Quantitative Analyses of the Dutch Low-Carbon Bioeconomy

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MSc Thesis Agricultural Economics and Rural Policy

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Foreword

This master thesis marks the final chapter of the master program Biobased Sciences at Wageningen University and Research (WUR). The specialisation Biobased and Circular Economy has inspired me on a wide range of topics. As such, the transition towards the low-carbon bioeconomy in the Netherlands seemed a highly interesting topic to analyse. In general, I am fascinated on what drives structural change and how we can stimulate sustainable development. As the world moves further into the digital age, collecting data has been integrated into our society. This enabled me to model and analyse human behaviour within the transition towards the low-carbon bioeconomy.

I would like to offer a special thanks to dr. ir. Jack Peerlings for supervising my thesis, his useful criticism and the continuous encouragement to dig deeper. During the thesis meetings, I got answers to all my questions but got challenged by new ideas at the same time. Since flexibility is required for carrying out a master thesis and an internship simultaneously, I would like to thank my internship mentor Mark van Eert as well. Also, I could not have achieved the current level of the thesis without the strong support from my family and friends. Especially my parents inspired me on sustainable life sciences and related topics in general.

Abstract

The bioeconomy potential is a highly discussed topic among policymakers in the global political field. The low-carbon bioeconomy based on renewable energy resources, as a mixture of wind-, solar- and bioenergy, enables future’s elimination of the highly polluting fossil fuels. The Netherlands recognizes the bioeconomy potential, as it implies economic growth accompanying climate change mitigation. Restructuring the current production regime of products and energy is challenging and time consuming but is expected to pay-off. Due to its high complexity, policymakers demand for appropriate tools that help deepening the understanding of human behaviour. This study provides a unique insight in the Dutch low-carbon bioeconomy by applying an Input-Output (IO) model and an Applied General Equilibrium (AGE) model. The IO model measures the current economic and environmental size of the Dutch bioeconomy as a base line. Whereafter supply and use tables are used for more detailed information on how to treat non-renewable and renewable energy separately. To address the complex road from the present to a future system, i.e. the transition towards a low-carbon bioeconomy, an AGE model is included. The results of the AGE model explain how an external shock, i.e. the introduction of an energy taxation policy, affects the economy as a whole. In conclusion, the results add to the political discussion on the low-carbon bioeconomy potential.

Keywords: *Bioeconomy; Technological Change; Renewable Energy; Input-Output Model; Applied General Equilibrium Model*

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1. Introduction

A bioeconomy can be defined in different ways, referring either to fossil material replacement by biomass, to biotechnology in life sciences, or to solving global problems using biotechnological advances (Pfau et al., 2014). The European Commission (2012) has defined a bioeconomy as “the production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy”. The Netherlands as a leader in green resources has recognized the potentials of the bioeconomy (Rijksoverheid, 2018).

Increased human population and wealth put pressure on the current economic system and have caused emissions to rise over time (Philip, 2017). Especially, depleting fossil resources and the dramatic negative effects of their use on the climate are problematic. Therefore, the main motivation for driving the bioeconomy are its contribution to sustainability both from an environmental, social and economic perspective (McCormick & Kautto, 2013). The bioeconomy is expected to reduce global greenhouse gas (GHG) emissions and national fossil resource dependence, to improve natural resource management and food security, and to stimulate job creation due to new non-food biomass-based markets (European Commission, 2012; McCormick & Kautto, 2013; Rijksoverheid, 2018; IEA, 2020). According to Philip (2017), a bioeconomy is an economy which potentially addresses economic growth and social wellbeing, while at the same time mitigating climate change.

The bioenergy sector plays an important role in the bioeconomy (McCormick & Kautto, 2013). Bioenergy refers to renewable energy originating from biological resources, enabling fossil fuel replacement. Mitigating GHG emissions and reducing global warming can be addressed by using renewable energy technologies (Panwar et al., 2011). As decarbonizing global energy systems is one of the most challenging global goals, a renewable energy sector has increasingly gained interest over time (Teske et al., 2018). In order to produce energy from renewable sources, both sunlight, wind and biomass can be used. The mixture of solar-, wind- and bioenergy provides opportunities for optimal use of clean energy sources (Panwar et al., 2011), fostering the transition towards a low-carbon bioeconomy.

Biorefineries are important for the bioeconomy (Philip, 2017). More specifically, biorefineries are necessary for bioenergy production as biorefineries refer to “sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)” (IEA, 2008). Biomass covers all organic material coming from microorganisms, animals and plants. Wood and shrubs, agricultural crops, post-consumer waste and by-products can be used for biomass-based production (Lewandowski, 2015).

Technically and politically, several setbacks and obstacles are expected in the transition towards a bioeconomy (Philip, 2017). Limited availability of inputs coming from biomass can be seen as one of the main challenges for a bioeconomy (Lewandowski, 2015). Other concerns are on water usage, nutrient supply for crop growth, and land-use change impacts in general (Rosengrant et al., 2013; Lewandowski, 2015). According to Philip (2017), the biggest conundrum for the bioeconomy is finding the optimal balance between competing agricultural and industrial needs. Due to food priority, biomass cannot fully be used for industrial production in an ethical way (Pfau et al., 2014; Lewandowski, 2015; Philip, 2017). In order to overcome points of debate, first generation biofuels coming from food crops can be replaced by more advanced fuels or other sources for renewable energy (McCormick & Kautto, 2013).

The European Union has formulated challenging goals regarding renewable energy systems (RETs), as a matter of course leading to related commitments from the Dutch government (Ministry of Economic Affairs, 2016; PBL, 2019). National climate- and energy policy is consequently faced with a 49 percent GHG emission reduction within the period 1990-2030. Meaning the amount of reduced emissions to be doubled in upcoming ten years compared to the past thirty years (PBL, 2019). The report of Ministry of Economic Affairs (2016) has stated that the current Dutch economic structure has to change in order to realise low-carbon energy source integration. Understanding structural technological change can however be extremely difficult (Angenendt et al., 2018).

International organisations and governmental bodies such as Organisation for Economic Cooperation and Development (OECD), the United States of America (USA) and the European Union (EU), have published policy agendas driving bioeconomy development (McCormick & Kautto, 2013; German Bioeconomy Council, 2015). Moreover, the general acknowledgement of a and subsidy programs worldwide have been stimulating its development bioeconomy (Lewandowski, 2015). However, realizing the fuel petrochemical economies of scale for biorefineries is still required (Philip, 2017). According to an analysis of Angenendt et al. (2018), more attention should be paid to instruments and tools to depict possible transition paths as well. In order to realize informed policy decision-making, it is further useful to measure the environmental and economic potential of the Dutch bioeconomy and how its potential can be affected (Heijman & Schepman, 2018). In conclusion, the future is multi-faced and complex, and policymakers need a better understanding (Philip, 2017).

Research objective and research questions

The low-carbon bioeconomy based on renewable energy resources, as a mixture of wind-, solar- and bioenergy, requires structural change. Restructuring the current production regime of products and energy is challenging and time consuming but is expected to pay-off (Philip, 2017). Quantification of the bioeconomy enables clarification of elusive structural relations, looking inside the economic mechanism (Klein et al., 2004). The objective of this research is therefore: ‘To assess fossil fuel replacement by renewable (biological) energy sources, in order to measure the economic and environmental potential of the Dutch bioeconomy’.

The research objective can stepwise be addressed by answering the following questions:

1. What is the current size of the Dutch bioeconomy?
2. How is the Dutch bioeconomy affected when fossil fuels are replaced by a mix of bio-, wind- and solar energy?
3. How can the transition towards the bioeconomy be stimulated using economic instruments?

Methodology

Input-output (IO) modelling is used in this study as a quantitative method for the measurement of the Dutch bioeconomy (i.e. research question 1). IO analysis is a useful widespread tool for economic analysis, showing the interconnectedness of industries (Zhou et al., 1997; Miller & Blair, 2009). The IO tables show outputs produced by industries, and inputs used by industries and final users such as consumers, government and exports (Miller & Blair, 2009). The system boundary of an IO analysis is often determined by a geographical boundary (Miller & Blair, 2009; Zhou et al., 1997). The boundary in this study can be defined as the Dutch economic system including inter-industry transactions, income creation and spending, factor demand, and imports and exports. Data of 2018 is used, provided by Statistics Netherlands (CBS, 2020).

The principles of IO modelling originates from an analytical framework developed by Professor Wassily Leontief in the late 1930s (as stated in Miller & Blair, 2009). Traditional IO modelling assumes output as a linear function of the final demand (Duchin & Steenge, 2009). An important controversy in IO modelling are its microeconomic foundations, while dealing with a macroeconomic analysis (Cabrer et al., 1991). The concept of IO modelling is simple, transparent, and simultaneously including a high degree of sectorial detail (Zhang & Folmer, 1998; Duchin & Steenge, 2009). The original system of linear equations has been extended for different purposes, explained by different studies of Leontief (1970), Miller & Blair (2009), Ten Raa (2009), and van de Pas (2015) among others. Underlying advantages, assumptions and limitations are known and well-documented (Zhou et al., 1997).

To answer research question 2, different ways of producing energy are included in the IO table. So, supposing that energy is produced by the present energy production industry that uses a certain mix of inputs, an alternative industry is assumed using a different mix of inputs (i.e. using less or no fossil fuels). Including alternative technologies affects the way a bioeconomy is measured and how it can be expressed (Loizou et al., 2019). To identify renewable energy systems as an alternative technology, supply and use tables are applied. New and old sizes are compared to determine the effect of a shift towards a bioeconomy.

Research question 2 describes two alternative systems but does not address the road from the present to a future system. Economic instruments as taxes or subsidies can help to transform the economy. The use of economic instruments results in relative price changes that lead to input substitution effects e.g.

reducing the use of fossil fuel energy production (Bun, 2018). However, input substitution in an IO model is not possible because of the use of Leontief production functions. To analyse the effects of taxes and subsidies the Leontief production function has to be replaced by a more flexible production structure that allows for price-induced substitution (Klijs et al., 2015; Bun, 2018). One possibility is the use of Constant Elasticity of Substitution (CES) functions (Klijs et al., 2015). Properties of CES functions are explained by Varian (1984) and Punt et al. (2003). Applied General Equilibrium (AGE) models enable the inclusion of CES functions. Over time, AGE models have led to varying optimism about its usefulness. The model provides insights on the allocation of resources and equilibrium prices, according to demand and supply interaction. It is seen as an interesting tool for policymakers in order to deal with important policy issues (Shoven & Whalley, 1984).

The second, third and fourth chapter provides insights on the first, second and third research question respectively. To all, a section on theory, data application, and the simulation is included. The fifth chapter combines the first four chapters, provides answers to the research questions and makes concluding remarks. Furthermore, the last chapter provides a brief discussion including three main elements of improvement and recommendations for further research.

2. The Dutch bioeconomy

Input-output (IO) modelling is used to measure the economic and environmental size of the bioeconomy. IO modelling is discussed in section 2.1. IO tables provide the data for IO models. The IO table used in this research is discussed in section 2.2, together with other datasets used for simulation. The last section specifies scenarios and discusses their outcomes.

2.1 Theory

IO modelling is based on the mathematical model of Leontief (Miller & Blair, 2009). Consider an economy with n industries. Each industry i distributes its product as an intermediate input or as final demand directly:

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + f_i \qquad (2.1)$$

Where: x_i is total output of industry i, f_i is the total final demand (i.e. household consumption, public demand, exports and investment demand) of industry i's product, and z_{ij} represents inter-industry sales by industry i to all industries j. Let:

$$\boldsymbol{x} = \begin{matrix} x_1 \\ \vdots \\ x_n \end{matrix} \qquad \boldsymbol{Z} = \begin{matrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{matrix} \qquad \boldsymbol{f} = \begin{matrix} f_1 \\ \vdots \\ f_n \end{matrix} \qquad (2.2)$$

The following matrix notation summarizes 2.1 and 2.2:

$$\boldsymbol{x} = \boldsymbol{Z} + \boldsymbol{f} \qquad (2.3)$$

Upper-case bold letter represents matrices, while lower-case bold letters (column) vectors. The technical coefficients show the relationship between an industries' output and its input (Hebbink et al., 2018). Technical coefficients are calculated as:

$$a_{ij} = \frac{z_{ij}}{x_j} \qquad (2.4)$$

According to Ten Raa (2009), the A matrix is the centre-piece of an IO-analysis. The A matrix represents the technical coefficients, describing the commodity inputs per units of commodity outputs:

$$\boldsymbol{A} = \begin{matrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{matrix} \qquad (2.5)$$

Leontief's production function, assuming constant returns of scale, is given by:

$$x_j = min\left\{\frac{z_{ij}}{a_{1j}}, \ldots, \frac{z_{nj}}{a_{nj}}\right\} \qquad (2.6)$$

Leontief's production function represents fixed input proportions, meaning that equation 2.1 can be rewritten ($z_{ij} = a_{ij}x_j$):

$$x_j = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n + f_i \quad (2.7)$$

Rewriting 2.7 as a matrix expression gives:

$$\boldsymbol{X} = \boldsymbol{Ax} + \boldsymbol{f} \quad (2.8)$$

$$(\boldsymbol{I} - \boldsymbol{A})\boldsymbol{x} = \boldsymbol{f} \quad (2.9)$$

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} = \boldsymbol{Lf} \quad (2.10)$$

Where $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse and I the identity matrix.

The application of the abovementioned steps, including the use of the Leontief inverse, enables extension of the model. More specifically, assuming a fixed ratio between value-added, import, employment or emissions of a certain pollutant and output, value-added, imports, employment and pollution related to a certain level of final demand can be determined (Loizou et al., 2019).

Due to fixed ratios between value-added and output, the following equation holds (Miller & Blair, 2009):

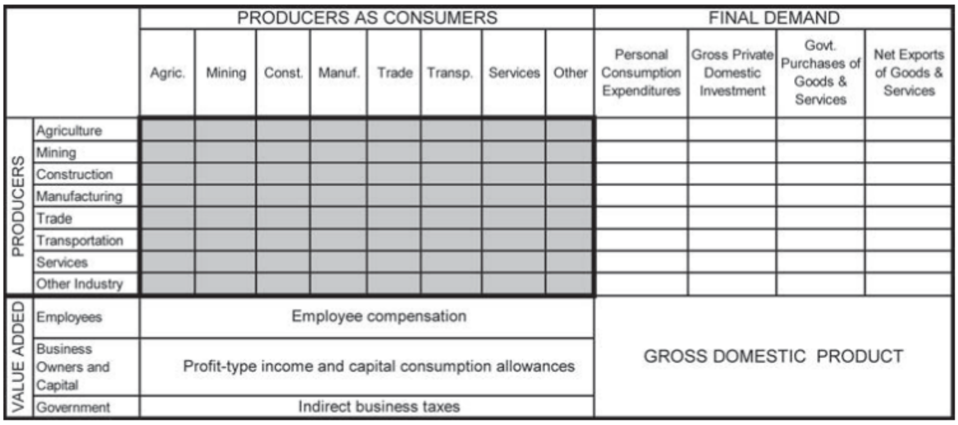
$$v = \hat{v}(I - A)^{-1}f = \hat{v}x \quad (2.11)$$

Where $\hat{v}$ is the diagonal matrix with IO-coefficients of the factor input use (= value-added). Equation 2.11 implies that knowing output enables determination of factor inputs. Similar equations hold for imports, employment and emissions of pollutants.

2.2 Data

The general structure of an IO table is summarized by Miller & Blair (2009) and shown in figure 2.1, including intermediary demand and supply, value-added, final demand and Gross Domestic Product (GDP). Rows (horizontally) describe the distribution of a producer's output throughout the economy, while columns (vertically) represent inputs required for the production of an industries' product (Miller & Blair, 2009).

IO tables of the Dutch economy are most recently published for 2018 by Statistics Netherlands (CBS, 2020). The structure of the dataset of Statistics Netherlands slightly differs each year. Intermediary demand and supply are in 2018 represented by 81 different industries (appendix I). Imports and taxes are separately measured and presented in different rows (see appendix I). Industries of main importance for the bioeconomy, based on Loizou et al. (2019), are e.g. crop, animal production, hunting and related activities (S0), forestry and logging (S1), fishing and aquaculture (S2), and manufacture of food products (S6), beverages (S7), tobacco products (S8), textiles, wearing appeal and leather (S9), wood and products (S10), paper and paper products (S11), chemicals and chemical products (S14), pharmaceutical products (S15) and rubber and plastics (S16).



		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business Owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 2.1: Matrix framework of inter-industry exchanges - IO table (Miller & Blair, 2009)

The Dutch energy industry is still dominated by fossil fuels. Gas and coal are main inputs for the energy supply and electricity generation. In 2018, the total primary energy supply was produced using 42% of natural gas, 37% of oil, 11% of coal, 5% of biofuels and waste, and other remaining small shares of nuclear, wind, solar, geothermal and hydropower. The Netherlands is a gas exporter due to gas production in Groningen. However, oil needs to be imported due to excess domestic demand (EIA, 2020). Electricity, gas, steam and air conditioning supply (S28) refers to the supply of energy, and is therefore an important industry of the Dutch IO table for this study.

The Dutch IO table of 2018 is a Monetary Input-Output Table (MIOT), using current (or nominal) prices in millions of euro. Prices are basic prices showing the value of a good the seller receives plus the transport margins. In the IO table the buyer has to pay for indirect taxes, so the IO table includes separate rows to make row and column totals equal.

Value-added is the reward for primary inputs as labour and capital (Hebbink et al., 2018), it is residual income. Value-added includes wages and salaries, employers' social contribution (together reward for the factor input labour) and operating surplus which is the reward for the factor input capital (UN, 2018).

Final demand is in the Dutch 2018 IO table not a vector but a matrix, including different types of final demand. The total of consumer demand, government spending, investments (capital formation), and foreign trade (export) equals the final demand. In IO models total production is a function of final demand, whereas final demand can be treated as an independent variable (Reyes & Mendoza, 2013). For developed countries, consumer demand contributes commonly for the largest part to final demand (Miller & Blair, 2009). The IO table of 2018 shows the same result for the Netherlands in 2018.

Cost, Insurance and Freight prices (CIF) differ from Free On Board (FOB) prices. CIF prices include shipment, insurance and transaction costs. The included Cif/fob correction in the Dutch 2018 IO table means that there is a correction for the difference between imports of goods, valued at CIF prices, compared to imports of goods, valued at FOB prices (UN, 2018).

The size of the bioeconomy can also be expressed in environmental terms. For environmental-economic modelling, the monetary value needs to change into a physical value (Idenburg & Wilting, 2000; Hoekstra & van den Bergh, 2006). Those tables are also called Physical Input-Output Tables (PIOTs), which include e.g. greenhouse gas emissions and fossil fuel depletion (Hoekstra & van den Bergh, 2006).

The primary data used for emissions to the air, provided by Statistics Netherlands (CBS, 2020 b), does not apply rules on classification and accounting that resembles with underlying principles of IO tables. Hence, data needs to be adjusted. To integrate environmental accounts in IO tables, the technical environmental coefficients need to be calculated by industry. The variables are related to, and assumed to be proportional to the output, as they are calculated in a similar way as the input coefficients (equation 2.4). Environmental coefficients show emissions per unit of output per industry, in physical units per monetary unit (EEA, 2013). The available data of air emission accounts are associated with domestic industries only (i.e. no imports and exports). To normalise for imports and exports, emission intensities for different industries in different regions have to be calculated (Schoenaker & Delahaye, 2017). This, however, lies outside the scope of this research.

In order to deal with empty columns or rows, the following industries have been aggregated: imputed rents owner-occupied dwellings (S53), gambling and betting activities (S74), other personal service activities (S78), activities of households as employers of domestic personnel (S79), and goods and services not elsewhere classified (n.e.c.) (S80). Industries are newly labelled from A0-A76, see appendix II.

To measure the size of the bioeconomy in environmental terms, the Dutch 2018 IO table needs to be matched with the dataset of emissions to the air (provided by CBS 2020 a; CBS 2020 b) by industrial aggregation. Appendix II shows how industries are aggregated. The ‘new’ industries are labelled using E0 to E36. E36 (including S53, S74, S78, S79, S80) is classified as n.e.c., while classifications of other industries have remained the same.

The final demand columns of final consumption expenditure of households (F2) and final consumption expenditure NPIs serving households (F3), are consolidated in order to simplify the analysis. Social transfers (F4), other individual final consumption of general government (F5) and collective final consumption of general government (F6) refer to final demand of the Dutch government, which means that those are aggregated as well.

2.3 Scenarios and results

Scenarios

For the measurement of the Dutch bioeconomy, agriculture, forestry, fishery and aquaculture (E0, E1 and E2) are assumed to produce primary biobased products. These activities are natural-resource based and provide biomass directly as an input to other industries or as final demand. Further processing of biobased products is done by manufacturing industries, e.g. manufacture of food, wood and paper, and other industries that make novel use of biomass, e.g. chemical, rubber and plastic products (Heijman & Schepman, 2019; Kardung et al., 2021). Industries that to some extent use biobased inputs are only to some extent part of the bioeconomy, e.g. biobased chemicals from total chemical activities and pellet production from wood products. The share of biobased products being used in a certain industry determines the share of that specific industry to the bioeconomy. The study of Kardung et al. (2021) also includes service-related industries, as they use processed biological sources. However, in order to prevent overestimation, service-related activities are not counted as bioeconomy industries within this research.

Two scenarios are assumed for the measurement of the size of the bioeconomy. The first scenario includes E0, E1 and E2 as core bioeconomy industries. Other industries, that are indirectly linked to the bioeconomy, only partly contribute to the bioeconomy. The share of those industries is determined by the share of the use of core bioeconomy intermediate inputs in the total intermediate input use plus imports. This is given by the following equation:

$$f_i^* = \frac{z_{\mathrm{E0},j}+z_{\mathrm{E1},j}+z_{\mathrm{E3},j}}{y_j+m_j} * f_i \qquad (2.13)$$

Where f_i^* refers to the final demand for products from the bioeconomy for each industry i after adjusting for the bioeconomy share, all z refers to the intermediate demand for inputs from E0, E1 and E2 by each industry j, and y_j represents the total of intermediate inputs for each industry j. Note that i equals j. Table 2.1 represents the industries included, partly included and excluded. For core bioeconomy industries f has to be multiplied by 1, for industries without bioeconomic production f equals 0, and for industries with an indirect link to the bioeconomy the function for f is expressed by equation 2.13.

Table 2.1 – Inclusion or exclusion for scenario 1

	Core	**Indirect**	**No link**
Industry	E0, E1, E2	E4, E5, E6, E7, E9, E10, E11, E12	E3, E8, E13, E14, E15, E16, E17, E18, E19, E20, E21, E22, E23, E24, E25, E26, E27, E28, E29, E30, E31, E32, E33, E34, E35, E36
Share	1	f_i^*	0

The second scenario also includes the specific part of electricity, gas, steam and air conditioning supply (E21) that uses renewable energy sources for energy production, i.e. biomass, solar, and wind energy, to the core of the bioeconomy. According to Statistics Netherlands (CBS, 2020 c), a total of 114.5 billion kWh was produced in 2018 while 18.9 billion kWh came from renewable energy sources. For this reason, the ratio for the renewable energy industry (as partly coming from E21) equals 18.9/114.5 (0.165). As the value of the bioeconomy is now also determined by clean energy, equation 2.13 can be rewritten in:

$$f_i^{**} = \frac{z_{\mathrm{E0},j}+z_{\mathrm{E1},j}+z_{\mathrm{E2},j}+\frac{18.9}{114.5}*z_{\mathrm{E21},j}}{y_j+m_j} * f_i \qquad (2.14)$$

Table 2.2 represents scenario 2. For each industry that is indirectly linked to the bioeconomy the value of f can be expressed by equation 2.14. Note that f_i^{*} holds for scenario 1 and f_i^{**} holds for scenario 2.

Table 2.2 – Inclusion or exclusion for scenario 2

	Core		Indirect	No link
Industry	E0 E1 E2	E21	E4, E5, E6, E7, E9, E10, E11, E12	E3, E8, E13, E14, E15, E16, E17, E18, E19, E20, E22, E23, E24, E25, E26, E27, E28, E29, E30, E31, E32, E33, E34, E35, E36
Share	1	$\frac{18.9}{114.5}$	f_i^{**}	0

The share of electricity, gas, steam and air conditioning supply is determined by domestic electricity production. However, according to Statistics Netherlands (CBS, 2019 a) the share of renewable energy in gross final energy demand equalled 7.4 percent in 2018, which is substantially lower than the renewable energy share of total electricity production. Differences can be addressed by e.g. measurement techniques and/or trade of energy.

The size of the bioeconomy in environmental terms is for this study determined by the greenhouse gas (GHG) emissions carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). CO_2 emissions are related to fossil fuel combustion, while fertilized (manured) soils mostly contribute to the emission of N_2O, and CH_4 emissions are caused by farm and manure practices (RVO, 2016).

As the dataset on emissions to the air does not subdivide the agricultural industry in E0, E1 and E2 as the IO table does, the agricultural industry needs to be disaggregated. For disaggregation N_2O and CH_4 are fully addressed to industry E0, due to the application of manure to land and other farm practices. Meaning that N_2O and CH_4 emissions for industry E1 and E2 equal zero. However, CO_2 emissions are caused by all three agricultural industries E0, E1 and E2 due to fossil fuel combustion. The intermediary demand of industries E0, E1 and E2 for manufacture of coke and refined petroleum products (E9), and electricity, gas, steam and air conditioning supply (E21) determines how the agricultural industry is disaggregated. All three industries are assumed to emit CO_2 proportionally to the use of inputs from industry E9 and E21. For disaggregation the following formula is used:

$$CO2_i = CO2_{agriculture,forestry,fishery} * \frac{z_{i,\mathrm{E9}} + z_{i,\mathrm{E21}}}{\sum_{i=0}^{3} z_{i,\mathrm{E9}} + \sum_{i=0}^{3} z_{i,\mathrm{E21}}} \qquad (2.15)$$

Where $CO2_i$ refers to the emission of CO_2 for industries E0 (i=1), E1 (i=2) and E2 (i=3), $CO2_{\text{agriculture, forestry, fishery}}$ equals the amount of CO_2 emissions for the agricultural industry provided by Statistics Netherlands (CBS, 2020 e), $z_{i,\mathrm{E9}}$ and $z_{i,\mathrm{E21}}$ refers, respectively, to the use of coke and petroleum products (j=10) and energy inputs (j=22) required of industry i's product.

To calculate the size of the bioeconomy in economic and environmental terms, datasets for environmental pressures and employment are used (CBS, 2020 b; CBS, 2020 d). Technical IO-coefficients by industry are calculated (similar to equation 2.4), and equation 2.11 is used to link employment and emissions proportionally to the output of the bioeconomy. In this way, the data for environmental pressures (CBS, 2020 b) and employment (CBS, 2020 d) is coupled to the IO table, which originates from Statistics Netherlands (CBS, 2020).

Results

Table 2.3 shows the (relative) size of the bioeconomy in terms of value-added and employment. Final demand is exogenously determined, while value-added, gross output, employment and emissions are calculated using technical IO-coefficients. Noting that industries without a direct or indirect link to the bioeconomy still contribute to the size of the bioeconomy due to cascading effects (i.e. backward linkages). Employment is given in labour years, which is a measurement for the volume of labour in full-time equivalents (fte). For example, a full-time job equals 1 labour year, while two jobs of each 0.5 fte also equals 1 labour year.

Table 2.3 – Value-added (in million euros), employment (in labour years) and in % of the total economy

	Value-Added	**Employment**
Reference	692,632 (100%)	6,267 (100%)
Scenario 1	15,347.1 (2.2%)	109.1 (1.7%)
Scenario 2	16,453.3 (2.4%)	114.7 (1.8%)

Table 2.3 shows that the current share of the bioeconomy is relatively low. The share in scenario 2 is larger than in scenario 1 due to inclusion of renewable energy sources in the bioeconomy.

Table 2.4 – Emissions (in million kilograms) and in % of the total economy

	CO_2	**N_2O**	**CH_4**
Reference	157,722.0 (100%)	27.9 (100%)	573.5 (100%)
Scenario 1	9,291.8 (5.9%)	13.3 (47.7%)	334.9 (58.4%)
Scenario 2	13,819.0 (8.8%)	13.4 (47.9%)	335.5 (58.5%)

Table 2.4 summarizes the (relative) environmental pressure in terms of CO_2, N_2O and CH_4 for the total economy (reference), and the bioeconomy in scenario 1 and 2. The results show that the bioeconomy, as simulated in scenario 1 and 2, largely contributes to total N_2O and CH_4 emissions. The emissions attributed to the bioeconomy are in line with theory, since those are commonly attributed to the use of manure and other farm practices (RVO, 2016). CO_2 emissions, however, are mostly caused by other parts of the economy. Currently, total CO_2 emissions are only affected by the bioeconomy for around 6 to 9 percent (see table 2.4). The simulation does however not account for negative emissions caused by bioeconomy practices (e.g. sequestration by forests and soil), meaning that CO_2 emissions shown in table 2.4 are higher than the real environmental pressure of the bioeconomy.

Background information on calculating both the economic as the environmental is given in appendix A. The first table shows the structure of the document, i.e. where to find data on aggregation, calculation of technical IO-coefficients, the determination of the final demand and results sections for value-added, gross output, employment and environmental pressures.

3. Renewable energy systems

The goal of this chapter is to differentiate the production and consumption of renewable energy from non-renewable energy within the Dutch economy. This chapter focuses on the Dutch supply and use tables of 2018, which can be seen as the origin of the IO table. Section 3.1 shows the basic rule of integrating structural technological change into an IO table. How data is adapted in the supply and use table is discussed in section 3.2.

3.1 Theory

Integrating structural change in economic analysis is difficult. We are often unable to adequately assess potential effects of new technologies. The issue of measuring (sustainable) development is that it has a long-term dimension (Pan, 2006). Long-term structural change in human society is fundamentally driven by technical change (Rose, 1984; Pan, 2006). The transition towards the use of non-fossil energy sources can be seen as a long-term structural change to the society, driven by technical change.

To implement technological change in an economic system, production technology has to allow for structural changes in an economy or any part of it. Generally, integrating technological change results in a new technical coefficient matrix as the variables of the IO model, supply or use table are affected by a new or expanding industry. This means that equation 2.5 can be rewritten using the following matrix equation (Mutl, n.d.):

$$\boldsymbol{A}^{*} = \boldsymbol{A} + \boldsymbol{T} \qquad (3.1)$$

Where: **A*** refers to the new technical coefficient matrix and **T** represents the matrix of technological change. Equation 2.8 can also be rewritten into (Mutl, n.d.):

$$\boldsymbol{x}^{*} = \boldsymbol{A}^{*}\boldsymbol{x}^{*} + \boldsymbol{f} \qquad (3.2)$$

Where: **x*** denotes the output vector after implementing technological change in the model, and **f** refers to the vector final demand.

Issues concerning the implementation of technological change in an IO table have widely been discussed in literature (Domar, 1961; Rose, 1984; Pan, 2006). Two main issues are: 1) how to reflect technological change correctly using IO-coefficients, and; 2) the way technological change is related to the IO-structure.

Technological change can be incorporated in two ways, as a exogenous or endogenous variable. The economist Solow developed the classical exogenous growth theory, where economic growth is assumed to be exogenously determined by technological process. The endogenous growth theory, however, identifies that long-term growth is sustained by R&D, resulting in cumulative knowledge and positive externalities (Pan, 2006). Since this chapter does not focus on behaviour on R&D and other (positive) externalities, technological change is assumed to be an exogenous variable for further calculations.

3.2 Data

The production of renewable energy, i.e. energy coming from biomass, solar and wind sources, is mainly classified under industry 'electricity, gas, steam and air conditioning supply' (E21) in the Dutch aggregated IO table of the previous chapter. Disaggregation on product basis means closer process analysis of technological change (Rose, 1984). To disaggregate the energy industry and energy products, use and supply tables are used due to the increased level of detail. Supply and use tables relate products and industries, and give detailed information on interdependencies of production, the use of goods and services, production processes, and income generated (ADB, 2017). The use table represents the purchased goods and services (row) per industry (column), while the supply table shows what types of goods and services are produced by a certain industry. The use table includes value-added and final demand, while the supply table adds imports, product related taxes and subsidies, and trade and transport margins. In this study, the Dutch supply and use tables of 2018 in current prices are used.

For disaggregation of the energy industry into: 1) renewable electricity, steam and air conditioning supply, and 2) non-renewable electricity, gas, steam and air conditioning supply, the following equation is used:

$$X_E = X_N + X_R \qquad (3.3)$$

Where: X_E represents the supply or use of industry E21 (electricity, gas, steam and air conditioning supply), X_N refers to the supply or use coming from the conventional system of non-renewable energy only, and X_R to the new technology using renewable energy sources.

Since renewable energy systems have already been introduced in the Dutch economy of 2018, the energy industry includes renewable energy systems. The original data has to be disaggregated in order to split the technology and to get two different industries. For disaggregation the following equations are used:

$$X_N = S_N * X_E \qquad (3.4)$$

$$X_R = S_R * X_E \qquad (3.5)$$

$$S_N + S_R = 1 \qquad (3.6)$$

Where: S_N represents the share of non-renewable energy being produced, and S_R refers to the share of energy being produced from renewable sources. The equations hold for disaggregation of both the energy industry as energy products, as well for the use (consumption) and supply (production) table. Although, the shares may differ between the tables.

Since the supply and use table are used for disaggregation, the industries and products are labelled accordingly. The new labels are shown in appendix III. Note that industry I29 and product P41 also represents the distribution (trade) of electricity, gas, steam and air conditioning in the supply and use table. Production and distribution of renewable and non-renewable energy is assumed to be proportional to the total monetary value of energy being produced, such that the ratio of renewable and non-renewable energy equals its average.

Non-renewable energy consists of gas, coal, oil, other fossil fuels and nuclear energy. To renewable energy systems belongs wind, solar and biomass sources, plus to a small extent hydrogen power (CBS, 2021). Renewable energy sources other than biomass-related, i.e. wind and solar energy sources, are assumed to be classified under industry I29 due to lack of data. This means that classification of products under renewable energy sources are, for all other products than P41, solely determined by its biological origin. Since necessary data for disaggregation is not complete, additional information is assessed.

Supply table

To identify renewable and non-renewable energy systems in the supply table, both columns (industries) and rows (commodities) need to be disaggregated. The order for disaggregation that is generally applied in this study is to:

1. Search for S_N and S_R, based on literature and other available data.
2. Unknown S_N's and S_R's are chosen such that the average share of S_R for domestic supply (and domestic use) equals $\frac{18.9\text{ kWh}}{114.1\text{ kWh}}$.
3. All the unknown S_N's and S_R's are assumed equal.
4. The share $\frac{18.9\text{ kWh}}{114.1\text{ kWh}}$ represents total renewable energy over total energy produced in the Netherlands in 2018 (CBS, 2020 a; CBS, 2020 c). This share is assumed to be reliable and equal to the average share for the domestic supply and use.

Supply table row

Disaggregation of the row energy products in the supply table is most straight forward, since often the 'type' of energy produced can be identified. For example, the 'extraction of crude petroleum and natural gas' industry is assumed to refer to non-renewable rather than renewable energy.

Shares that are known, based on literature and other available data, are that of industries I4 (everything non-renewable), I14 (everything non-renewable) and I29 (share $\frac{18.9\text{ kWh}}{114.1\text{ kWh}}$). Data from The PRODCOM list of Statistics Netherlands (CBS, n.d), specifies products in more detail than the supply and use table, see appendix B. The list shows whether or not e.g. organic matter is involved in production. In contrast, the share of industry I29 is determined by Statistics Netherlands (CBS, 2020 a; CBS, 2020 c).

For other industries it is not obvious what type of energy they produce, i.e. industries I1, I15, I19, I31, I41. For these industries, S_R is calculated such that the average share for domestic supply equals $\frac{18.9 \text{ kWh}}{114.1 \text{ kWh}}$. The following equation is used to determine the share for renewable energy commodities produced by industries I1, I15, I19, I31 and I41:

$$S_R = \frac{S_{D\,I29} * \frac{18.9}{114.1} - x_{P41,I29} * \frac{18.9}{114.1}}{\sum M_U} \tag{3.7}$$

Where: $S_{D\,I29}$ represents the total domestic energy supply, $x_{P41,I29} * \frac{18.9}{114.1}$ the supply of renewable energy products by industry I29, and $\sum M_U$ refers to the sum of the monetary value of all industries with an unknown S_R.

Domestic energy supply excludes import, trade and transport margins, and taxes and subsidies on products. The share of renewable energy imported from total imported energy is according to Statistics Netherlands (CBS, 2020 c) equal to $\frac{21.5 \text{ PJ}}{10395 \text{ PJ}}$. Therefore, S_R for imports is assumed to be 1.0%. The renewable energy shares for trade and transport margins, and taxes on products are assumed to be the average share of $\frac{18.9 \text{ kWh}}{114.1 \text{ kWh}}$. The monetary value of subsidies is however denoted to renewable energy products only, since the Dutch government supports renewable and clean energy systems (CBS, 2019).

Note that the average share of $\frac{18.9 \text{ kWh}}{114.1 \text{ kWh}}$ does not hold for total energy commodities including imports, trade and transport margins and taxes and subsidies on products. The share for total energy commodities after disaggregation equals $\frac{1{,}747}{17{,}205} = 0.103$, see appendix B.

Supply table column

After disaggregation of the energy commodities (row), the energy industry (column) needs to be disaggregated. Disaggregation of the energy industry follows the same order as explained on the previous page. The part of the energy industry that can be classified under either the renewable or non-renewable energy industry, depends on the 'type' of energy demanded for the production in each industry. Inputs needed for the non-renewable energy industry are e.g. 'coke and refined petroleum products'.

To disaggregate the column of the supply table, only a few values need to be adjusted due to the little amount of products and services produced by the energy industry (see appendix B). Shares based on Statistics Netherlands (CBS, 2020 c) are that of P35, P42, P45 and P46. The share for the 'electricity, gas, steam and air conditioning' product is however determined by Statistics Netherlands (CBS, 2020 a). Products that are valued using the calculated share are P60, P61, P69, P70, P71 and P81. Trade and transport margins are however determined by the average share.

Use table

The use table shows which goods and services are purchased by each industry in the columns. The rows show how much each industry uses of a certain good or service. The share for renewable energy in 2018 is 7.4% of total final energy demand (CBS, 2019 a). The row and column totals of the supply and use table have to be equal. So, the calculated totals for the supply table determine the totals of the use table. Therefore, several objective equations are set in order to calculate S_R and S_N for all unknown shares of the use table:

$$x_{i,P22A} = 1{,}748 \tag{3.8}$$

$$x_{i,P22B} = 15{,}277 \tag{3.9}$$

$$x_{i,P22} = 17{,}025 \tag{3.10}$$

$$x_{I29A,i} = 2{,}953 \tag{3.11}$$

$$x_{I29A,i} = 14{,}876 \tag{3.12}$$

$$x_{I29,i} = 17{,}892 \tag{3.13}$$

Where: I29A and I29B refers to the renewable and non-renewable energy industry, and 22A and 22B to renewable and non-renewable energy commodities, both respectively. The same order for disaggregation as stated on page 16 has been applied for the disaggregation of the use table. Additionally, equation 3.7 is used for the calculation of all unknown S_R's. Total domestic energy supply is however replaced by either total use at purchasers' prices (column), domestic use or final demand (row).

Use table row

To know whether or not, and to what extent an industry purchases renewable energy products, the electricity balance sheet of Statistics Netherlands (CBS, 2020 c) has been used. The dataset specifies final consumption for the industries I1 – I20, I23 – I25, I30 – I34, I38 – I43, and exports, see appendix B.

All industries that, according to Statistics Netherlands (CBS, 2020 c), only consume non-renewable energy are industries I3 – I6, I10, I14, I16, I19, I20, I23 – I25, I38 – I43, and are denoted by $S_N = 1$. There are no industries that only consume renewable energy commodities. For all industries that partly consume renewable energy commodities, i.e. I1, I2, I7 – I9, I11 – I13, I15, I17, I18, I30 – I34, $S_R > 0$. For example, the agricultural industry (I1) purchases 5% and 95% of renewable and non-renewable energy from its total energy demanded respectively. Shares for industries that are unknown are that of

I21, I22, I26 – I29, I35 – I37, I44 – I81. For those, S_R is calculated taking the average S_R for domestic use into account, which equals 7.4% (CBS, 2019 a).

The energy balance sheet of 2018 (CBS, 2020 e) shows that of total energy products exported from the Netherlands, only 0.68% was produced from renewable energy sources. The share of S_R for exports is therefore fixed and equals 0.0068. For all other types of final demand, S_R is calculated taking into account the average share of total renewable energy products and services $\left(\frac{1{,}748}{17{,}025}\right)$. Note that there are two different calculated values of S_R for disaggregation of the use table row.

Use table column

The energy industry I29, which purchases different goods and services, needs to be disaggregated into two different industries. For products P1 – P18, P23, P24 and P26, S_N and S_R are indicated by the PRODCOM list of Statistics Netherlands (CBS, n.d.). For all other products, S_R is calculated and equals 0.212. For example, for a product like wearing apparel, it is unknown whether it is purchased as an intermediate input by the renewable or non-renewable energy industry.

The monetary value of subsidies is classified under renewable energy products only, which is similar to the disaggregated supply table. The share for the renewable energy industry by other types of value-added are unknown, and are therefore calculated taking into account the average renewable energy industry share $\left(\frac{2{,}953}{17{,}892}\right)$. Note that all unknown S_N's and S_R's are equal.

4. Financial incentives by government

Governments often try to affect the outcomes of the market mechanism by using financial instruments. Commonly, taxes and subsidies are used. Section 4.1 explains how taxes work and what their effects are. Section 4.2 explains data adaptations, and the economic model of the Dutch economy including taxes. Scenarios are specified in the last section, after which outcomes are discussed.

4.1 Taxes

This study researches the effect of the introduction of a tax on non-renewable energy products for the Dutch economy using an Applied General Equilibrium (AGE) model. The type of taxation is classified as an indirect tax of goods, and more specifically as an environmental tax (De Kam & Wellink, 2016).

Different types of economic and fiscal instruments exist, for instance taxes, subsidies, loans or concessions of rights. Financial incentives particularly correct for market failure in respect to a common good such as climate (Bouwma et al., 2015). Financial incentives can stimulate (providing a subsidy) or hinder (introducing a tax) the production and consumption of a good.

A tax is a unvoluntary payment to the government, and is collectively charged. There is a difference between direct (or non-product) and indirect (or product) taxes. In the model direct taxes are charged on labour and capital income, while indirect taxes make the price a demander pays that includes the price suppliers' get plus a fixed percentage tax (i.e. ad valorem tax). Indirect taxes are cost-increasing taxes, that in the end are assumed to be paid by the consumer (De Kam & Wellink, 2016). Renewable energy products are generally excluded from the environmental energy tax, provided that biomass sources are clean (Belastingdienst, n.d.).

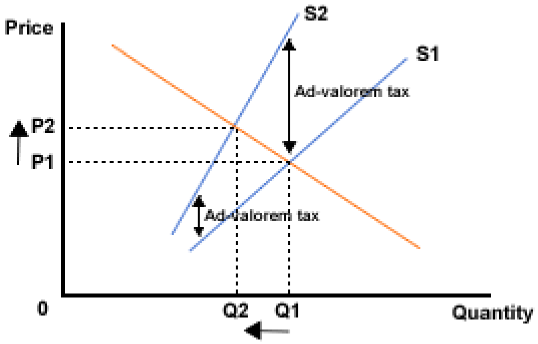


Figure 4.1 – Demand and supply curves after an ad-valorem tax

Figure 4.1 shows the working of an ad valorem tax, that is applied in the model. An ad valorem tax increases the price by a fixed percentage, which makes the tax dependent on the initial pre-tax price. An example is the Value-Added Tax (VAT) on the final purchase price of products. Another taxation design is a unit tax. The unit tax rate is equal for every unit bought or sold, independent of its price. The price-dependent ad valorem tax rate is calculated by the following equation (Gaudin & White, 2014):

$$p_{demand} = (1 + r)p_{supply} \qquad (4.1)$$

Where: r refers to the ad valorem tax rate, and p to a specific price. Assuming that the government does not incur any collecting cost, tax revenue is given by multiplying the left and right hand side of equation 4.1 with the quantity traded (Q):

$$p_{demand} * Q = (1 + r)p_{supply} * Q \qquad (4.2)$$

Where: expenditure equals $p_{demand} * Q$, the revenue of the seller equals $p_{supply} * Q$, and government tax revenues equal $r * p_{supply} * Q$.

Alternatively, a subsidy can be provided in order to stimulate the production or consumption of a product. The subsidy affects the price in an opposite way, resulting in a lower price than the initial pre-tax price. For a subsidy, r in equation 4.1 and 4.2 has a negative sign. Note that the government does not capture revenues but losses.

4.2 Model

An AGE model describes an economy by means of an explicit modelling of all markets within an economy. The data source of an AGE model is a social accounting matrix (SAM), which provides an abstract numerical representation of an economy. The AGE model is generally applied in economics, and is used to analyse the effects of an external shock to the economy or the introduction of a (taxation) policy.

The model describes that factor inputs labour and capital are purchased by firms in order to produce commodities (i.e. goods and services), and that factor income is allocated to the suppliers of labour and capital (i.e. private households). Commodities are bought from other industries as intermediate inputs. Commodities produced are also consumed by both the private household and public household or government. The government pays for the commodities by means of tax revenues. Commodities are also imported and exported, which is also incorporated in the model.

In an AGE model, commodity and factor markets are supposed to be in equilibrium. This means that demand is equal to supply for all commodities and factors. An equilibrium implies that a certain price makes that supply and demand are equal for each commodity and factor input (Shoven & Whalley, 1984). In equilibrium, consumer expenditures plus savings are assumed to equal consumer income, government income equals tax collected and is equal to government spending plus savings, and investments equal savings. Total income generated equals total expenditure. The model does not only solve for equilibrium prices and quantities but also for the equilibrium revenues and expenditures. Note that the equilibrium outcome is not affected by absolute prices but only by relative prices. This implies that a price numeraire has to be selected, and all prices are relative to this price numeraire. In the model, the exchange rate is used for this purpose.

To find the equilibrium prices and quantities, it is important to understand that the equilibrium follows from utility and profit maximizing behaviour of both producers and consumers. Optimization leads to the demand and supply functions of commodities and factor inputs.

The production structure of the AGE model in this study is based on a series of nested Constant Elasticity of Substitution (CES) functions. Unlike the Leontief production function applied in the IO model (chapter 2), relative price changes can be modelled using CES production functions. CES functions are used in order to specify substitutability between labour, capital, energy and other intermediate inputs in domestic production (Böhringer et al., 2003). Introducing substitution elasticities enables evaluation of the distribution of inputs such as capital, labour, energy inputs and non-energy inputs, making it a powerful tool (Miller, 2008).

Homogeneity to degree one in inputs is assumed for the CES production functions, making that the functions are characterized by constant returns to scale. The assumption of constant returns to scale implies that, in equilibrium, the selling price of each commodity (excluding taxes) equals the per-unit cost price. This translates profit maximisation into cost minimisation. Therefore, supply is determined by demand and factor use (Varian, 1984).

The substitution elasticity between non-renewable energy (N) and renewable energy (R) is given by the following equation:

$$\sigma = \frac{\%\,\Delta\,(\frac{N}{R})}{\%\,\Delta\,MRTS} \qquad (4.3)$$

Where: σ denotes the substitution elasticity between renewable and non-renewable energy, and MRTS refers to the marginal rate of technical substitution. The MRTS shows the rate at which renewable energy can be substituted for non-renewable energy, holding total output constant along an isoquant (Miller, 2008). When $\sigma < 1$, the share of non-renewable energy will decrease due to a higher relative price of renewable energy. Alternatively holding $\sigma > 1$, the ratio N/R will increase when non-renewable energy increases due to the opposite working. Note that one price change alters the value of all other endogenous variables.

Other functional forms are encompassed by CES functions. The Leontief production function is established when σ is zero, for the Cobb-Douglas σ is one (Miller, 2008). A major difference between those functions is that CES functions allow for a greater flexibility than e.g. the Cobb-Douglas function. In this research an AGE model is used that is developed by Peerlings (2021). A description can be found in the Appendix IV.

In the model a welfare change is measured using a Laspeyres index of private and public consumption, and investments. The index compares expenditure before and after a change using the initial prices (Komen, 2000, p.124).

4.3 Data

The data used for the economic model is coming from the Dutch supply- and use table of 2018 (CBS, 2020). Before reading the data into GAMS, the data is aggregated in such a way that all variables of the AGE model can be read easily. Meaning that in the use table non-product taxes and subsidies paid by each industry are aggregated. Moreover, labour income and gross capital income are aggregated for each industry. Final demand is aggregated by commodity into exports, private household consumption, public household consumption and gross investment. The supply table contains besides the supply of the commodities, aggregated imports and product related taxes and subsidies. Moreover, data is adjusted such that the Cif/fob correction has been deleted in order to simplify the model.

Several industries are aggregated in order to meet the emission data of OECD (2021), i.e. I4 - I6; I7 - I9; I26 - I27; I32 - I34; I49 - I50; I54 - I55; I61 - I62; I67 - I68; I73 - I75, and; I78 - I81. The industries are newly labelled by using B1 – B64, see appendix III. I29, the energy industry, has been split into B24, green energy industry, and B25 grey energy industry. The commodities are also aggregated in order to simplify the model, i.e. I91 – I96. The commodities are newly labelled from G1 to G91. The energy commodity has been split into G41, green energy commodity, and G42, grey energy commodity. Note that the amount of industries and commodities of the supply and use tables have to equal. The tables are checked by adding all totals.

To determine the environmental impact of a policy, data for industrial CO_2 emissions (in tonnes of CO_2 equivalents) is provided by OECD (2021), and are added to the model. In chapter 2, the emissions were assumed to be proportional to the output. Here emissions are linked to the energy consumption instead of the output. It is difficult to determine an emission coefficient for renewable and non-renewable energy industries. Most simplistically, the emission coefficient of the renewable energy industry is assumed to be zero. In this case, all emissions are caused by the non-renewable energy industry. The following equation shows how the emission coefficient of non-renewable energy for each industry B ($Coeff_B$) is calculated:

$$Coeff_B = \frac{Emis_B}{Enerf_B} \qquad (4.4)$$

Where: $Emis_B$ refers to the CO_2 emissions emitted by each industry B, and $Enerf_B$ to the amount of non-renewable energy commodities used by each industry B.

4.4 Scenarios and results

Scenarios

In order to get a more comprehensive understanding on how the economy is affected by the introduction of an environmental taxation policy, the following scenarios are simulated:

- Basic scenario: Solving the model calculates back the actual situation in 2018. The results of the other scenario are compared to the outcomes of the basic scenario.
- Scenario I: An ad valorem tax and subsidy are imposed. The subsidy rate increases with almost 60 percent of the original rate, resulting in a change from -0.314 to -0.5. The original value of the tax rate equals 0.18, which it is set to 0.5. Doing so, the tax rate increased with around 177 percent. It is expected that the taxation policy leads to a decrease in the use of non-renewable energy products and an increase in the use of renewable energy products. Furthermore, welfare is expected to decrease due to the equilibrium distortion in the model.
- Scenario II: Identical to the first scenario but now the CES substitution elasticity between renewable and non-renewable energy products is increased from 1.6 to 3. When the CES substitution elasticity increases, it gets easier to substitute both inputs in all industries. It is to be expected that this will lead to a larger effect of the introduction of the tax and subsidy.
- Scenario III: Identical to the first scenario but it is now expected that 15 percent of total carbon dioxide emissions are caused by the consumption of renewable energy. Consequently, only 85 percent is caused by the non-renewable energy consumption (instead of 100 percent). The scenario is assumed to be more realistic, since the use of renewable energy contributes to the total carbon dioxide emissions as well. It is to be expected that the total CO_2 emission reduction will be lower than in the first scenario. Since the price and quantities of commodities do not depend on the emissions, other variables are expected to stay constant.

Results

The results of scenario I, II and III are summarized in the table 4.1. The Laspeyres welfare index in table 4.1 is expressed in million euros. In order to find out which stakeholders loose, the Laspeyres welfare measurement is split into the private and public household, and investments. The CO_2 emissions are calculated in tonnes of CO_2-equivalents, and the balance of trade in million euros.

In scenarios I and III, the Laspeyres welfare index shows an increase in welfare compared to the basic scenario. Distortions to the equilibrium that already existed in the basic model, are apparently partly solved due to the government intervention. This phenomenon is called a second-best solution. According to Taylor (2020), the second-best policy scenario can be explained by the initial absence of a full pricing scheme where negative fossil fuel externalities are accounted for. Furthermore, all three scenarios show a negative private household welfare index, while that of the public household and investments are positive. The public household welfare index seems to result from the tax revenue on non-renewable energy commodities, that exceeds the costs of the subsidy program on renewables.

Table 4.1 – Results of scenario I, II and III (initial values in between brackets)

	Scenario I	**Scenario II**	**Scenario III**
Welfare index (0)	0.242	- 0.014	0.242
Private household (0)	- 0.839	- 0.885	- 0.839
Public household (0)	0.943	0.783	0.943
Investments (0)	0.137	0.088	0.137
CO_2 emissions (147,269)	- 10.42%	- 10.76%	- 7.92%
Trade (81.413)	- 1.26%	- 1.08%	- 1.26%

A major difference of the second scenario compared to scenario I is that both the carbon dioxide emissions as the Laspeyres welfare index decreases. There has emerged a trade-off between carbon dioxide emissions and welfare, where the government has to prioritize one over the other. The decrease in welfare can be seen as the price of the carbon dioxide emission reduction. Moreover, it is expected that increased elasticities should cause less distortions to an economy. This is however not applicable to scenario two, since the Laspeyres welfare index is lower than in the first and third scenario. This is the case because with a higher substitution elasticity price elasticities are larger, making that the quantity changes are larger than price changes. As the Laspeyres welfare index measures quantity changes, the welfare effect is larger.

Generally, the taxation policy seems an effective tool in order to decrease total carbon dioxide emissions as shown in table 4.1. In all three scenarios, the reduction of carbon dioxide emissions caused by the non-renewable energy industry equals around 8 to 10 percent. According to Komen (2000, p. 104), technological changes enable carbon dioxide emission reductions without reducing the output. Since the total reduction of scenario I is higher than scenario III (ceteris paribus), the statement seems valid.

The output of the renewable energy industry is increased in all three scenarios with around 15 to 20 percent, while that of the non-renewable energy industry decreased with approximately 10 percent. The quantity changes are larger in the second scenario with an increased substitution elasticity. The results were as expected.

The price of intermediate renewable energy inputs decreased in all scenarios, while that of non-renewable commodities increased. In the second scenario, the renewable energy commodity price decreased less than in the first and third scenario. This can be explained by the higher substitution elasticity of the second scenario. When it gets easier to substitute between inputs, the price of those inputs are likely to converge.

In all three scenarios, exports and imports of renewable energy commodities increased. The balance of trade, i.e. exports minus imports, is in all three scenarios lower than in the basic scenario, as shown in table 4.1. The exports are still larger than the imports but its difference decreased. Commodities that show a relatively large decrease in exports are expected to be energy-intensive. This seems to be true for all three scenarios, looking at coal and lignite (G6), crude petroleum and natural gas (G7), metal ores (G10) and mining (G11), non-renewable energy commodities (G42), and constructions works (G46).

It is expected that energy-intensive industries will suffer more from the taxation policy than others. Industries that show a larger decrease in aggregate primary inputs (i.e. value-added) are the energy-intensive non-renewable energy industry (B25), the mining and quarrying industry (B4), and the manufacturing of coke and refined petroleum products industry (B10), of chemicals and chemical products (B11), and of basic metals (B15).

5. Conclusion and discussion

The first section recapitulates the results of the study, answers the research questions, and draws conclusions. Section 5.2 provides a discussion on the data and methods used for this study.

Conclusion

The research objective for this study, as formulated in the first chapter, is to assess fossil fuel replacement by renewable (biological) energy sources, in order to measure the economic and environmental potential of the Dutch bioeconomy. Complementary methods are used to get a more comprehensive understanding of the low-carbon bioeconomy, in order to answer the research questions. The study provides insights in the linkages between the economy and the environment, and how the economy is affected by governmental intervention. The year 2018 is taken as the base year for the analyses, which one may view as a realistic representation of the current Dutch economy.

In chapter 2, the environmental and economic size of the bioeconomy is measured by using a Dutch input-output (IO) model that is developed for this purpose. Two scenarios were created, i.e. one scenario where the bioeconomy includes industries that (to some extent) produce biobased products, and one similar to the first scenario but including renewable energy commodities as well. In both scenarios, the economic and environmental size of the bioeconomy is calculated by using the exogenously determined final demand. The economic size is measured in value-added and employment, and the environmental size is quantified in CO_2, N_2O and CH_4 emissions. The results are expressed in percentages relative to the reference scenario, which represents the total Dutch economy. Simulations show that the economic size is generally smaller than the environmental size. The N_2O and CH_4 emissions are to a large extent linked to the bioeconomy, which can logically be explained by its production and use of manure and other farm practices. Contractionary, the calculated environmental size of the bioeconomy in terms carbon dioxide emissions is relatively small. To analyse environmental repercussions of the economic structure by applying an IO model is recognized by Leontief (1970), among others.

Chapter 3 provides a more comprehensive understanding on renewable (biological) energy systems in the Dutch economy. For this purpose, supply and use tables are applied and disaggregated in order to identify renewable and non-renewable energy systems. The rows and columns of the supply and use tables require different approaches for disaggregation of energy commodities and the energy industry. All unknown shares for (non-)renewable energy are calculated, while considering the average shares quantified by Statistics Netherlands. The disaggregation of the supply table rows (i.e. energy commodities produced) is assumed to be most reliable, since the type of energy produced can most straightforwardly be identified. Therefore, the disaggregated supply table is taken as the basis from which the use table totals are determined. There is however neither specific data nor consensus on how to distinguish between non-renewables and renewables. In the end, a few arbitrary decisions had to be made based on different data sources. The result provides an abstract representation on how the current Dutch bioeconomy is affected by the replacement of non-renewable by renewable energy.

Environmental and economic effects of the introduction of an environmental taxation policy are measured in chapter 4. Similar as to the policy agendas of the OECD, USA, and the EU, the taxation policy aims to incentivize the use of clean energy over fossil energy. The effects are measured through an applied general equilibrium (AGE) model by simulating three different scenarios. The simulations give a proper insight into the economy-wide effects of the taxation policy, via the linkages between energy use, carbon dioxide emissions and the rest of the economy. In general, the taxation policy seems an appropriate tool in order to measure environmental and economic values. In scenarios with a lower CES substitution elasticity between primary energy inputs, both the environment (first dividend) as the welfare (second dividend) are positively affected by the introduction of the taxation policy. This result meets the environmental ambition of policymakers to decouple economic growth from carbon dioxide emissions. In the second scenario, it is shown that a higher CES substitution elasticity between primary energy inputs, which generally implies the longer run, leads to increased distortionary costs. The findings of Komen (2000) also show the dependence of substitution elasticities on the simulation. Higher substitution elasticities however generally lead to larger quantity differences than price changes.

As specified in the first chapter, one of the main objectives of stimulating the bioeconomy is to mitigate climate change by reducing GHG emissions. Chapter 4 has shown that an environmental taxation policy results in a welfare gain while at the same time reducing total carbon dioxide emissions. Since technological change intrinsically reduces carbon dioxide emissions without the necessity to reduce the amount of energy consumed, another important task for the government could be to incentivize innovation on low-emission technologies in the bioeconomy.

In conclusion, the methods applied in this study can be seen as a support in the transition towards a bioeconomy. The IO model forms a strong numerical basis to further elaborate on bioeconomy linkages, and incorporating data reflective of the real Dutch economy. IO tables originate from supply and use tables but the latter provide a higher level of detail. Therefore, supply and use tables were used in order to simulate a realistic bioeconomy where renewable and non-renewable commodities and industries are treated separately. To add complexity, an AGE model is applied that shows how equilibrium prices and quantities are affected by policy intervention. Since policymakers aim to effectively drive bioeconomy development, it seems logical to use AGE models as a tool for adequate decision-making. The study in its entirety broadens the scope of policymakers in the ongoing discussion of the bioeconomy potential, i.e. the carbon dioxide reduction capacity and the extent to which welfare increases.

Discussion

Main arguments of criticism are data issues on availability and quality. Since datasets did not provide an all-encompassing overview on e.g. the split of renewable and non-renewable energy, arbitrary decisions had to be made. With improved quality of the data the necessity to make assumptions would disappear. Moreover, the IO, supply and use tables are coming from Statistics Netherlands. Statistics Netherlands manipulates datasets in order to improve its usability. Therefore, the quality of the datasets can be discussed and results should be interpreted with care. Note that in the second chapter the dataset from Statistics Netherlands is applied for the carbon dioxide emissions per industry rather than the OECD dataset that is used in chapter four.

There are some methodological restrictions on the applied models that are discussed in literature. Main issues of the applied IO model are its fixed technical coefficients that implies proportionality, and underestimation of substitution possibilities. Another weakness of the IO model is that final demand is exogenously determined. The AGE model knows several issues as well, although its increased flexibility on the production structure. Substitution elasticities greatly affect the results of the model but are in this study exogenously determined. A proper analysis on how to determine the substitution elasticities would improve the quality of the results. Moreover, a sensitivity analysis can be carried out to add quality.

To analyse structural change in an economy, i.e. the transition towards a bioeconomy, the way technological change is integrated to the model is an important determinator. Renewable energy systems are innovative technologies meaning that current datasets are not able to reflect the real-life economy. By determining technological change endogenously, the quality of the results would improve. Moreover, social-cultural values must be considered when deciding for an effective policy that fosters the bioeconomy transition. The model does e.g. not incorporate welfare inequalities between different income groups, or differences between small and large energy users. By broadening the perspective, the applicability of the study would improve for policymakers.

Although the abovementioned weaknesses, the models applied were useful to trace inter-industry linkages between bioeconomy and non-bioeconomy industries. The study contains a high academic relevance since there is little scientific literature on how the applied (complementary) methods provide unique insights on the bioeconomy.

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Appendices

Appendix I – IO table labels

Label	Industry
S0	Crop, animal production, hunting and related activities
S1	Forestry and logging
S2	Fishing and aquaculture
S3	Extraction of crude petroleum and natural gas
S4	Other mining and quarrying, except petroleum and gas
S5	Mining support activities
S6	Manufacture of food products
S7	Manufacture of beverages
S8	Manufacture of tobacco products
S9	Manufacture of textiles, wearing apparel and leather
S10	Manufacture of wood and products, except furniture
S11	Manufacture of paper and paper products
S12	Printing and reproduction of recorded media
S13	Manufacture of coke and refined petroleum products
S14	Manufacture of chemicals and chemical products
S15	Manufacture of pharmaceutical products and preparations
S16	Manufacture of rubber and plastic products
S17	Manufacture of building materials
S18	Manufacture of basic metals
S19	Manufacture of metal products, except machinery, equipment
S20	Manufacture of computer, electronic and optical products
S21	Manufacture of electrical equipment
S22	Manufacture of machinery and equipment n.e.c.
S23	Manufacture of motor vehicles, trailers and semi-trailers
S24	Manufacture of other transport equipment
S25	Manufacture of furniture
S26	Other manufacturing
S27	Repair and installation of machinery and equipment
S28	Electricity, gas, steam and air conditioning supply
S29	Water collection, treatment and supply
S30	Sewerage, waste management, materials recovery activities
S31	Construction of buildings

S32	Civil engineering
S33	Specialised construction activities
S34	Trade and repair of motor vehicles and motorcycles
S35	Wholesale trade, except of motor vehicles and motorcycles
S36	Retail trade, except of motor vehicles and motorcycles
S37	Land transport and transport via pipelines
S38	Water transport
S39	Air transport
S40	Warehousing and support activities for transportation
S41	Postal and courier activities
S42	Accommodation
S43	Food and beverage service activities
S44	Publishing activities
S45	Movies, TV and music production etc
S46	Programming and broadcasting activities
S47	Telecommunications
S48	Computer programming, consultancy and related activities
S49	Information service activities
S50	Financial service activities, except insurance and pension funding
S51	Insurance and pension funding, except compulsory social security
S52	Activities auxiliary to financial services and insurance activities
S53	Imputed rents owner-occupied dwellings
S54	Real estate services excluding imputed rents
S55	Legal and accounting activities
S56	Activities of head offices; management consultancy activities
S57	Architectural, engineering activities; technical testing and analysis
S58	Scientific research and development
S59	Advertising and market research
S60	Other professional, scientific and technical activities
S61	Veterinary activities
S62	Rental and leasing activities
S63	Employment activities
S64	Travel agency, tour operator reservation and related activities
S65	Security and investigation activities
S66	Services to buildings and landscape activities
S67	Office administrative and other business support activities

S68	Public administration and defence; compulsory social security
S69	Education
S70	Human health activities
S71	Residential care and social work activities
S72	Creative, arts and entertainment activities
S73	Libraries, archives, museums and other cultural activities
S74	Gambling and betting activities
S75	Sports, amusement and recreation activities
S76	Activities of membership organisations
S77	Repair of computers, personal and household goods
S78	Other personal service activities
S79	Activities of households as employers of domestic personnel
S80	Goods and services n.e.c.

Label	Intermediate demand
Z0	Imports of goods
Z1	Imports of services
Z2	Import duties
Z3	Other taxes on imports
Z4	Taxes on domestic products
Z5	Import subsidies (–)
Z6	Subsidies on domestic products (–)
Z7	Trade and transport margins

Label	Value-added
V0	Other taxes on production
V1	Other subsidies on production (–)
V2	Wages and salaries
V3	Employers' social contributions
V4	Operating surplus (gross)

Label	Final demand
F0	Exports of goods
F1	Exports of services
F2	Final consumption expenditure of households

F3	Final consumption expenditure of NPIs serving households
F4	Social transfers in kind
F5	Other individual final consumption of general government
F6	Collective final consumption of general government
F7	Gross fixed capital formation
F8	Change in inventories
F9	Trade and transport margins

Appendix II – IO table (dis)aggregation

Industry	(Dis)aggregation to avoid data errors	(Dis)aggregation to match data
Crop, animal production, hunting and related activities	A0	E0
Forestry and logging	A1	E1
Fishing and aquaculture	A2	E2
Extraction of crude petroleum and natural gas	A3	E3
Other mining and quarrying, except petroleum and gas	A4	
Mining support activities	A5	
Manufacture of food products	A6	E4
Manufacture of beverages	A7	
Manufacture of tobacco products	A8	
Manufacture of textiles, wearing apparel and leather	A9	E6
Manufacture of wood and products, except furniture	A10	E7
Manufacture of paper and paper products	A11	E8
Printing and reproduction of recorded media	A12	E9
Manufacture of coke and refined petroleum products	A13	E10
Manufacture of chemicals and chemical products	A14	E11
Manufacture of pharmaceutical products and preparations	A15	E12
Manufacture of rubber and plastic products	A16	E13
Manufacture of building materials	A17	E14
Manufacture of basic metals	A18	E15
Manufacture of metal products, except machinery, equipment	A19	E16
Manufacture of computer, electronic and optical products	A20	E17
Manufacture of electrical equipment	A21	E18
Manufacture of machinery and equipment n.e.c.	A22	E19
Manufacture of motor vehicles, trailers and semi-trailers	A23	E20
Manufacture of other transport equipment	A24	
Manufacture of furniture	A25	
Other manufacturing	A26	
Repair and installation of machinery and equipment	A27	
Electricity, gas, steam and air conditioning supply	A28	E21
Water collection, treatment and supply	A29	E22

Sewerage, waste management, materials recovery activities	A30	
Construction of buildings	A31	E23
Civil engineering	A32	
Specialised construction activities	A33	
Trade and repair of motor vehicles and motorcycles	A34	E24
Wholesale trade, except of motor vehicles and motorcycles	A35	
Retail trade, except of motor vehicles and motorcycles	A36	
Land transport and transport via pipelines	A37	E25
Water transport	A38	
Air transport	A39	
Warehousing and support activities for transportation	A40	E26
Postal and courier activities	A41	
Accommodation	A42	
Food and beverage service activities	A43	
Publishing activities	A44	E27
Movies, TV and music production etc	A45	
Programming and broadcasting activities	A46	
Telecommunications	A47	
Computer programming, consultancy and related activities	A48	
Information service activities	A49	
Financial service activities, except insurance and pension funding	A50	E28
Insurance and pension funding, except compulsory social security	A51	
Activities auxiliary to financial services and insurance activities	A52	
Real estate services excluding imputed rents	A53	E29
Legal and accounting activities	A54	
Activities of head offices; management consultancy activities	A55	E30
Architectural, engineering activities; technical testing and analysis	A56	
Scientific research and development	A57	
Advertising and market research	A58	
Other professional, scientific and technical activities	A59	
Veterinary activities	A60	
Rental and leasing activities	A61	E31
Employment activities	A62	

Travel agency, tour operator reservation and related activities	A63	
Security and investigation activities	A64	
Services to buildings and landscape activities	A65	
Office administrative and other business support activities	A66	
Public administration and defence; compulsory social security	A67	E32
Education	A68	E33
Human health activities	A69	E34
Residential care and social work activities	A70	
Creative, arts and entertainment activities	A71	E35
Libraries, archives, museums and other cultural activities	A72	
Sports, amusement and recreation activities	A73	
Activities of membership organisations	A74	
Repair of computers, personal and household goods	A75	E36
S53, S74, S78, S79, S80	A76	

Appendix III – Supply and use table

Commodities	Labels	Aggregation
Crops and planting material	P1	G1
Live animals and animal products	P2	G2
Agricultural and animal husbandry services	P3	G3
Products of forestry, logging and related services	P4	G4
Fish, other fishing products and support services	P5	G5
Coal and lignite	P6	G6
Crude petroleum and natural gas	P7	G7
Metal ores	P8	G8
Other mining and quarrying products	P9	G9
Mining support services	P10	G10
Fish and meat	P11	G11
Processed and preserved fruit and vegetables	P12	G12
Vegetable and animal oils and fats	P13	G13
Dairy products	P14	G14
Grain, starches, bakery products	P15	G15
Other food products	P16	G16
Prepared animal feeds	P17	G17
Beverages	P18	G18
Tobacco products	P19	G19
Textiles	P20	G20
Wearing apparel	P21	G21
Leather and related products	P22	G22
Wood and products of wood and cork	P23	G23
Paper and paper products	P24	G24
Printing and recording services	P25	G25
Coke and refined petroleum products	P26	G26
Chemicals and chemical products	P27	G27
Basic pharmaceutical products and preparations	P28	G28
Rubber and plastics products	P29	G29
Other non-metallic mineral products	P30	G30
Basic metals	P31	G31

Fabricated metal products	P32	G32
Computer, electronic and optical products	P33	G33
Electrical equipment	P34	G34
Machinery and equipment n.e.c.	P35	G35
Motor vehicles, trailers and semi-trailers	P36	G36
Other transport equipment	P37	G37
Furniture	P38	G38
Other manufactured goods	P39	G39
Repair and installation of machinery and equipment	P40	G40
Electricity, gas, steam and air conditioning	P41	
Renewable electricity, steam and air conditioning		G41
Non-renewable electricity, gas steam and air conditioning		G42
Natural water; water treatment and supply services	P42	G43
Sewerage, waste management, materials recovery	P43	G44
Buildings and building construction works	P44	G45
Constructions and works for civil engineering	P45	G46
Specialised construction works	P46	G47
Repair services of motor vehicles and motorcycles	P47	G48
Wholesale trade services, except of motor vehicles and motorcycles	P48	G49
Retail trade services, except of motor vehicles and motorcycles	P49	G50
Land transport services and transport via pipelines	P50	G51
Water transport services	P51	G52
Air transport services	P52	G53
Warehousing and support services for transportation	P53	G54
Postal and courier services	P54	G55
Accommodation services	P55	G56
Food and beverage serving services	P56	G57
Publishing services	P57	G58
Audiovisual production services	P58	G59
Programming and broadcasting services	P59	G60
Telecommunications services	P60	G61
Computer programming and consultancy services	P61	G62
Information services	P62	G63

Financial bank services	P63	G64
Insurance, reinsurance and pension funding services	P64	G65
Services auxiliary to financial and insurance services	P65	G66
Imputed rents owner-occupided dwellings	P66	G67
Real estate services excluding imputed rents	P67	G68
Legal and accounting services	P68	G69
Services of head offices; management consulting	P69	G70
Architectural and engineering; testing and analysis	P70	G71
Scientific research and development services	P71	G72
Advertising and market research services	P72	G73
Other professional, scientific and technical services	P73	G74
Veterinary services	P74	G75
Rental and leasing services	P75	G76
Employment services	P76	G77
Travel agency, tour operator and related services	P77	G78
Security and investigation services	P78	G79
Services to buildings and landscape	P79	G80
Office and other business support services	P80	G81
Public administration and defence services	P81	G82
Education services	P82	G83
Human health services	P83	G84
Residential care and social work services	P84	G85
Creative, arts and entertainment services	P85	G86
Library, archive, museum and other cultural services	P86	G87
Gambling and betting services	P87	G88
Sporting, amusement and recreation services	P88	G89
Services furnished by membership organisations	P89	G90
Repair of computers, personal and household goods	P90	G91
Other personal services	P91	
Services of households as employers	P92	
Margins on merchanting	P93	
Other services n.e.c.	P94	
Other goods n.e.c.	P95	

Industries	Label	Aggregation
Crop, animal production, hunting and related activities	I1	B1
Forestry and logging	I2	B2
Fishing and aquaculture	I3	B3
Extraction of crude petroleum and natural gas	I4	B4
Other mining and quarrying, except petroleum and gas	I5	
Mining support activities	I6	
Manufacture of food products	I7	B5
Manufacture of beverages	I8	
Manufacture of tobacco products	I9	
Manufacture of textiles, wearing apparel and leather	I10	
Manufacture of wood and products, except furniture	I11	B7
Manufacture of paper and paper products	I12	B8
Printing and reproduction of recorded media	I13	B9
Manufacture of coke and refined petroleum products	I14	B10
Manufacture of chemicals and chemical products	I15	B11
Manufacture of pharmaceutical products and preparations	I16	B12
Manufacture of rubber and plastic products	I17	B13
Manufacture of building materials	I18	B14
Manufacture of basic metals	I19	B15
Manufacture of metal products, except machinery, equipment	I20	B16
Manufacture of computer, electronic and optical products	I21	B17
Manufacture of electrical equipment	I22	B18
Manufacture of machinery and equipment n.e.c.	I23	B19
Manufacture of motor vehicles, trailers and semi-trailers	I24	B20
Manufacture of other transport equipment	I25	B21
Manufacture of furniture	I26	B22
Other manufacturing	I27	
Repair and installation of machinery and equipment	I28	B23
Electricity, gas, steam and air conditioning supply	I29	
Renewable electricity, steam and air conditioning supply	I29A	B24
Non-renewable electricity, gas, steam and air conditioning supply	I29B	B25
Water collection, treatment and supply	I30	B26

Sewerage, waste management, materials recovery activities	I31	B27
Construction of buildings	I32	B28
Civil engineering	I33	
Specialised construction activities	I34	
Trade and repair of motor vehicles and motorcycles	I35	B29
Wholesale trade, except of motor vehicles and motorcycles	I36	B30
Retail trade, except of motor vehicles and motorcycles	I37	B31
Land transport and transport via pipelines	I38	B32
Water transport	I39	B33
Air transport	I40	B34
Warehousing and support activities for transportation	I41	B35
Postal and courier activities	I42	B36
Accommodation	I43	B37
Food and beverage service activities	I44	
Publishing activities	I45	B38
Movies, TV and music production etc	I46	B39
Programming and broadcasting activities	I47	
Telecommunications	I48	B40
Computer programming, consultancy and related activities	I49	B41
Information service activities	I50	
Financial service activities, except insurance and pension funding	I51	B42
Insurance and pension funding, except compulsory social security	I52	B43
Activities auxiliary to financial services and insurance activities	I53	B44
Imputed rents owner-occupided dwellings	I54	B45
Real estate services excluding imputed rents	I55	
Legal and accounting activities	I56	B46
Activities of head offices; management consultancy activities	I57	B47
Architectural, engineering activities; technical testing and analysis	I58	B48
Scientific research and development	I59	B49
Advertising and market research	I60	B50
Other professional, scientific and technical activities	I61	B51
Veterinary activities	I62	

Rental and leasing activities	I63	B52
Employment activities	I64	B53
Travel agency, tour operator reservation and related activities	I65	B54
Security and investigation activities	I66	B55
Services to buildings and landscape activities	I67	B56
Office administrative and other business support activities	I68	
Public administration and defence; compulsory social security	I69	B57
Education	I70	B58
Human health activities	I71	B59
Residential care and social work activities	I72	B60
Creative, arts and entertainment activities	I73	B61
Libraries, archives, museums and other cultural activities	I74	
Gambling and betting activities	I75	
Sports, amusement and recreation activities	I76	B62
Activities of membership organisations	I77	B63
Repair of computers, personal and household goods	I78	B64
Other personal service activities	I79	
Activities of households as employers of domestic personnel	I80	
Goods and services n.e.c.	I81	

Appendix IV – AGE model description

Demand and supply equations

Aggregate output in industry b (Y_b) is composed of a hypothetical aggregate energy input (AEN_b), aggregate intermediate input (AIN_b) and aggregate factor input (APR_b) according a CES production function with constant returns to scale (see glossary at the end of this appendix for overview of variables, coefficients and sets). Intermediate inputs g in industry b ($IN_{b,g}$) are transformed into an aggregate energy and aggregate intermediate input according CES production functions with constant returns to scale. Labour ($PR_{b,1}$) and capital ($PR_{b,2}$) in industry b are transformed into the aggregate factor input, using a CES production function with constant returns to scale. Cost minimisation yields CES demand functions for the aggregate energy (I.1), aggregate intermediate (I.2), aggregate factor (I.3), energy (I.4), intermediate (I.5) and factor inputs (I.5):

$$AEN_b = f^{CES}_{AEN_b}(Y_b, WAEN_b, WAIN_b, WAPR_b) \qquad \forall b \in B \qquad \text{(I.1)}$$

$$AIN_b = f^{CES}_{AIN_b}(Y_b, WAEN_b, WAIN_b, WAPR_b) \qquad \forall b \in B \qquad \text{(I.2)}$$

$$APR_b = f^{CES}_{APR_b}(Y_b, WAEN_b, WAIN_b, WAPR_b) \qquad \forall b \in B \qquad \text{(I.3)}$$

$$IN_{b,g} = f^{CES}_{EN_{b,g}}(AEN_b, \boldsymbol{WIN_g}) \qquad \forall b \in B, \forall g \in S_{en} \qquad \text{(I.4)}$$

$$IN_{b,g} = f^{CES}_{IN_{b,g}}(AIN_b, \boldsymbol{WIN_g}) \qquad \forall b \in B, \forall g \in S_{mat} \qquad \text{(I.5)}$$

$$PR_{b,j} = f^{CES}_{PR_{b,j}}(APR_b, \boldsymbol{WPR_{b,j}}) \qquad \forall b \in B, \forall j \in J \qquad \text{(I.6)}$$

Supply of output g by industry b ($Y_{b,g}$) is proportional to the aggregate output (Y_b) by industry b (I.7). Aggregation of outputs over industries gives domestic production DP_g of commodity g (I.8):

$$YY_{b,g} = \delta^{Y}_{b,g} . Y_b \quad \sum_{g \in G} \delta^{Y}_{b,g} + \delta^{mar}_{b} = 1 \qquad \forall b \in B, \forall g \in G \qquad \text{(I.7)}$$

$$DP_g = \sum_{b=1}^{B} YY_{b,g} \qquad \forall g \in G \qquad \text{(I.8)}$$

Domestic production (DP_g) and imports (IM_g) are aggregated into total supply of commodity g (SP_g) using a CES production function with constant returns to scale. This implies that the Armington assumption is adopted. Total supply is then divided into domestic use (DU_g) and exports (EX_g) using a CET product transformation function with constant returns to scale. Cost minimisation yields CES demand equations for domestic production (I.9) and imports (I.10) and revenue maximisation yields CET supply equations for domestic use (I.11) and exports (I.12):

$$DP_g = f^{CES}_{DP_g}(SP_g, WDP_g, WIM_g) \qquad \forall g \in G \qquad \text{(I.9)}$$

$$IM_g = f^{CES}_{IM_g}(SP_g, WDP_g, WIM_g) \qquad \forall g \in G \qquad \text{(I.10)}$$

$$DU_g = f^{CET}_{DU_g}(SP_g, WDU_g, WEX_g) \qquad \forall g \in G \qquad (1.11)$$

$$EX_g = f^{CET}_{EX_g}(SP_g, WDU_g, WEX_g) \qquad \forall g \in G \qquad (1.12)$$

Total labour (j=1) and total capital (j=2) available in the economy (TPR_j) are divided into supply of labour $(PR_{b,1})$ and capital $(PR_{b,2})$ by industry using CET product transformation functions with constant returns to scale. Revenue maximisation yields supply functions for labour and capital respectively (I.13):

$$PR_{b,j} = f^{CET}_{pr_{b,j}}(\overline{TPR_j}, \boldsymbol{WPR_{b,j}}) \qquad \forall b \in B, \forall j \in J \qquad (I.13)$$

Maximisation of the CES utility functions yields CES demand equations for the private household (I.14) and public household (I.15):

$$CON_g = f^{CES}_{con_g}(EXP^{con}, \boldsymbol{WCON_g}) \qquad \forall g \in G \qquad (I.14)$$

$$GOV_g = f^{CES}_{gov_g}(EXP^{gov}, \boldsymbol{WGOV_g}) \qquad \forall g \in G \qquad (I.15)$$

The demand for investment goods (X^{inv}_g) is given by (I.16):

$$INV_g = \delta^{inv}_g . INV \quad \sum_{g \in g} \delta^{inv}_g = 1 \qquad \forall g \in G \qquad (I.16)$$

Zero profit conditions

The value of disaggregated outputs by industry equals the value of aggregate output plus margins produced by industry (I.17). The value of aggregate output equals the value of the aggregate energy input, aggregate intermediate input and aggregate factor input (I.18):

$$\sum_{g \in G} WDP_g \, Y_{b,g} = WY_b Y_b + WMAR.MAR_b \qquad \forall b \in B \qquad (I.17)$$

$$WY_b Y_b = WAEN_b AEN_b + WAIN_b AIN_b + WAPR_b APR_b \qquad \forall b \in B \qquad (I.18)$$

The value of the aggregate energy input equals the value of the energy inputs by industry (I.19). The value of the aggregate intermediate input equals the value of the intermediate inputs by industry (I.20). The value of the aggregate factor input equals the value of labour and capital by industry (I.21):

$$WAEN_b . AEN_b = \sum_{g \in S_{en}} WIN_{b,g} . IN_{b,g} \qquad \forall b \in B \qquad (I.19)$$

$$WAIN_b . AIN_b = \sum_{g \in S_{mat}} WIN_{b,g} . IN_{b,g} \qquad \forall b \in B \qquad (I.20)$$

$$WNAPR_b . APR_b = \sum_{j=1}^{2} WPR_{b,j} PR_{b,j} \qquad \forall b \in B \qquad (I.21)$$

The value of total supply (SP_g) equals the sum of the value of domestic production and imports minus the value of the imported margins (I.22) and the sum of the value of domestic use and exports by commodity (I.23):

$$WSP_g.SP_g = WDP_g.DP_g + WIM_g.IM_g \qquad \forall g \in G \qquad \text{(I.22)}$$

$$WSP_g.SP_g = WDU_g.DU_g + WEX_g.EX_g \qquad \forall g \in G \qquad \text{(I.23)}$$

The value of the supply of labour and capital equals the value of the total availability of labour and capital respectively (I.24).

$$\sum_{B \in b}\left(WPR_{b,j}.PR_{b,j}\right) = WTPR_j.\overline{TPR_j} \qquad \forall j \in J \qquad \text{(I.24)}$$

The value of the demand for individual investment goods equals the expenditure on investment (I.25):

$$\sum_{g \in G}\left(WINV_g.INV_g\right) = WINV.INV \qquad \text{(I.25)}$$

Margins

Margins are produced by the domestic industries and are assumed to be proportional to the aggregate output (see also I.7):

$$PRMAR_b = \delta_b^{mar}.Y_b \qquad \sum_{g \in G} \delta_{b,g}^{Y} + \delta_b^{mar} = 1 \qquad \forall b \in B \qquad \text{(I.26)}$$

Part of the margins are imported, imports are assumed to form a fixed share of the total imports (I.27):

$$IMAR = r_{imar}.\sum_{g \in G} IM_g \qquad \text{(I.27)}$$

The value of demand for margins per commodity (MAR_g) is assumed to form a share of the value of the different demand categories and is given by (I.28). To get the quantity the value has to be divided by the price of margins (see I.29).

$$MAR_g = m_g^{sp}.WDU_g.DU_g + m_g^{sp}.WEX_g.EX_g \qquad \forall g \in G \qquad \text{(I.28)}$$

The demand for margins equals supply (I.29):

$$\left(\sum_{g \in G} MAR_g\right)/PMAR = \sum_{b \in B} PRMAR_b + IMAR \qquad \text{(I.29)}$$

Equilibrium conditions for commodities

Total domestic use equals intermediate, private household, public household and investment demand (I.30):

$$DU_g = \sum_{b \in B} IN_{b,g} + CON_g + GOV_g + INV_g \qquad \forall g \in G \qquad \text{(I.30)}$$

Price equations

Indirect taxes and wholesale margins drive a wedge between the buyers' and sellers' price of domestic use. This goes for commodities consumed by the private household (I.31), the public household (I.32), as investment commodities (I.33), as intermediate inputs (I.33) and as exports (I.35):

$$WCON_g = \left(1 + m_g^{sp} + t_g^{sp}\right).WDU_g \qquad \text{(I.31)}$$

$$WGOV_g = \left(1 + m_g^{sp} + t_g^{sp}\right).WDU_g \tag{I.32}$$

$$WINV_g = \left(1 + m_g^{sp} + t_g^{sp}\right).WDU_g \tag{I.33}$$

$$WIN_g = \left(1 + m_g^{sp} + t_g^{sp}\right).WDU_g \tag{I.34}$$

$$WGEX_g = \left(1 + m_g^{sp} + t_g^{sp}\right).WEX_g \tag{I.35}$$

The price received for exports (I.36) and paid for imports (I.37) are equal to the world market price times the exchange rate. The price of margins equals its world market price times the exchange rate (I.38):

$$WGEX_g = WPEX_g.ER \tag{I.36}$$

$$WIM_g = WPIM_g.ER \tag{I.37}$$

$$PMAR = WPMAR.ER \tag{I.38}$$

Non-product related taxes are levied on the total value of labour and capital used by industry (I.39):

$$WAPR_b = \left(1 + t_b^{apr}\right).WNAPR_b \tag{I.39}$$

Income formation and distribution

Tax revenue from product (PTX) and non-product related taxes ($NPTX$) and social contribution ($SOCCON$) is given by equation I.40, I.41 and I.42 respectively:

$$PTX = \textstyle\sum_{g \in S}\left(t_g^{sp}.WDU_g.DU_g + t_g^{sp}.WEX_g.EX_g\right) \tag{I.40}$$

$$NPTX = \textstyle\sum_{b \in B}\left(t_b^{apr}.WNAPR_b.APR_b\right) \tag{I.41}$$

$$SOCCON = r_{soccon}.LABI \tag{I.42}$$

Labour income ($LABI$), capital income ($CAPI$) and capital depreciation (*DEP*) are given by equation I.43, I.44 and I.45 respectively :

$$LABI = WTPR_1.\overline{TPR_1} \tag{I.43}$$

$$CAPI = WTPR_2.\overline{TPR_2} \tag{I.44}$$

$$DEP = r_{capdep}.CAPI \tag{I.45}$$

The income (I^{con}), expenditure EXP^{con} and savings (SAV^{con}) of the private household are given by equations I.46, I.47 and I.48 respectively:

$$I^{con} = (1 - r_{soccon}).LABI + (1 - r_{capdep}).CAPI \tag{I.46}$$

$$EXP^{con} = (1 - s^{con}).I^{con} \tag{I.47}$$

$$SAV^{con} = s^{con}.I^{con} \tag{I.48}$$

The income (I^{gov}), expenditure EXP^{gov} and savings (SAV^{gov}) of the public household are given by equations I.49, I.50 and I.51 respectively:

$$I^{gov} = PTX + NPTX + SOCCON \tag{I.49}$$

$$EXP^{gov} = (1 - s^{gov}).I^{gov} \tag{I.50}$$

$$SAV^{gov} = s^{gov}.I^{gov} \tag{I.51}$$

Total savings (I.52) equal the sum of the savings of the private household, public household and capital depreciation minus the surplus on the balance of trade (BBAR). As the balance of trade is expressed in foreign price it has to be multiplied by the exchange rate (ER):

$$SAV = SAV^{con} + SAV^{gov} + DEP - BBAR.\overline{ER} \tag{I.52}$$

The surplus on the balance of trade (I.53) equals:

$$BBAR = \sum_{g \in G}\left(\overline{WPEX}_g.EX_g\right) - \sum_{g \in G}\left(\overline{WPIM}_g.IM_g\right) - IMAR.WPMAR \tag{I.53}$$

The value of investment ($INVT$) equals the value of the savings (I.54) but also the value of the investment commodities (I.55). Because of Walras's Law one equation has to be dropped to keep the model identified. In the operational model this is equation I.55.

$$INVT = SAV \tag{I.54}$$

$$INVT = WINV.INV \tag{I.55}$$

Price numéraire

An applied general equilibrium model is homogenous of degree zero. This model selects the exchange rate as price numéraire.

Environment

The environmental value of the economy is measured in terms of CO_2 equivalents. The emission coefficient describes the ratio between carbon dioxide emissions caused by each industry b (E_b) and the amount of energy demanded by each industry b (X_b^{en}). The emission coefficient of renewable energy (δ_b^{ren}) is assumed to be zero as stated in equation I.56, unless otherwise mentioned. The emission coefficient of non-renewable energy (δ_b^{nen}) is specified by equation I.57:

$$\delta_b^{ren} = 0 \qquad \forall g \in S_{ren} \tag{I.56}$$

$$\delta_b^{nen} = \frac{E_b}{X_b^{nen}} \qquad \forall g \in S_{nen} \tag{I.57}$$

Emissions in each industry b are either caused by renewable or non-renewable energy consumption, denoted by $ENR_{g,b}$ and $ENN_{g,b}$ respectively. Equations I.58 and I.59 explain how those emissions are calculated. The total environmental size of the economy (EE) is given by equation I.60:

$$ENR_{g,b} = \delta_b^{ren} * YY_{g,b} \qquad \forall g \in S_{ren} \qquad \text{(I.58)}$$

$$ENN_{g,b} = \delta_b^{nen} * YY_{g,b} \qquad \forall g \in S_{nen} \qquad \text{(I.59)}$$

$$EE = \sum_b (\sum_{g \in S_{ren}} (ENN_{g,b}) + \sum_{g \in S_{nen}} (ENR_{g,b})) \qquad \text{(I.60)}$$

Welfare change

As a welfare measure the Laspeyres index of real income change is taken. This index compares commodity bundles between two equilibria (e.g. before and after a policy change), using the prices of the initial equilibrium (I.56). This welfare measure allows for the calculation of the welfare effects of savings other than the private savings of which the underlying optimising behaviour is not modelled explicitly (i.e. capital depreciation, government deficit and the balance of trade). Since savings are equal to investments, the bundle of investment commodities represent welfare derived from saving.

$$WELF =$$

$$\sum_{g \in S} \left(WCON_g^{old} . CON_g^{new} \right) + \sum_{g \in S} \left(WGOV_g^{old} . GOV_g^{new} \right) + \sum_{g \in S} \left(WINV_g^{old} . INV_g^{new} \right) -$$

$$\sum_{g \in S} \left(WCON_g^{old} . CON_g^{old} \right) - \sum_{g \in S} \left(WGOV_g^{old} . GOV_g^{old} \right) - \sum_{g \in S} \left(WINV_g^{old} . INV_g^{old} \right) \qquad \text{(I.61)}$$

Glossary

Variables:

Y_b	aggregate output of industry b
AEN_b	aggregate intermediate energy input in industry b
AIN_b	aggregate intermediate materials input in industry b
APR_b	aggregate factor input in industry b
$IN_{b,g}$	intermediate input g in industry b
$PR_{b,j}$	labour (j=1) and capital (j=2) in industry b
$YY_{b,g}$	output g of industry b
DP_g	domestic production of commodity g
IM_g	import of commodity g
SP_g	total supply of commodity g
DU_g	domestic use of commodity g
EX_g	export of commodity g
TPR_j	labour (j=1) and capital (j=2) endowment in the economy
CON_g	consumer demand for commodity g
GOV_g	government demand for commodity g
INV_g	demand of investment good g
INV	aggregate investment good
$PRMAR_b$	production of margins by industry b
MAR_g	demand for margins by commodity g
$IMAR$	import of margins
E_b	environmental value of industry b (carbon dioxide emissions)
ENR_b	carbon dioxide emissions by industry b caused by clean energy inputs
ENN_b	carbon dioxide emissions by industry b caused by fossil energy inputs

$WAEN_b$	price of aggregate intermediate energy input in industry b
$WAIN_b$	price of aggregate intermediate materials input in industry b
$WAPR_b$	price of aggregate factor input including tax in industry b
$WNAPR_b$	price of aggregate factor input excluding tax in industry b
WIN_g	price of intermediate input g
$\mathrm{WPR}_{b,j}$	price of labour (j=1) or capital (j=2) used in industry b
WIM_g	price of import of commodity g
$WPIM_g$	world market price of import of commodity g

WSP_g	price of total supply of commodity g
WDU_g	price of domestic use of commodity g
WEX_g	price of export excluding taxes and margins of commodity g
$WGEX_g$	price of export including taxes and margins of commodity g
$WPEX_g$	world market price of export of commodity g

$WCON_g$	price of commodity g demanded by the private household
$WGOV_g$	price of commodity g demanded by the public household
$WTPR_j$	price of labour (j=1) and capital (j=2) endowment in the economy
$WINV_g$	price of investment good g
$WINV$	price of aggregate investment good
$WMAR$	price of margins
$WPMAR$	world market price of margins
ER	exchange rate

I^{con}	income of private household
I^{gov}	income of public household
EXP^{con}	expenditure of private household
EXP^{gov}	expenditure of public household
SAV^{con}	expenditure of private household
SAV^{gov}	expenditure of public household
SAV	total savings
$BBAR$	surplus on the trade balance (in foreign prices)
DEP	capital depreciation
$INVT$	value of the investment

PTX	value of the product related taxes
$NPTX$	value of the non-product related taxes
$SOCCON$	social contributions

$WELF$	welfare change

Other:

m_g^{sp}	margins for commodity g
t_g^{sp}	tax rate for product related taxes on commodity g
t_b^{apr}	tax rate for non-product related taxes in industry b

$\delta_{b,g}^{Y}$	coefficient dividing aggregate output into outputs g in industry b
δ_b^{mar}	production of margins per unit of aggregate output in industry b
δ_g^{inv}	coefficient dividing aggregate investment good into investment good g

δ_b^{en}	carbon dioxide emission coefficient of industry b

s^{con}	savings rate of the private household
s^{gov}	savings rate of the public household

r_{soccon}	share of labour income that goes to social contributions
r_{imar}	imported margins as share of total domestically produced margins
r_{capdep}	capital depreciation as share of capital income

Sets and subsets:

G: goods, g = 1 to 91

B: industries, b = 1 to 64

J: factors, j = 1 (labour) j = 2 (capital)

$S_{en} \subset G$	subset energy commodities: g = 41,42
$S_{mat} \subset G$	subset materials: g = 1,…,40,43,…,91
$S_{ren} \subset S_{en}$	subset renewable energy commodity: g = 41
$S_{nen} \subset S_{en}$	subset non-renewable energy commodity: g = 42

Miscellaneous

gov = public household; con = private household; inv = investment; en = energy; ren = renewable energy; nen = non-renewable energy; old = base year value; CES = Constant Elasticity Substitution; CET = Constant Elasticity of Transformation

Bold printed variables represent a vector; variables with a bar represent exogenous variables.

Production structure

Figure 1 shows that energy ($IN_{b,g} \;\; \forall g \in S_{en}$), material intermediate inputs ($IN_{b,g} \;\; \forall g \in S_{mat}$) and primary inputs ($PR_1, PR_2$) are aggregated into 3 aggregate inputs respectively. This is done using 3 CES functions each with their own substitution elasticity. Aggregate inputs are then aggregated into aggregate output (Y_b) using a CES function with again its own substitution elasticity. The aggregated output is then divided into different outputs ($YY_{b,g}$) using a Leontief transformation function (i.e. using fixed ratios).

Outputs:	$YY_{b,g} \;\; \forall g \in G$		
Aggregated output:	Y_b (CES, Leontief)		
Aggregated inputs:	AEN_b (CES)	AIN_b (CES)	APR_b (CES)
Inputs:	$IN_{b,g} \;\; \forall g \in S_{en}$	$IN_{b,g} \;\; \forall g \in S_{mat}$	PR_1, PR_2

Figure 2 shows that in the next step of the model outputs produced by different industries are aggregated commodity by commodity. This will give domestic production (DP_g) of a commodity. This domestic production competes with imports of the same commodity (IM_g) The competition can be seen as an aggregation into total supply (SP_g) using a CES production function. This total supply is then disaggregated using a CET transformation function into domestic use (DU_g) and exports (EX_g). Domestic use equals the sum of intermediate demand ($\sum_{b \in B} IN_{b,g}$), private household demand (X_g^{con}), public household demand (X_g^{gov}) and investment demand (X_g^{inv}).

	$DU_g = \sum_{b \in B} \left(IN_{b,g} + X_g^{con} + X_g^{gov} + X_g^{inv} \right)$	
Domestic use and exports	DU_g	EX_g
Domestic supply	SP_g (CES/CET)	
Domestic production and imports	$DP_g = \sum_{b=1}^{B} YY_{b,g}$	IM_g