were included in the current bridge matrix. FIGARO is a relatively new IO database, which despite its high-quality data and environmental extensions, has not been used in many studies since its release in 2021. The development of a complete bridge matrix could further stimulate the use of FIGARO in empirical research.

Another improvement to the model lies in the incorporating of the household emissions. The simulated carbon tax was calculated based on the direct industrial emissions and did not account for the household emissions. FIGARO's household emissions are primarily based on emissions from domestic heating/cooling and private road transport (European Commission, 2024). These emissions are, thus, indirectly linked to the electricity and transport sector and could have been accounted to these sectors. However, the precise details about which sector drives which part of the household emissions is unknown. Many studies only consider the household emissions at macro-level, while there are also multiple, lower-scale factors that drive the household emissions (Wang et al., 2015), such differences in income between households (Lenzen, 1998; Wang et al., 2015). Due to these complexities in accounting for the household emissions, these emissions were excluded in this research. However, future research should investigate how to properly account for the household emissions, since the excluded household emissions in this thesis were quite significant.

Third, quantification of elasticities of substitution that can be used in the flexible cost-push model are rare. The elasticities used in this thesis were estimated by Bun et al. (2018) for their specific case-study about energy-capital/labour substitution. However, there were little alternative sources to check the validity of the elasticities by Bun et al. (2018). While a limited number of alternative estimations were available, such as Bulavskaya and Reynès (2018), these estimations often lacked the sectoral detail that the elasticities by Bun et al. (2018) had. As discussed in Section 4.4.2, the outcomes of the flexible cost-push model are sensitive to the specific substitution elasticities. This is a common limitation with climate policy models using elasticities of substitution (Jacoby et al., 2006; Lazkano & Pham, 2016), which makes reliable estimation of substitution elasticties more vital. Yet, the estimation of elasticities of substitution is inherently complex and not always reliable, as Henningsen et al. (2019) discovered. This was also reflected in the work by Bun et al. (2018), who included negative elasticities of substitution in their original documentation of the flexible cost-push model. Negative substitution elasticities are impossible (Debertin, 2012; McKenzie, 2020) and the estimations were most likely due to the specific method used by Bun et al. (2018). The reliability of the results of the flexible cost-push model, and it future use in research, could have been improved if the elasticities of substitution could have been compared to other estimates. Additionally, if more elasticities of substitution are quantified, the flexible cost-push model could also be more easily applied to different contexts. For instance, the effects of the global tax on the Dutch economy could not be modelled with the flexible cost-push model since elasticities of substitution were only available for the Dutch industries.

Development of the flexible cost-push model

Furthermore, there are also several opportunities for further development of the flexible cost-push model itself. The flexible cost-push model designed by Bun (2018) and Hebbink et al. (2018) for the Dutch National Bank is based on Liew (1984), who first introduced an input-output model in which the coefficients are adapted following input price changes. In Liew (2000) and Liew (2005), the author argues for the use of dynamic flexible input-output models, since these models are able to simulate the consequences of changing input prices over time and give a more nuanced estimate of input-substitutions and its potential ripple effects (Liew, 2000; Liew, 2005). The lack of time dynamics is an important limitation of the flexible cost-push model used in this research, since investments and input-substitutions are assumed to happen directly after tax implementation. In reality, these investments might happen more gradually (Hebbink et al., 2018) and the additional price impacts of input-substitution might be less pronounced, since the impacts are spread out over a longer period of time.

Equation 3.4 is at the core of the flexible cost-push model. The results showed that the model is still to some extent restricted in its capacity to model input-substitution, which for an important part goes back to the structure of Equation 3.4. Vats et al. (2021) is one of the few other examples that also use a flexible Leontief price model, but they use a different logic and econometric approach to incorporate input-substitution in their model. Future research could explore if the use of an approach similar to that of Vats et al. (2021) results in different outcomes than Equation 3.4 and might combat some of the limitations of the current model, such as the stable relative influence of input-substitution in the different scenarios.

Section 5.1.3 discussed how the assumption of energy-capital/labour substitution limited the flexible cost-push model. There are, thus, multiple possibilities to expand the current model. The model now disregards all forms of input-substitution beyond the energy-capital/labour substitution as well as the possibility of substitution between energy types. Future research can investigate how these assumptions could be incorporated into the structure of the flexible cost-push model. However, since this method was originally developed to model a carbon tax, it would be best to first further improve the model for carbon taxing research before potentially expanding the model to be used in other empirical contexts.

Lastly, CGE (Computable General Equilibrium) models are mentioned by multiple researchers as alternatives to flexible/variable input-output models (Bun, 2018; Liew, 2000; Miller & Blair, 2009). CGE models are able to capture substitutions by default without having to introduce additional calculation steps as in the flexible IO model (Bun, 2018). And as mentioned in Section 2.2.1, both types of models are preferable for different kinds of analyses (de Koning, 2018). Since the flexible cost-push model is to some degree still limited in its ability to model input-substitution due to the many underlying assumptions, sceptics might argue that the flexible cost-push model insufficiently captures input-substitution and that CGE models might be more suitable for this type of research. It is important to mention here that both models are inherently sensitive to the uncertainties associated with the estimation of elasticities of substitution that were discussed above. Hence, the endogenous inclusion of substitution elasticities does not make CGE models better by default. Nonetheless, future research can compare the outcomes of two types of models, similar to West (1995). From this, lessons can be learned about input-substitution for both IO and CGE models.

6

Conclusion

This thesis aimed to investigate carbon taxing impacts on the elderly in the Netherlands using environmentally-extended input-output analysis. Specifically, the main research questions of this thesis was: *How can the Leontief price model be applied in multi-regional EEIOA to assess the impacts of carbon taxing on the purchasing power of the elderly in the Netherlands?*

This study researched the purchasing power of the elderly in Netherlands following an economy-wide carbon tax in the Netherlands and a tax on the Dutch *'Electricity, gas, steam and air conditioning supply'* sector with carbon prices of €50, €150, and €250 per tonne CO_2. Additionally, the analysis used both a conventional Leontief Price model as well as an flexible cost-push model developed by the Dutch National Bank that can capture additional price impacts of input-substitution. The price changes computed by these models were combined with consumption data specified per age group of main earner to calculate the purchasing power impacts for the elderly using the Consumer Price Index.

Although the overall impacts on the purchasing power of elderly in the Netherlands remained relatively unaffected in the different scenarios, carbon taxes can still pose a risk to the Dutch elderly. In particular, their ability to afford essential expenses would be threatened, such expenses on electricity. Given the limited disposable income, large expenditures on electricity, and existing issues with purchasing power for the elderly in the Netherlands, carbon taxation could increase energy poverty among Dutch elderly. Due to differences in their total income and consumption pattern, elderly above 75 are more at risk than elderly between 65 and 75 and other age groups.

Moreover, the results also point out the difficulty of taxing all emissions of a trade-oriented economy like the Netherlands, since domestic carbon taxing will not be able to cover displaced emissions. Lastly, this thesis confirmed that the conventional Leontief price model tends to overestimate price impacts due to the lack of input-substitution in the model. The flexible cost-push model showed systematically lower outcomes. Yet, at the same time, this thesis also highlighted that in its current form the flexible cost-push model is still somewhat restricted in its ability to account for input-substitution. Therefore, several possibilities for further development of the flexible model are required to improve its empirical value.

This thesis made a valuable contribution to the limited recent literature about flexible IO model by using and expanding on the flexible cost-push model proposed by the Dutch

National Bank. To this author's best knowledge, the flexible cost-push model model had not been empirically tested since its development in 2018. Moreover, in identifying potential distributional impact of carbon taxing for elderly in the Netherlands, this thesis once again confirms the importance of explicitly considering the consumption pattern in determining vulnerability to carbon taxing of specific groups. Therefore, this thesis underlines the importance of balancing environmental and social sustainability for the design of truly sustainable carbon taxes.

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A

Detailed information on carbon pricing schemes

There are several different forms of carbon taxing. Firstly, consumption taxes on emission-intensive goods are based on the carbon footprint of the product from production to consumption and is incorporated in the price paid by the final consumer (Grubb et al., 2022; Sumner et al., 2011). Alternatively, a carbon-added tax puts a price on a product's gross-added carbon and taxes the CO2 emitted in each production step. The tax's value reflects the total carbon costs of a product's total life cycle (de Bruyn et al., 2015; McLure Jr, 2010). Thirdly, a carbon extraction tax is levied when fossil fuels are extracted and imported (Hardisty et al., 2019). More recently, border carbon adjustments have been introduced, which aim to streamline the carbon price of domestic and foreign produce. Goods that are imported from other countries are subjected to a carbon price with the same height as that of domestic produce. This tax internalizes the emissions embedded in the import and can be implemented as a tax, but also as an obligation to buy an allowance (Mehling et al., 2019). Alternatively to carbon taxes, there are emissions trading systems (ETS), which are 'cap and trade' systems. The maximum number of GHG emissions of economic sectors is capped and this number is translated into carbon allowances that can be purchased and traded on a carbon market. The number of allowances is lowered every year to make the total GHG emissions decrease over time (European Commission, n.d.-b; Martin et al., 2014). ETS are highly influential. In 2022, ETS covered more emissions that carbon taxes (World Bank, 2023). Table A.1 compares the five different carbon pricing schemes discussed here.

Table A.1: Overview of different carbon pricing schemes.

Carbon tax	*Tax base*	*Tax rate*	*Where is it levied?*	*Source*
Carbon consumption tax	Consumption of emission-intensive goods	Dependent on carbon footprint of good (e.g., €/ton of CO2)	At final consumption	*Grubb et al. (2022) and Sumner et al. (2011)*
Carbon Added Tax	The gross added carbon of total production process	A fixed tax per kilogram of CO2-equivalent emitted.	At every production step & final consumption	*de Bruyn et al. (2015) and McLure Jr (2010)*
Carbon border adjustment (as a tax)	Difference in carbon prices between countries	Dependent on differences between carbon prices and emissions embeded in import.	When product is imported	*Grubb et al. (2022) and Mehling et al. (2019)*
Extraction carbon tax	Extraction and imports of fossil fuels	Dependent on carbon footprint of good (e.g., €/ton of CO2)	At the fossil fuel producers & fossil fuel importers.	*Hardisty et al. (2019)*
Emission trading systems	Permitted amount of GHG by certain economic sectors	Dependent on total number of emission allowances.	When emission allowances are bought on carbon market	*European Commission (n.d.-b) and Martin et al. (2014)*

B

Supplementary Information Methods

B.1. Online material

This Appendix includes supporting information for the research methods used in this thesis. Some of this material could not be included in written form and can be obtained via https://github.com/Lvangeene/thesis. This online material consists of:

1. The Python code used to run the input-output analysis, calculate the Consumer Price Index, and to do the sensitivity analysis.
2. The IO data and CO_2-accounts used in this thesis.
3. The concordance table used to align the FIGARO Input-Output Data and the CBS consumption data.
4. The elasticities of substitution used for this thesis.

The input-output data and CO_2-accounts used in this thesis (2023 edition of FIGARO) for the year 2015 can also be obtained freely from **FIGARO's website**.

B.2. Other material

B.2.1. Consumption patterns per age group of main earner (2015)

Table B.1: The consumption patterns for different age groups of main earners in the Netherlands in 2015 in percentage (%) of total disposable income.

Expenditure Category	**up to 25 year**	**25 to 35 year**	**35 to 45 year**	**45 to 55 year**	**55 to 65 year**	**65 to 75 year**	**75 year and older**
Food	8.4	8.7	9.9	10.4	9.8	10.1	10.7
Non-alcoholic beverages	1.2	1.1	1.2	1.3	1.1	1.1	1
Alcoholic beverages	1.3	1	1	1.2	1.7	1.9	1.5
Tobacco	1.7	1.5	1.7	1.5	1.8	1.7	1.7
Clothing	4	4.2	4.3	4.1	3.2	3.2	3

Footwear	1	1.1	1.3	1.1	0.8	0.7	0.7
Actual rentals for housing	21.6	12.7	6.8	5.2	6	8.6	14.2
Imputed rentals for housing	3	11.7	15.4	15.5	16.9	17	15
Maintenance of housing	0.5	0.6	0.6	0.5	0.5	0.5	0.3
Costs of utilities	3.8	3.2	2.8	2.5	2.7	3.4	4
Electricity, gas, and other fuels	5.3	4.5	4.4	4.5	4.7	5	5.4
Furniture and furnishings	1.1	2.1	2	1.8	2	2.6	3.1
Household textiles	0.3	0.4	0.6	0.6	0.4	0.5	1.1
Household appliances	0.3	0.7	0.7	0.7	0.7	0.7	0.5
Household utensils	0.4	0.5	0.4	0.4	0.4	0.4	0.5
Tools for house/-garden	0.4	0.4	0.5	0.5	0.6	0.6	0.6
Household maintenance services	0.5	0.9	1.2	1.1	1.1	1.3	1.6
Medicines and health products	0.7	0.6	0.6	0.7	1.1	1.2	1.3
Outpatient care services	0.2	0.4	0.6	0.5	0.6	0.5	0.7
Inpatient care services	0	0	0	0	0	0	0
Purchase of vehicles	3.1	3.9	4.3	4.9	5.5	4.7	1.7
Operation of personal vehicles	4.6	7.3	7.3	7.8	7.3	5.4	4.1
Passenger transport services	3.2	2.1	1.4	1.6	1.4	1.3	1.3
Postal and parcel services	0.2	0.1	0.1	0.1	0.1	0.1	0.2
Telephone equipment	0.4	0.3	0.3	0.3	0.2	0.2	0.3
Telephone services	3.2	3.6	2.9	3	2.9	2.8	2.9
Audio and photographic equipment	1.7	0.9	1.2	1.4	1.1	1	0.8

Recreational goods	0	0.4	0.6	0.4	0.6	0.4	0.1
Toys, garden products, and pets	1.3	1.7	1.9	1.8	1.9	1.7	1.5
Recreational services	3.8	3.4	4.1	4.1	3.6	3.5	2.9
Newspapers, books, and stationery	1.4	0.7	0.9	1.1	1.2	1.5	1.7
Package holidays	1	0.9	0.9	1.5	1.6	1.6	1.5
Primary education	0	0	0.1	0.1	0	0	0
Secondary education	0	0	0	0.1	0	0	0
Tertiary education	7.1	1	0.5	1.4	0.6	0.1	0
Education not defined by level	0.3	0.3	0.3	0.5	0.3	0.2	0.1
Catering services	5.2	5.2	4.4	4.3	4.1	4	3.6
Accommodation services	2.1	1.7	1.9	1.7	1.5	1.3	0.8
Personal care	1.8	2.2	2.3	2.1	2	2	2.1
Other personal effects	0.3	0.4	0.4	0.4	0.4	0.3	0.3
Social protection	0	1.4	1.9	0.2	0	0	0.1
Insurance	1.7	2.6	3	3.3	3.6	3.1	2.9
Financial services, n.e.c.	0.5	0.8	0.7	1	0.8	0.7	0.6
Other services, n.e.c.	0.4	0.6	0.6	0.6	0.8	0.9	1.2
Sewage charges	0.4	0.4	0.4	0.3	0.3	0.4	0.4
Motor vehicle tax	0.5	1.3	1.4	1.5	1.5	1.4	1.1
Dog tax	0	0	0	0	0	0	0
Charitable donations	0.1	0.3	0.3	0.3	0.5	0.6	0.8

B.2.2. Elasticities of Substitution by Bun et al. (2018)

Table B.2: Elasticities of substitution used in this thesis for the FIGARO sectors alongside the original sectors and elasticities used by Hebbink et al. (2018)

Figaro Sector	Original sector in Bun et al. (2018)	Elasticity by Bun et al. (2018)	Elasticity used in model
Crop and animal production, hunting and related service activities	Agriculture and forestry	0.323	0.323
Forestry and logging	Agriculture and forestry	0.323	0.323
Fishing and aquaculture	*Taken the average of all sectors, because no comparable industries	0.249	0.249
Mining and quarrying	Mining and quarrying	0.266	0.266
Manufacture of food products; beverages and tobacco products	Food, drinks, and tobacco	0.123	0.123
Manufacture of textiles, wearing apparel, leather and related products	Textile, clothing	0.499	0.499
Manufacture of wood and of products of wood and cork	Wood and paper	-0.183	**0**
Manufacture of paper and paper products	Wood and paper	-0.183	**0**
Printing and reproduction of recorded media	Other industry and repair	0.476	0.476
Manufacture of coke and refined petroleum products	Oil industry	-0.034	**0**
Manufacture of chemicals and chemical products	Chemical Industry	-0.166	**0**
Manufacture of basic pharmaceutical products and pharmaceutical preparations	Pharmaceutical Industry	-0.067	**0**
Manufacture of rubber and plastic products	Rubber, plastic, and other non-metallic mineral products	0.637	0.637
Manufacture of other non-metallic mineral products	Rubber, plastic, and other non-metallic mineral products	0.637	0.637
Manufacture of basic metals	Basic metals	0.023	0.023
Manufacture of fabricated metal products, except machinery and equipment	Basic metals	0.023	0.023

Manufacture of computer, electronic and optical products	Computer, electronic and optical products	-0.38	**0**
Manufacture of electrical equipment	Electrical equipment	0.232	0.232
Manufacture of machinery and equipment n.e.c.	Machine Industry	0.038	0.038
Manufacture of motor vehicles, trailers and semi-trailers	Other industry and repair	0.476	0.476
Manufacture of other transport equipment	Other industry and repair	0.476	0.476
Manufacture of furniture; other manufacturing	Other industry and repair	0.476	0.476
Repair and installation of machinery and equipment	Other industry and repair	0.476	0.476
Electricity, gas, steam and air conditioning supply	Energy companies	0.16	0.16
Water collection, treatment and supply	Water and sewage	-0.037	**0**
Sewerage, waste management, remediation activities	Water and sewage	-0.037	**0**
Construction	Construction	0.163	0.163
Wholesale and retail trade and repair of motor vehicles and motorcycles	Trade and repair	0.242	0.242
Wholesale trade, except of motor vehicles and motorcycles	Trade and repair	0.242	0.242
Retail trade, except of motor vehicles and motorcycles	Trade and repair	0.242	0.242
Land transport and transport via pipelines	Transportation	0.498	0.498
Water transport	Transportation	0.498	0.498
Air transport	Transportation	0.498	0.498
Warehousing and support activities for transportation	Transportation	0.498	0.498
Postal and courier activities	Transportation	0.498	0.498
Accommodation and food service activities	Culture, sports, and recreation	-0.007	**0**
Publishing activities	Information and communication	1.575	1.575
Motion picture, video, television programme production;	Information and communication	1.575	1.575

Telecommunications	Information and communication	1.575	1.575
Computer programming, consultancy, and information service activities	Information and communication	1.575	1.575
Financial service activities, except insurance and pension funding	Financial services	0.423	0.423
Insurance, reinsurance and pension funding, except compulsory social security	Financial services	0.423	0.423
Activities auxiliary to financial services and insurance activities	Administrative and support services	0.38	0.38
Real estate activities	Real estate services	-0.078	**0**
Legal and accounting activities;	Professional, scientific and technical activities	0.445	0.445
Architectural and engineering activities; technical testing and analysis	Professional, scientific and technical activities	0.445	0.445
Scientific research and development	Professional, scientific and technical activities	0.445	0.445
Advertising and market research	Professional, scientific and technical activities	0.445	0.445
Other professional, scientific and technical activities; veterinary activities	Professional, scientific and technical activities	0.445	0.445
Rental and leasing activities	Real estate services	-0.078	**0**
Employment activities	Administrative and support services	0.38	0.38
Travel agency, tour operator reservation service and related activities	Administrative and support services	0.38	0.38
Security and investigation, service and landscape, office administrative and support activities	Public administration and defense	0.407	0.407
Public administration and defence; compulsory social security	Public administration and defense	0.407	0.407
Education	Education	0.051	0.051
Human health activities	Healthcare	-0.075	**0**

Residential care activities and social work activities without accommodation	Healthcare	-0.075	0
Creative, arts and entertainment activities;	Culture, sports, and recreation	-0.007	0
Sports activities and amusement and recreation activities	Culture, sports, and recreation	-0.007	0
Activities of membership organisations	Other services	0.31	0.31
Repair of computers and personal and household goods	Other services	0.31	0.31
Other personal service activities	Other services	0.31	0.31
Activities of households as employers;	Other services	0.31	0.31
Activities of extraterritorial organisations and bodies	Other services	0.31	0.31

C

Supplementary Information Results

This Appendix includes supplementary information about the results of this thesis that could not be included in the main text.

C.1. Sectoral price changes following global tax

Table C.1: Sectoral price changes in percentages (%) following the a global carbon tax.

Sector	Price change (%)		
	€50 per tCO_2	**€150 per tCO_2**	**€250 per tCO_2**
Manufacture of basic metals	14.6	43.9	73.2
Manufacture of other non-metallic mineral products	8.3	24.8	41.3
Manufacture of coke and refined petroleum products	8.2	24.6	41.0
Electricity, gas, steam and air conditioning supply	7.8	23.4	38.9
Manufacture of chemicals and chemical products	5.6	16.9	28.1
Manufacture of fabricated metal products	4.3	12.9	21.4
Postal and courier activities	4.0	12.0	20.0
Other professional, scientific, veterinary activities	4.0	11.9	19.8
Air transport	3.5	10.6	17.7
Manufacture of basic pharmaceuticals	3.3	10.0	16.7

C.2. Input substitution & the Dutch Energy tax

Table C.2: The relative influence of input-substitution on the changes in Consumer Price Index (%) for a Dutch energy tax under different carbon prices

Carbon price		Between 35 and 45	Between 65 and 75	75 years and older
€50/tCO2	CPI *(without substitution)*	0.33	0.36	0.38
	CPI *(with substitution)*	0.28	0.30	0.32
	Relative influence (%)	-15	-16	-17
€150/tCO2	CPI *(without substitution)*	0.99	1.07	1.13
	CPI *(with substitution)*	0.82	0.90	0.95
	Relative influence (%)	-17	-16	-16
€250/tCO2	CPI *(without substitution)*	1.65	1.79	1.88
	CPI *(with substitution)*	1.36	1.49	1.57
	Relative influence (%)	-18	-17	-16