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Danish Research Institute for
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The GreenREFORM EU model

Final paper of TSI project 101195159 GreenREFORMEU

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Preface

This paper presents the comprehensive outcomes of the TSI project GreenREFORM EU, serving as the final deliverable (D4.3). It outlines the project's objectives and outcomes, and presents the GreenREFORM EU model, accompanied by two policy experiments designed to illustrate the model's capabilities in real-world applications.

In Section 1, we detail the project's objectives, which aim to enhance modelling capacity for assessing the macroeconomic impacts of green policies across various sectors, as well as the outcomes of the project. This is supplemented by extracts from the 'Description of Action' section of the project grant agreement found in Appendix A. Also, a list of contact persons is available in Appendix B.

Section 2 provides an accessible description of the GreenREFORM EU model, highlighting its modular structure. While rigorous formal documentation is beyond the scope of this project, essential components, including the 'abatement model' described in Appendix C, are included for reference. Advanced users are invited to access the GAMS code upon request.

Section 3 discusses the data requirements and presents a Danish benchmark dataset that serves as a reference for these needs. It elaborates on the methodologies used to calibrate the model to the Danish economy, including the incorporation of detailed input-output tables and energy statistics.

Sections 4 and 5 present analyses of the simulated effects of a broad-based increase in CO2e taxation in Denmark. Section 4 explores the model dynamics with the abatement model turned off, showcasing the core CGE dynamics and immediate economic impacts. In contrast, Section 5 activates the abatement model, introducing discrete technological changes and examining their influence on emissions reductions and economic performance.

Summary

The GreenREFORM EU model, developed under the EU Commission's Technical Support Instrument, aims to improve modelling capabilities for assessing the macroeconomic impacts of green policies. The project’s primary objective is to equip policymakers with a customizable "workhorse" version of the Danish GreenREFORM model.

The model is dynamic, featuring forward-looking agents and employing advanced macroeconomic modelling techniques. It incorporates an engineering perspective on technological choices through the abatement model, which is inspired by existing energy optimization frameworks. This allows for analyses of technological adoption patterns, cost curves, and emissions reduction potentials across various policy scenarios.

In Section 3, the paper emphasizes the importance of data that encompasses the dimensions relevant to economic and environmental policies, ensuring accurate modelling outcomes. In the present case, the model is calibrated using a benchmark dataset for the Danish economy, which includes 57 distinct industries, 25 energy goods and 5 types of emissions. This section also outlines the data requirements for the abatement model and the methodology for calibrating technology-specific data to align with energy use in the Danish benchmark dataset.

The model's implementation, utilizing GAMS integrated with Python, features a modular design that enables both simultaneous solutions of sub-models and separation of modules, as illustrated by the analysis in section 4 and 5.

The simulations without the abatement model in Section 4 indicate (a priori) that a projected increase in CO_2e taxation of €100 is expected to reduce emissions by approximately 6%, primarily by encouraging a shift in production from emission-intensive to labour-intensive industries. The tax revenue is recycled to households; however, there is still a decline in household welfare due to the combined effects of higher prices and lower wages.

Section 5 demonstrates how the activation of the abatement model alters the model’s predictions. Emission reductions are greater as electrification technologies are adopted to mitigate the tax increase. Output prices rise less compared to those in Section 4, as technology costs are assumed (ad hoc) to be relatively low in comparison to the tax burden. This also explains why wage rates, GDP, and household welfare improve compared to Section 4. However, these results are ambiguous; if technology costs were closer to the tax burden, firms would carry the same cost increase as in section 4, but with less tax revenue being collected and recycled to households.

Overall, the GreenREFORM EU model empowers policymakers with the insights needed to identify efficient investments and evaluate the effectiveness of green policies, thus supporting a sustainable transition towards a low-carbon economy. The findings underscore the model's relevance for future research and its potential for adaptation to include sector-specific sub-models and national regulations, enhancing its applicability across various contexts.

Table of contents

1. Objectives and outcomes of the project

This section outlines the objectives and outcomes of the GreenREFORM EU project, and it provides insights into the collaborative efforts among participating nations, emphasizing the exchange of knowledge and best practices to support the implementation of sustainable policies across Europe.

The GreenREFORM EU model is developed as part of a project funded by the EU Commission under the Technical Support Instrument[1]. The objective of the project is to enhance modelling capacity to assess policies aimed at modelling the macroeconomic effects of green policies and investments. The beneficiaries of the project are the Ministries of Finance of respectively Finland, Austria and Italy, as well as Belgium's Federal Planning Bureau (FPB) and Poland's National Centre for Emissions Management.

The project was conceived in 2023 amid growing interest in the modelling of concrete policies aimed at decarbonizing the European economy. For decades, climate policy was largely confined to theoretical academic models. In recent years however, it has become increasingly operational, as the Fit-for-55 framework was passed into law and got shaped in the National Energy and Climate Plans (NECP).

The picture that emerges from the NECPs is one of a policy environment that cannot readily be captured by the broad concepts of theoretical analysis. In addition to a carbon price – the preferred instrument of academic economists–the NECPs contain a wide range of regulations, fiscal measures and subsidies shaped by concrete challenges faced by policymakers operating in a real-world environment face.

Notably, a substantial share of policies is linked to specific technologies. Examples include electric vehicles, various types of heat pumps, and industrial abatement options such as CCS. By now, the technologies required to achieve net-zero are known, which is reflected in the policies typically observed in the NECPs.

At the same time, the European Commission– with good reason – requests that policies are scored not only for their impact on emissions, but also on the macro-economy, on employment, investment needs as well as distributional effects. This is a tall order for even the best equipped national modelling teams.

It is in this context that Belgium's FPB sought – and found – a good practice in the Danish GreenREFORM model. As a state-of-the-art macro-economic model, derived from DREAMs MAKRO, it was the model of choice for analysing policies aimed at fostering investment. Its novel abatement module enables the modelling of the concrete, detailed policies now found in the NECPs. The ease with which like-minded member states could be found to join the TSI request testifies to an urgent need for improved analysis of real-world climate policies.

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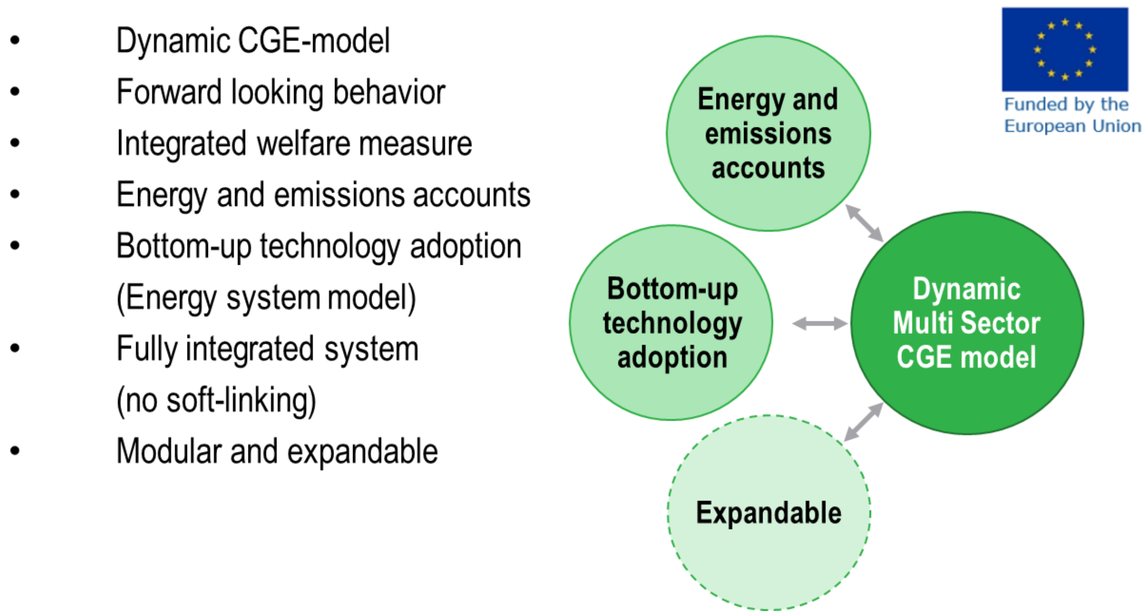
[1] TSI project 101195159 GreenREFORMEU

By the end of the project the beneficiaries obtained a "workhorse" version of the GreenREFORM model[2]. This will enhance the beneficiaries' ability to identify, assess, and select the most efficient and effective policies and investments for the green transition. In the long term, when a solid data foundation has been established and the institutional framework has been developed, the model can be adapted to include additional sector-specific sub-models and more detailed descriptions of national regulations, like the approach taken with the original GreenREFORM model for Denmark.

Figure 1.1
Key features of GreenREFORM EU



- Dynamic CGE-model
- Forward looking behavior
- Integrated welfare measure
- Energy and emissions accounts
- Bottom-up technology adoption (Energy system model)
- Fully integrated system (no soft-linking)
- Modular and expandable

Source: Author

The abatement model of GreenREFORM EU allows for approximately discrete changes in the energy input composition in any particular industry based on bottom-up information on the character of alternative technologies. The inspiration for the abatement model is found in existing energy system optimisation models, like the TIMES model, which is often soft-linked to static CGE-models[3]. This implies that the models are solved independently of each other with information passed between models in an iterative process. In contrast, GreenREFORM EU is a dynamic model with forward-looking behaviour and the model is solved by hard-linking the CGE-model with the abatement model. This implies that all sub-models are solved simultaneously, with information passed between models in real time. The typical argument against this approach is increased complexity, which however is mitigated by the modular design approach of GreenREFORM EU.

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[2] GreenREFORM is a state-of-the-art environmental economic CGE-model, which has become a centrepiece for climate policy analysis of the Government of Denmark in recent years. Visit www.GreenREFORM.dk for more information.

[3] This is the case in many EU countries. One example is the InterACT model of the Danish Energy Agency, which also provide technical data and expertise for the GreenREFORM model.

Based on recent experience by DREAM from the development of the MAKRO model[4], GreenREFORM EU features sluggishness in export demand, capital accumulation, wage adjustment (Phillips curve), and myopic behaviour of a share of households. In experience, these are the key features for achieving realistic Keynesian multiplier effects in a model for a small open economy.

Besides model development, the project included two multi day study visits in Copenhagen, and an offer of ongoing support for the beneficiaries' own efforts towards developing country-specific datasets for the model, for those beneficiaries who chose to follow an implementation track. As part of this support, and as a showcase, Statistics Denmark developed a complete Danish benchmark dataset for the model and documentation thereof.

At the end of the project 4 out of 5 beneficiaries remain committed and are striving towards implementing the model in their respective institutions. Only one beneficiary is close to completing the task of collecting all necessary data for the model, as raising internal funding and building capacity has proven to take longer than the one-year time span of the project.

The following bullet points summarize the key outcomes in terms of developments, enhanced capabilities, and impacts from the project across the participating Member States. They draw on beneficiary reflections, highlighting progress in model development, capacity-building, data adaptation, and policy relevance.

- **Overall Project Outputs**: The project delivered a customized "workhorse" GreenREFORM EU model - a dynamic, environmental-economic CGE model featuring a modular design inspired by Danish models (GreenREFORM and MAKRO). Key innovations include a hard-linked abatement sub-model for discrete energy technology shifts, forward-looking behaviour, and Keynesian dynamics (e.g. sluggish export demand, capital accumulation, wage adjustments via a Phillips curve, and myopic household behaviour). Beneficiaries received training through multi-day study visits in Copenhagen, ongoing support for data development, and a Danish benchmark dataset as a showcase. The GreenREFORM EU model enables beneficiaries to assess macroeconomic effects of green policies and investments, forecast energy balances and emissions, and identify efficient policies for the green transition.

- **Belgium's Progress**: The Federal Planning Bureau (FPB) started with two goals. First, FPB wanted to advance to the state-of-the-art in CGE modelling, integrating a dynamic model with forward-looking behaviour. This has been achieved with a near-complete national dataset (supply-use tables, energy balances, and emissions) that would allow initial model runs. Second, FPB looked to integrate GreenREFORM's novel abatement module, gaining the capacity to model choice among specific technologies. Using this second advance, the FPB entered a project-based relationship with the regional partners operating the technology-rich TIMES energy system model. Even though this funding is temporary, the foundations have been laid for a structural institutional setup, allowing Belgium to score policies aimed at clean investment. In the manufacturing sector, a concrete example under consideration involves a combination of carbon pricing at the European level and national subsidies targeted at specific technologies.

- **Finland's Progress**: Under the leadership of the Ministry of Finance, Finland has built national expertise in the GreenREFORM model and related approaches, that contributes to the integration of climate policy into broader economic planning. A

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[4] MAKRO is developed by DREAM for marrying short and long-term macroeconomic forecasts and for analysis of economic policy at the Ministry of Finance of Denmark. In MAKRO, sound short-term dynamics are achieved by introducing various nominal short-term rigidities inspired by the DSGE-literature.

dataset for Finland is under preparation. Research institutions, in collaboration with universities and ministries, are applying for funding to enhance model calibration. A national consortium has been formed, including the Prime Minister's Office and key research institutes (Luke, SYKE, VTT), with ongoing dialogue across ministries. The TSI project has strengthened Finland's national and EU-level networks, supporting peer exchange and cost-effective collaboration. Finland is also assessing the institutional set-up of the Danish DREAM modelling group as a potential framework, with focus on institutional roles and long-term sustainability.

- **Italy's Progress**: The Department of Finance in the Ministry of Economy and Finance (MEF), gained an in-depth understanding of the model's structure, function, and data requirements through workshops and study visits. The team has initiated adaptation of national datasets, including mapping supply-use tables, energy balances, and environmental accounts in alignment with ISTAT's national accounts. Despite challenges from limited resources and competing priorities, this has established groundwork for a consistent national database and enhanced CGE modelling capacity, particularly in integrating macroeconomic and energy system models. Collaboration with ENEA (TIMES-Italy developers) has been fostered, enabling future hybrid analyses—capabilities that were previously absent, allowing for more robust evaluations of green transition policies.
- **Austria's Progress**: The Ministry of Finance (MoF) has developed an internal strategy to embed green transition modelling into fiscal policymaking, aligning with Austria's Green Budgeting framework for identifying climate-related fiscal risks and evaluating policy options. Participation in workshops, bilateral technical assistance, and IT support from DREAM and Statistics Denmark has linked national efforts (e.g., CGE modelling by Umweltbundesamt, Universität Graz, and Institute for Advanced Studies) to fiscal processes, securing initial data for the model by transforming existing energy satellite accounts. Previously, the MoF lacked dynamic tools for quantifying transformation risks; now, it can integrate these into budget cycles, with institutional collaborations ensuring data flows and positioning the MoF as a key user of calibrated models for tax, transfer, and investment analysis.
- **Poland's Progress**: The National Centre for Emissions Management (KOBiZE) actively participated in capacity-building activities, including the Copenhagen workshop, gaining valuable insights into CGE modelling approaches. While not pursuing a full Polish version of the model due to commitments to an alternative CGE tool (MANAGE model from the World Bank), the project enhanced the team's understanding of environmental-economic modelling for green policy assessment. This built foundational knowledge that was previously limited, supporting broader efforts in emissions management and climate analysis through collaboration with the Ministry of Finance.
- **Broader Impacts and Enhanced Capabilities**: Across beneficiaries, the project has transitioned from fragmented or static modelling approaches to integrated dynamic tools for assessing green policies, enabling better identification of efficient investments and emissions forecasting—capabilities hindered by prior data and expertise gaps. It has fostered institutional collaborations (e.g., with national statistical offices and energy modelers) and EU-wide networks for peer exchange, reducing duplication and promoting methodological robustness. Stakeholder engagement and hands-on training have strengthened national expertise, integrating climate considerations into policymaking and supporting alignment with EU climate goals. Long-term, the GreenREFORM EU model provides a basis for adding sector-specific sub-models and national regulations, enhancing policy relevance for small open economies.

- **Challenges Encountered**: Data collection and adaptation progressed slower than anticipated due to funding constraints, resource limitations, and institutional priorities. Only one beneficiary (Belgium) neared full dataset completion, highlighting the need for sustained support to achieve complete implementation and avoid delays in building analytical capacity.

2. The current model

This section provides an accessible overview of the structure and key features of the GreenREFORM EU model. A comprehensive formal documentation is not yet available, as it falls outside the scope of the current project; however, it is expected to be released in the future. In the interim, advanced readers may refer to the model code, which is available upon request. Those studying the code will find Table 2.1 particularly useful, as it illustrates the correspondence between this section and the relevant modules in the code.

GreenREFORM EU is a general equilibrium model that describes a small open economy. It provides a coherent representation of transactions between households, the corporate sector, the public sector, and the rest of the world. The model is dynamic, and the current version is set to simulate the timespan from 2020 to 2050. Households and industries are forward-looking and exhibit partial rationality.

The model provides a detailed description of the supply and use of energy. Energy consumption is integrated into both production processes and household consumption. Energy-related greenhouse gas emissions are associated with energy use through emission coefficients, while non-energy-related emissions are linked to either the production process itself or specific inputs utilized in the relevant industries.

The model consists of 21 modules that together form the general equilibrium framework. This modular structure offers several technical advantages. Each module functions as an independent partial model. This is beneficial for testing, calibration, and understanding the partial as well as the overall system. Additionally, the modular design highlights the interactions between the modules, helping the user to understand the dynamics in a complex model.

Table 2.1
The modules in GreenREFORM EU

Section	Module	Section	Module
2.1 The input-output system	Input output	2.5 The public sector	Government
2.2 Financial accounts	Financial accounts		Energy and emission taxes
2.3 Corporate sector	Production inputs	2.6 Rest of the world	Imports
	Production outputs		Exports
	Factor demand		Energy exports
	Pricing	2.7 Energy and emissions	Energy market
	Non-energy markets		Energy demand from production
2.4 Household sector	Households		Disaggregated consumption (energy)
	Ramsey household		Emissions
	Disaggregated consumption	2.8 Abatement	Abatement
	Labour market		

Source: Author

2.1 The input-output system

The input-output system serves as the backbone of the model, providing a structured framework for understanding the interdependencies among various sectors of the economy. Each industry is represented by a matrix detailing its inputs and outputs, illustrating how resources are allocated and transformed within the economy. This system captures the flow of goods and services between industries and final consumers, enabling a comprehensive analysis of economic interactions.

The input-output framework allows the model to describe how changes in one sector can propagate throughout the entire economy. For instance, the introduction of a CO2e tax will not only impact industries directly responsible for greenhouse gas emissions but will also have broader implications for related sectors and consumer behaviour. Understanding these interconnections is essential for evaluating the economic impacts of such a tax, including shifts in production costs, changes in consumer demand, and the potential for innovation in low-carbon technologies.

2.2 Financial accounts

The financial accounts module describes the monetary flows between the four sectors of the model: households, the corporate sector, the public sector (also referred to as the government), and the rest of the world. It provides a detailed framework for understanding how income, expenditures, and investments circulate within the economy.

- **Households** generate income through labour and investments, which they use for consumption and savings.
- **The corporate sector** Representative firms in several industries produce goods and services, generating revenue that is reinvested into the economy through wages, dividends, and taxes.
- **The public sector** collects taxes and redistributes funds through public services and transfers.
- **The rest of the world** accounts for international trade and financial transactions between domestic sectors and foreign economies.

2.3 The corporate sector

Firms are owned partly by domestic households and partly by foreign households. Profits are returned to their owners as dividends. Firms operate under monopolistic competition, maximizing their profits by setting prices with a constant markup over production costs. The production of goods and services is determined by a CES (constant elasticity of substitution) production function.

Production

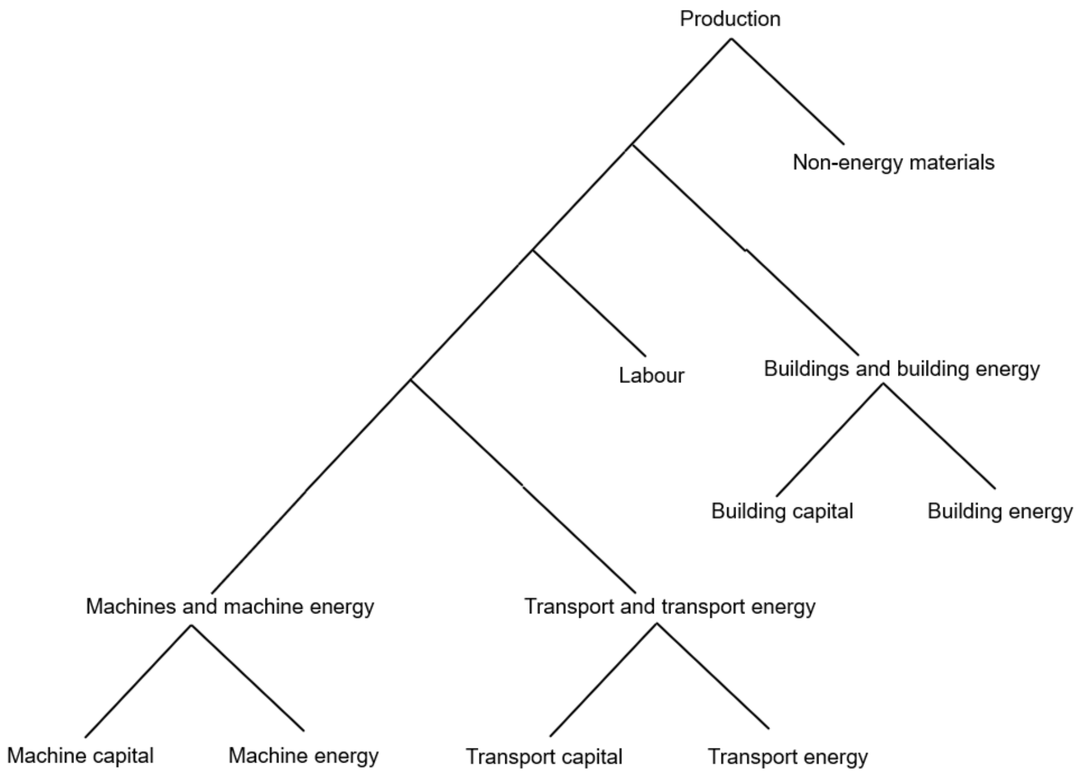
The production function determines how industries combine different inputs to produce outputs. This module employs a CES (constant elasticity of substitution) production structure. The module ensures that industries maximize profits by selecting the combination of inputs which allows them to meet demand for their outputs as cheaply as possible.

The structure of the CES production is organized hierarchically, with the top-level production function determining total output based on a combination of production inputs, as outlined in Figure 2.1.

As in most environmental economic CGE models, energy use is integrated with capital use in the production function. Capital however is divided into three distinct aggregates, thus leading to three capital-energy aggregates: *Buildings and building energy, Machines and machine energy, and Transport and transport energy.*

Figure 2.1

The structure of the CES nested production function



Source: Author

2.4 Household sector

The household sector describes the consumption and saving behaviour of households, thereby shaping final demand and overall economic welfare within the model.

Household income

Households have several sources of income. Labor income is the main source, with wages earned from employment. Additionally, households receive capital income, which includes returns from financial assets (dividends and interest payments). Government transfers also contribute to household income.

Intertemporal consumption and savings

The intertemporal consumption function was developed for the macroeconomic model MAKRO to accommodate short, medium, and long-term behaviour. This function incorporates perfect foresight, Ramsey behaviour, habit formation, and the marginal propensity to consume. Consequently, households make immediate adjustments to their spending in response to year-on-year income changes, while also reacting to anticipated future shifts. Additionally, they engage in consumption smoothing because of Ramsey behaviour. The habit formations ensure that shocks experienced in one year continue to affect consumption for several years thereafter, in line with empirical findings.

Furthermore, as an optional feature, the model includes an alternative consumption function reminiscent of Keynesian economics. In this approach, households consume a fixed proportion of their current income and wealth. This feature reduces the complexity of the model and may be adopted during development or in other cases, where simplification would be beneficial.

Consumption disaggregation

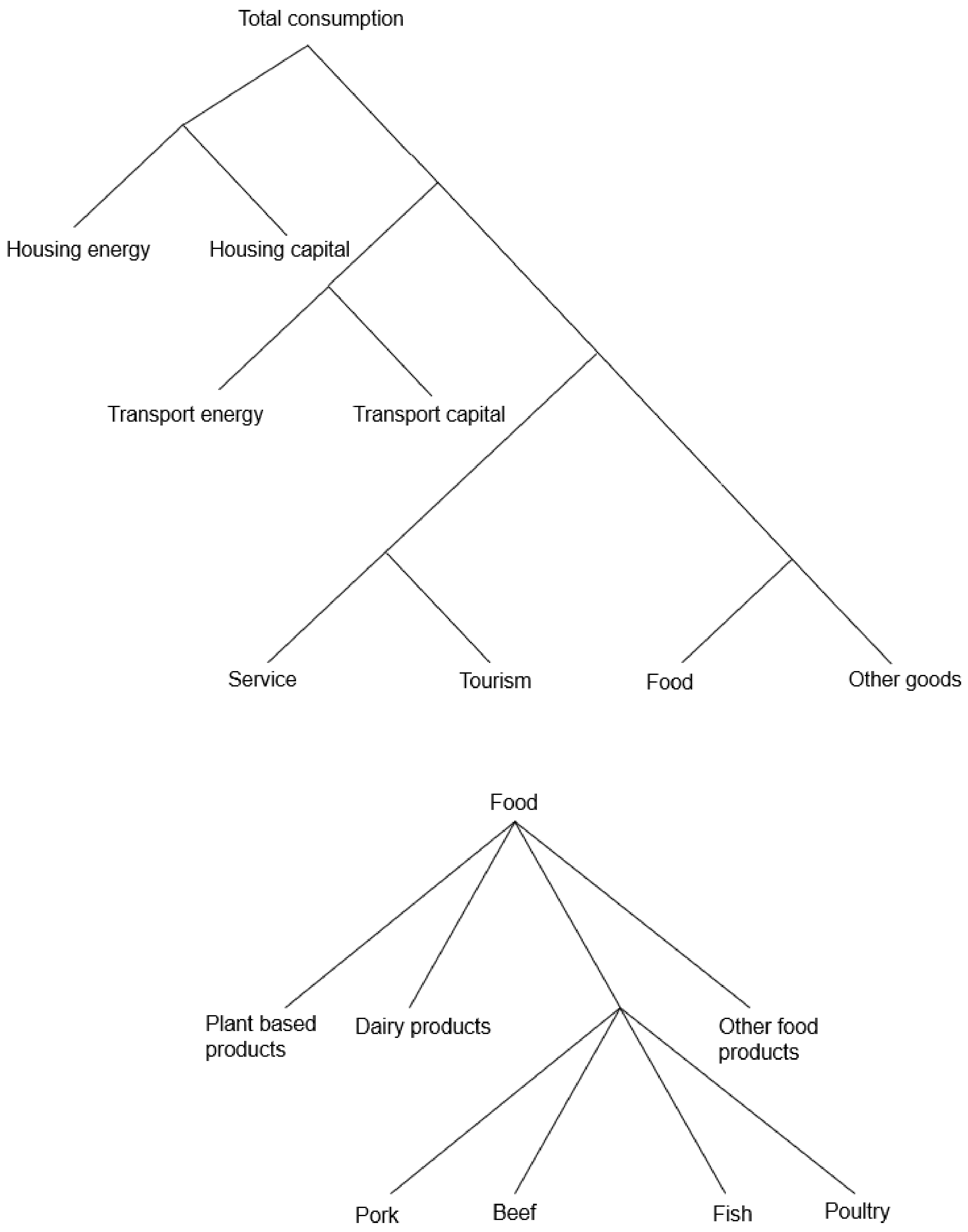
To analyse household spending in greater detail, the model incorporates a consumption disaggregation module. This module breaks down total household consumption into specific categories, enabling a nuanced understanding of how various policy measures impact consumption across different goods and services. Like the production function, energy consumption is modelled alongside capital use. Consequently, total consumption is divided into housing services—encompassing energy consumption related to housing—and non-housing consumption, which includes a wide range of goods and services. The full structure is illustrated in Figure 2.2.

Within the non-housing category, consumption is further subdivided into physical goods, tourism services, and transportation services, including energy used for transport. Food consumption is categorised into specific groups such as meat, dairy, vegetables, and beverages. This disaggregation provides valuable insights into consumer preferences and spending habits.

Labour market

Household labour supply and the level of structural unemployment is determined exogenously. Actual unemployment may deviate from its structural level, when the model is exposed to a shock due to sluggishness in the adjustment of the wage rate. This is governed by a Philips curve. The main feature of the Phillips curve is that growth in wages rises (falls) when actual unemployment is lower (higher) than the structural level. Thereby a positive (negative) economic shock creates a period of time with employment above (below) structural level until the wage level reaches the new higher (lower) equilibrium level.

Figure 2.2
Structure of the nested CES consumption function



Source: Author

2.5 The public sector

The public sector module incorporates a comprehensive fiscal system that captures the government's revenue collection, expenditure patterns, and financial flows with other sectors.

This detailed representation of fiscal flows and policy instruments provides a solid foundation for analysing the economic impacts of government policy changes. It ensures that fiscal policy analysis is grounded in a realistic understanding of government finances and their interactions with the broader economy.

Public expenditures

Government spending is categorised into three key groups: public consumption, transfer payments, and public investment. Each category plays a vital role in the overall functioning of the economy.

1. Public Consumption

The first category, public consumption, is modelled as a fixed ratio of Gross Domestic Product (GDP). This GDP-linked spending ensures that government consumption aligns with the overall economic performance of the country. The services and goods produced under public consumption are managed by a government sector that operates similarly to private industries within the economy. This approach facilitates efficient resource allocation and enables the provision of essential services to the public.

2. Transfer Payments

The second category comprises transfer payments to households and industries, as well as international transfers:

- **Household Transfers:** These include social benefits and various forms of financial assistance provided to households, which are indexed to wage growth. This indexing helps maintain the purchasing power of these transfers.
- **Corporate Transfers:** These consist of subsidies and other forms of support for businesses, such as public innovation funds. These transfers are modelled to be proportional to Gross Value Added (GVA), ensuring that the support aligns with the economic contributions of different industries.
- **International Transfers:** These include funds allocated for development aid and other forms of foreign assistance.

3. Public Investment

The third category is public investment. Public investments constitute a cost included in public expenditures. Furthermore, the depreciation of public capital is both a cost factored into the price of public consumption and a revenue counted directly in public revenues.

Public revenues

Government revenue is categorised into three main groups: direct taxes, indirect taxes, and other government revenue. Each category plays a crucial role in the overall financial landscape of the government.

1. Direct Taxation

The first category is direct taxation, which encompasses taxes on corporate profits, income tax on wages, capital tax on returns from private financial assets, and other taxes related to household income. Corporate profits are taxed based on earnings before interest, taxes, depreciation, and amortisation (EBITDA), minus depreciation. Income tax on wages is modelled to be proportional to household wages. Similarly, capital tax is modelled to be proportional to returns on household financial assets. Additional direct taxes are levied in proportion to household tax payments, calibrated to reflect actual direct tax revenues.

2. Indirect Taxes

The second category is indirect taxes, which significantly contribute to government revenue and support the green transition. In the indirect tax system, taxes are collected at the point of production and/or consumption. Environmental taxes are detailed to ensure the model incorporates the correct incentive structures. Indirect taxes are collected through three channels:

- **Duties on Production and Imports:** These are derived from the input-output system, reflecting the economic activities related to domestic production and imports. Energy and emission taxes are elaborated upon to ensure they maintain the correct incentive structure, as detailed in the subsection "Energy and Emission Taxes" below.
- **Production Taxes:** Also derived from the input-output system, these taxes are based on corporate production rather than the use of domestically produced goods and services or imports.
- **Other Indirect Taxes:** These are proportional to the gross value added by different industries, ensuring that tax burdens are distributed fairly across sectors.

3. Other Government Revenue

The third category comprises other government revenue, which includes income from sources beyond taxes. The main sources are:

- **Profits from Government-Owned Corporations:** Revenue generated through these entities contributes significantly to overall income.
- **Depreciation Revenue:** This accounts for the depreciation of public capital, as depreciation costs are part of the expenses associated with public consumption.
- **Mandatory Contributions from Households:** Indexed to wages, these contributions provide a stable source of funding for social security programmes.
- **Net Transfers from the corporate sector and the Rest of the World:** These transfers also contribute to the overall government revenue.

Marginal versus effective tax rates on energy and emissions

GreenREFORM EU is designed to be calibrated against detailed input-output tables and energy input-output (energy-IO) tables, like the benchmark data set referenced in Section 3. These statistics adhere to strict accounting principles, which the model must also respect. Consequently, effective tax rates are calibrated a priori to align with the observed tax payments of specific industries or households and the tax base in the model.

In practice, the effective tax rate based on national accounts will differ from the legislated marginal tax rates. This misalignment may arise from discrepancies between data sources etc. or it may arise from industries facing differentiated tax rates.

Given the particular importance of energy and emissions taxes, the model includes the option to exogenously set marginal tax rates on energy and emissions, which influences the marginal properties of the model. The discrepancy between the marginal tax rate and the effective tax rate is addressed through a bottom rate tax deduction[5].

2.6 Rest of the world

The 'rest of the world' module captures the international economic relationships through trade flows, financial transactions, and income transfers. As a small open economy, the domestic economy is significantly influenced by the structure of these international connections.

Imports

Import demand is determined using a Constant Elasticity of Substitution (CES) framework, which allows consumers and industries to substitute between domestic and imported goods and services based on relative prices. Consequently, import demand adjusts in response to changes in the relative price of imports compared to domestic goods, guided by the elasticity of substitution.

Exports

The rest of the world demands export goods and services from the domestic economy. The volume of exports is determined by an Armington export function, which indicates that exports fluctuate when the relative prices between domestic and foreign goods change. The price sensitivity of exports is governed by an export elasticity.

2.7 Energy and emissions

In a conventional economic Computable General Equilibrium (CGE) model, energy is represented as an abstract service often represented in base year monetary values. In GreenREFORM EU however, energy is represented in physical units of energy content.

The Energy Market

The energy market module provides a comprehensive representation of energy consumption, pricing, and market-clearing mechanisms. This integration ensures equilibrium between energy supply and demand in physical units and values. By combining detailed energy consumption patterns with the broader economic model structure, the module ensures that energy markets are interconnected with the input-output system, production processes, and real energy accounts.

Emissions

Energy-related greenhouse gas emissions are associated with energy use through emission coefficients, while non-energy-related emissions are linked to either the production process itself or specific inputs utilised in the relevant industries. The prime example is biogenic emissions from agriculture which is linked to the level of production in agriculture. This integrated approach to emission accounting allows for a comprehensive description of the connections between economic activities and greenhouse gas emissions.

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[5] For more detail, see Stephensen and Kirk (2022) *Modelling marginal tax rates while respecting national accounts statistics in the CGE-model GreenREFORM* (https://dreamgruppen.dk/publikationer/2022/februar/modelling-marginal-tax-rates-in-greenreform)

2.8 Abatement model

The abatement model provides a description of the production of energy services, where the demand for energy input and emission coefficients can change in a near-discrete fashion based on exogenous information about available technologies.

The model allows for a detailed analysis of how various technologies compete to provide equivalent services, enabling a comprehensive assessment of technological adoption patterns, cost curves, and emissions reduction potential across different policy scenarios.

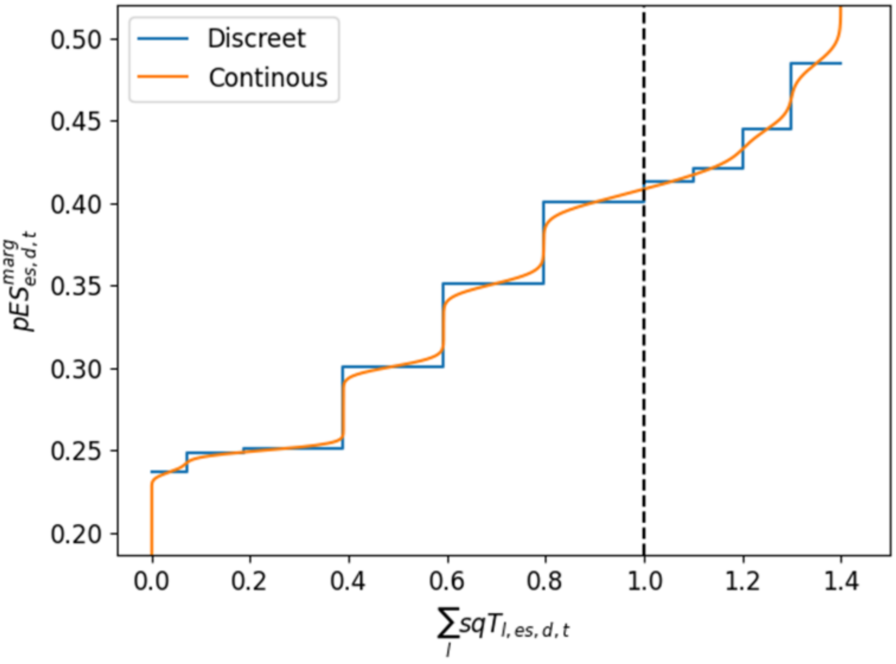
The abatement model has two distinct technical features that set it apart from energy system models, which are crucial for achieving full integration with the CGE model, allowing both models to be solved by the same solver.

First, in the tradition of CGE models, optimisation is decentralised to the respective agents of the model. This contrasts with energy system models like TIMES, which feature centralized cost minimisation. In the abatement model, representative agents for firms and households adopt all cheaper technology options at their respective potentials until the price point where demand for energy service is exactly satisfied.

Second, the true discrete choice of energy system models is replaced by a continuous approximation.

Figure 2.1 pictures an example of the technology choice in the abatement model. The blue line depicts different technologies, l, that can satisfy an energy service demand in the discrete case. The technologies are arranged by their costs, and the dotted line represents the point where supply equals demand for energy services. The orange line depicts the continuous approximation in the abatement model.

Figure 2.3
Illustration of bottom-up technology choice



Source: Author

The abatement model can function in full integration (hard-linked) with the CGE model or as a standalone partial model. In the latter case, the abatement model describes the cost-minimising technology mix at given input prices and given demand for energy services. When integrated with the CGE model, the demand for energy services and input prices are endogenously determined by the CGE model and provided to the abatement model, while the price of energy services and the demand for inputs (energy and capital) are determined by the abatement model and provided to the CGE model. Changes in input prices during simulation compared to baseline assumptions thus alter the merit order of technologies simultaneously, and changes in the price of energy services concurrently affect the demand for energy services.

Thus, the abatement model allows for in-depth analysis of how technology choices influence economic activity and emissions. It also features specific provisions for carbon capture and storage (CCS) technologies, enabling the examination of how CCS deployment impacts emissions and economic performance.

3. Data requirements

This section outlines the data requirements. The discussion is divided into four subsections: Section 3.1 covers base year data requirements; Section 3.2 provides insights into the Danish benchmark dataset developed by Statistics Denmark; Section 3.3 outlines how the model is calibrated to the benchmark data and the needs for forecasting a credible baseline scenario; Section 3.4 addresses data for the abatement model.

3.1 Base year data

This subsection provides an overview of the statistical data required for the GreenREFORM EU model. Most of this data can be sourced from National Statistics and Government Statistics. The primary challenge lies in constructing an integrated Input-Output (IO) system with energy accounts.

A bullet list of data requirements is presented below. The following text elaborates only in general terms on the first three bullets, serving as a guideline for prospective model users. Advanced readers are referred to the benchmark data and accompanying documentation provided by Statistics Denmark.

Data needs

- IO-table
- Energy- and emissions table
- Energy IO-table
- Production related taxes and subsidies
- Allocation of ETS allowances
- Investment IO-table
- Data on industry level accumulated capital in production
- Public sector finances
- Sector specific wealth

Scope and scale of the model

Prospective model users must first establish their ambitions regarding the scope and scale of their version of the model. These ambitions can vary significantly among users. The model itself is highly flexible in terms of the number of industries, energy goods, and emission categories, requiring minimal or no modifications to the model code, provided that the data is formatted in line with the benchmark data.

However, adapting the model to accommodate local tax codes and other regulatory frameworks, or to better reflect the production and competitive conditions of specific local industries, will necessitate changes to the code itself.

The level of detail within the data on which the model is built directly influences its precision and, consequently its capacity for detailed policy analysis. For instance, if cement production is inadequately described in the available data, it will be challenging to conduct thorough analyses of policies targeting that particular industry. This same principle applies to the potential disaggregation of energy use and emissions, where the data's level of detail should align with variations in tax codes, regulations, and available abatement options.

Input-Output table

The standard Input-Output table (IO-table) from the National Accounts serves as the backbone of the model, as well as any macroeconomic model. While it should be generally accessible in all countries, it may not always contain the desired level of sector-specific detail.

In Denmark, the National Statistical Office (Statistics Denmark) has been actively engaged since 2020 in developing and enhancing the quality of the data supplied to the Danish GreenREFORM model.

Energy and emissions tables

The Energy Supply-Use table contains information on production, domestic use, exports and imports of energy in both monetary value and quantity (measured in GJ) disaggregated into industries and types of energy. The value of energy use in purchase value is divided into elements of producer price, various taxes, wholesale and retail margins etc., everything in full consistency with aggregate values in the IO-table.

As described in the section on abatement data and elsewhere in the text, energy use is expected to be divided into 'Energy services'. This must also be reflected in the energy statistics.

Emissions tables are either delivered in quantities (tCO_2 etc.) or as energy specific emissions coefficients. It is important to be aware and make distinctions between emissions covered by national accounts standard (activity based) and UNFCCC standards (territorial emissions). In the case of Denmark this is done by distinction of bunkering fuel oil and bunkering jet fuel etc. as specific energy types.

Energy IO-table

To avoid double counting we need to subtract the value of energy in the Energy Supply-Use table from the standard IO-table. The challenge is that Energy Supply-Use tables only accounts for the total production of energy type *A* by industry *X*, and the total use of energy type *A* by industry *Z*. Hence, it does not account for the energy of type *A* used by industry *X* produced by industry *Z* as in the inter-industry matrix of the IO-table. This challenge is not unique to GreenREFORM, but one which is faced by all model developers working with describing the flow of energy in a macro economic framework.

In many cases, one will have to rely on ad hoc assumptions, while keeping the accounting identities of the IO table intact. In Denmark this is handled by Statistics Denmark, who supply the so-called Energy IO-table, which contains all the same information of the IO-table, but only for energy. The Energy IO-table is included in the benchmark dataset.

3.2 The benchmark dataset

This subsection provides a brief discussion of the benchmark data supplied by Statistics Denmark. The benchmark data contains all the base year data required for the model. It has been developed to provide a guiding example during the project, and for use as a showcase as in section 4 and 5.

The benchmark dataset is a tailored version of the data used for the Danish GreenREFORM model, with all data being presented at the level of aggregation of GreenREFORM EU model and in Microsoft Excel format to make it accessible.

Table 3.1

Energy use in the Construction industry divided in purposes and types of energy, 2020 PJ

	Electricity	Natural gas incl. biongas	Gasoline	Diesel	Liquid bio-fuels	Other oil products
Heating	1.41	0.24		4.48		0.11
Transport	0.02	0.01	0.96	13.12	1.11	
Normal process		0.11		1.11		0.03

Source: GreenREFORM EU Benchmark data

The benchmark dataset covers 57 industries, 25 different energy products, and 6 purposes of energy use. However, most industries will only use a few energy products for a few purposes. In the example presented in table 3.1., we see how the construction industry uses 6 different types of energy for 3 different purposes. As another example of the granularity of the benchmark data, figure 3.1 depicts CO_2e emissions and gross value added (GVA) of each of the 57 industries represented in the benchmark dataset, measured as shares of total emissions and GVA, respectively.

Figure 3.1

Emissions and gross value added in industries in 2020, share of total

Source: GreenREFORM EU Benchmark data

3.3 Calibration

Base year data (Section 3.1) is utilised for the calibration of scale and share parameters. Additionally, the model relies on several elasticities that determine the economic behaviour of the agents. In the workhorse version of the model, most elasticities are set ad hoc, while others align with the GreenREFORM DK model.[6]

To establish a baseline scenario, several variables must be set exogenously for the entire timespan of the model. As the model is designed to represent a small open economy, key exogenous determinants are such as the prices of imports, competing world market prices for exports, and the scale of export demand. Other important exogenous variables include the size of the population, the labour market participation rate, and parameters governing public transfers, tax rates, and other income sources, depending on the desired level of granularity for public sector finances. Most of this information can typically be derived from existing macroeconomic models used for forecasting within a specific country.

In the workhorse version of the model (utilised in Sections 4 and 5), most exogenous variables are forecasted at a constant value. This results in a stable long run forecast of the model, which is beneficial at the stage of development, to be able to study the fundamental characteristics of the model.

There are two notable exceptions. Firstly, the benchmark data indicates a public deficit in the base year (where public expenditures exceed revenues). If this were forecasted as a constant, it would not represent a steady-state equilibrium, as it would imply exponentially increasing public debt over time. To address this, we introduce a net transfer from the households to the government, which ensures that public expenditures align with revenues in the long term.

Secondly, the benchmark data indicate a positive income flow from the rest of the world in the base year. If this were forecasted as a constant, it would imply an exponentially increasing wealth over time. To counter this, the propensity to consume of households is calibrated to ensure that the net income flow from the rest of the world is zero in the long run.

3.4 Data for the abatement model

This subsection provides a discussion on the data required for the abatement model. The data serves both to establish a credible baseline for energy use and emissions, as well as to evaluate the technical changes induced by shifts in policy, energy prices, or other exogenous information compared to the baseline.

A technology is characterised by three key characteristics:

1. Potential: Defines the maximum share of energy service in an industry that can be supplied by the technology.
2. Energy Intensity: Defines the amount of energy input required to produce one unit of energy output of energy service. A technology can utilise multiple energy inputs.

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[6] Export and import elasticities are set at 5 and 2, respectively, for all industries. Substitution elasticities in the production function are uniform at 0.7 for all nests, except for the substitution between energy inputs, which is set at 0.1. Substitution elasticities in household consumption are based on the GreenREFORM DK model and range between 0.3 and 1.25.

3. Capital Intensity: Defines the amount of machinery capital required to generate one unit of energy output. The capital requirement consists of both initial investments and ongoing capital costs.

Technology data must specify which industry and energy service the technology can be applied to, the years in which the technology is available, and the type of energy input it requires. Furthermore, the technology must have a name to distinguish it from other technologies.

An example of data for a technology is provided in Table 3.1. The technology named "t1" has the potential to supply 13% of the total demand for the energy service ‘heating energy’ in the dairy industry (10030) in the year 2020. This technology uses gasoline, with an energy loss of 10%, as it requires 1.11 PJ of gasoline to produce 1 PJ of energy service (as shown in the energy intensity column). For each PJ supplied, the technology incurs an investment cost of €1 billion and annual variable costs of €0.1 billion. The technology has a lifespan of five years.

Table 3.2

Example of technology data in the abatement model

Name	Industry	Energy service	Year	Lifespan (years)	Potential (Share of energy demand)	Investment costs (billion EUR per PJ out)	Variable capital costs (billion EUR per PJ out)	Energy input	Energy intensity (PJ in per PJ out)
t1	10030	Heating	2020	5	0.13	1.0	0.1	Gasoline	1.11

Source: Author

To facilitate Carbon Capture and Storage (CCS) technologies, we define ‘Captured CO_2’ as a fictitious energy good measured not in PJ but in tonnes. A CCS-technology is thus simply defined by setting a negative ‘Captured CO_2’-input intensity, i.e. reflecting an *output* of ‘Captured CO_2’. To account for captured and stored CO_2 in the emission accounts, the CO_2-emission coefficient of ‘captured CO_2’ is simply set to -1.

Currently, there is no explicit representation of the transportation and storage of captured CO_2. Consequently, the associated costs should be included in the characteristics of the CCS technology. Defining 'Captured CO_2' as a commodity, however, lays the groundwork for more detailed modelling, such as establishing a market for captured CO_2 with supply and demand dynamics, as well as explicitly modelling CO_2 transportation and storage technologies.

An example of a technology featuring Carbon Capture and Storage (CCS) is presented in Table 3.3. The technology "t2" is essentially the same as "t1" in Table 3.2, but it incorporates CCS. “t2” possesses the same potential and uses gasoline with equivalent energy intensity as “t1”. However, “t2” also requires electricity to operate the CCS facility. To account for the capture and storage of CO_2, the technology has a negative energy input intensity for ‘Captured CO_2’. Additionally, the investment and operating costs of “t2” are higher than of "t1," reflecting the extra capital required for the CCS facility.

Table 3.3
Example of CCS in the abatement model

Name	Industry	Energy service	Year	Lifespan (years)	Potential (Share of energy demand)	Investment costs (billion EUR per PJ out)	Variable capital costs (billion EUR per PJ out)	Energy input	Energy intensity (PJ in per PJ out)
t2	10030	Heating	2020	5	0.13	1.2	0.2	Gasoline	1.11
								Electricity	0.1
								Captured CO_2	-60

Note: The unit for energy intensity regarding Captured CO_2 is ktCO_2 per PJ out.
Source: Author

In the workhorse version of the model, a technology catalogue is created to demonstrate the functionality of the abatement model. The technology data is developed to align with energy use in the base year of the benchmark data.[7] Additionally, four alternative electrification technologies are introduced for each energy service to facilitate technological change within the abatement model during policy experiments, such as in section 5. Each electrification technology has a potential of 10% and is more expensive than the other technologies in the base year. To establish the baseline scenario, all technology characteristics are forecast as constants. Hence, there is no technological change taking place in the current baseline scenario; however, this could be modified by adjusting technology characteristics over the time horizon of the model, i.e. by assuming that the costs of green technologies will fall and/or that the potential will increase going forward in time.

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[7] To reduce model dimensions, only the most emitting industries and energy services are included in the abatement data. The abatement data covers approximately 10 mtCO_2e or 50% of industry emissions.

4. Effects of a CO_2e-tax - without abatement model

In this section we investigate how the model reacts to a rise in CO_2e-taxation without the abatement model. This serves several purposes. Firstly, it is a demonstration of the possibility to turn modules on and off. Secondly, it is instructive for understanding the dynamics of the core CGE-model without the added complexity of the abatement model. Thirdly, it allows us to understand the effects of introducing green technologies in section 5.

We find that the model dynamics are similar to the Danish GreenREFORM model. All macroeconomic effects are in line with our expectations from similar shocks in the Danish GreenREFORM model. This alignment is particularly reassuring, as it was a primary objective of this project.

Specifically, we find that an increase in CO_2e taxation of €100 is expected to reduce emissions by approximately 6%, primarily by encouraging a shift in production from emission-intensive to labour-intensive industries. The tax revenue is recycled to households; however, there is still a decline in household welfare due to the combined effects of higher prices and lower wages.

4.1 A rise in CO_2e taxation

The tax increase is set at €100 per ton of CO_2e emissions on top of existing taxes and is phased in gradually from 2025 to 2030. The tax is announced in 2021 in the model, such that forward looking households and industries adjust their behaviour already in 2021.

Existing taxes (as of 2020) include CO_2 tax levied on energy use in both industries and households, as well as non-energy emissions in manufacturing processes of cement and other mineralogical activities.

To mitigate the financial impact on households, the revenue generated from this taxation is transferred directly to them. Thereby, the shock aims not only to incentivize reduced emissions but also to maintain consumer purchasing power in the face of rising prices. Moreover, unchanged production of public goods and services and neutral public finances are fundamental for accurate economic welfare cost evaluations.

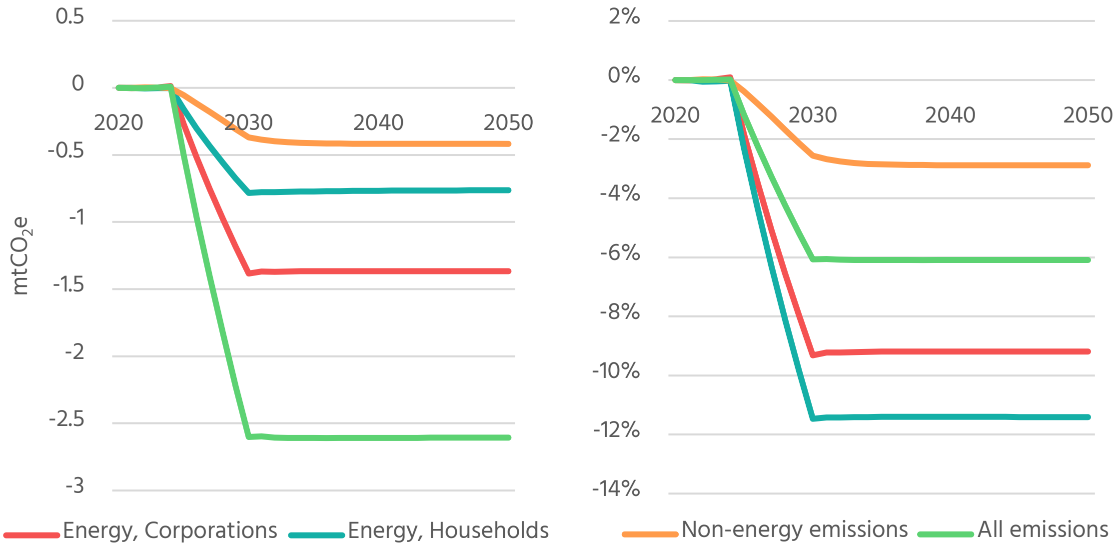
4.2 Effect on emissions

As the CO_2e tax increase is implemented, emissions are projected to decrease by approximately 6%. This reduction is primarily driven by a decline in energy-related emissions, as illustrated in Figure 4.1.

Energy-related emissions show the largest relative and absolute decreases, primarily because they account for the highest share of total emissions at the outset, making them the most significant target for reduction.

Figure 4.1

Changes in emissions: absolute (left) and percentage (right) relative to the baseline



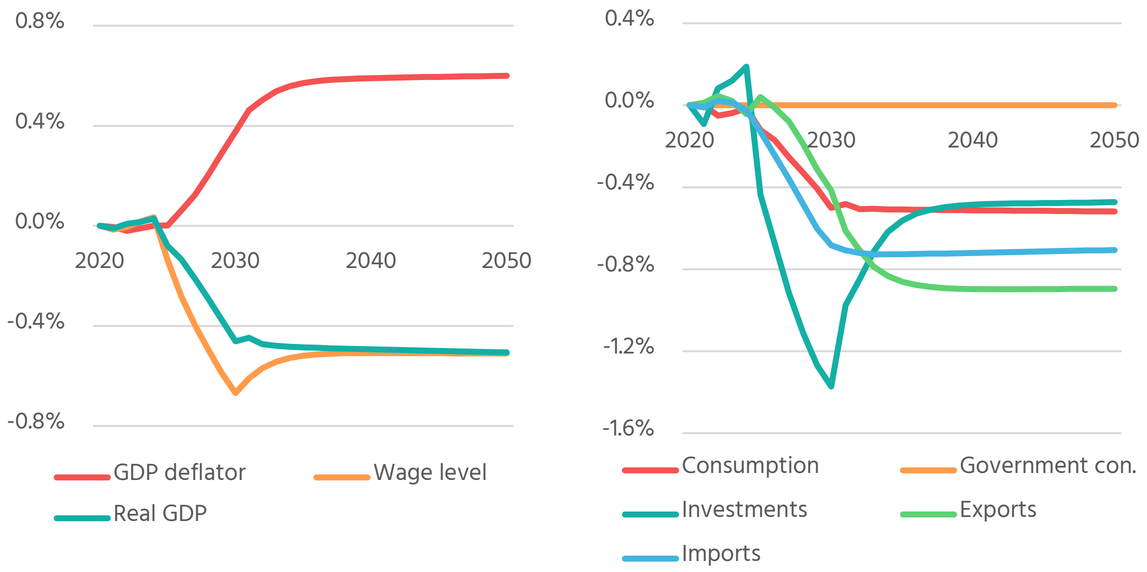
Source: Simulations on GreenREFORM EU

4.3 Macroeconomic effects

The increase in the CO$_2$e tax leads to higher prices, resulting in a GDP deflator increase of approximately 0.6%, as illustrated in Figure 4.2. These higher prices contribute to a decrease in demand, which immediately causes a decline in domestic production. This decline results in lower wages in the labour market and prompts a shift in production from high-emission industries to those with lower emissions and a higher labour share. Consequently, real GDP falls, primarily due to reduced energy consumption in production and a transition towards labour-intensive industries over capital- and material-intensive ones.

Figure 4.2

Changes in macro-economic variables, percentage change relative to baseline



Note: The right figure illustrates changes in quantities (vs values).
Source: Simulations on GreenREFORM EU

Real private consumption decreases, primarily because of rising consumer prices, as the nominal value of consumption is largely unchanged. Consumers' nominal consumption possibilities are influenced by two opposing effects that roughly offset each other: wages decline, but disposable income increases due to the revenue transferred from CO_2e taxation.

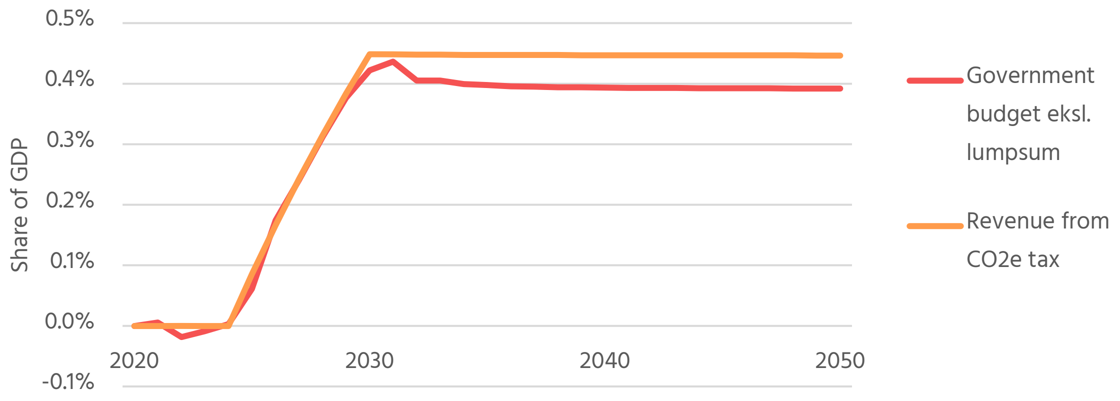
Exports also decline as export prices rise due to the tax increase, leading foreign markets to purchase fewer domestic goods and services. The desired level of capital falls as a result of the shift towards more labour-intensive industries. This trend results in a significant reduction in investments in the period leading up to 2035, when the capital stock stabilises at its new long-term level. Imports decrease as a consequence of lower levels of private consumption and investment.

4.4 The effect on public finances

The overall effect on public finances is neutral by design. The government budget improves due to the CO_2e tax, as illustrated in Figure 4.3. The net effect is that public finances enhance nearly in proportion to the revenue generated from the CO_2e tax, although this conceals a series of opposing effects. In this subsection, we will examine the various implications for public finances.

Figure 4.3

Public finances, changes in pct. of GDP



Source: Simulations on GreenREFORM EU

Public expenditures are affected by two main factors. Some expenses decline due to falling wages, while expenditures related to the lump-sum transfer increase.

The most significant changes occur on the revenue side. Direct taxes decrease as a result of lower wages, while indirect taxes rise, largely due to the direct effects of revenue generated from the CO_2e tax. Additionally, there are several notable effects: as energy consumption declines due to the tax, existing energy taxes also decrease. Conversely, VAT on energy goods increases, as it is applied on top of the direct CO_2e tax. Other indirect taxes, including VAT on non-energy goods, experience a slight reduction due to lower consumption levels.

Table 4.1

Public finances, absolute changes in 2040, bn. DKK

Expenditures	**6.5**	**Revenues**	**6.5**
Government consumption	-0.1	Direct taxes	-2.4
Household transfers	-2.1	Indirect taxes	8.5
Government investments	0.0	*CO2 tax, industries*	*4.2*
Other expenditures	-0.5	*CO2 tax, households*	*5.4*
Lump-sum transfer	9.1	*CO2 tax, non-energy*	*0.8*
		Duty on energy excl. CO2	*-1.9*
		VAT on energy	*0.8*
		Other indirect taxes	*-0.9*
		Other revenues	0.4

Source: Simulations on GreenREFORM EU

In summary, the CO_2e tax increase generates direct revenue for public finances. However, it also results in a decline in wages, leading to reduced expenditures and revenues that approximately offset each other. Additionally, while revenue from energy taxes decreases, VAT on energy goods increases.

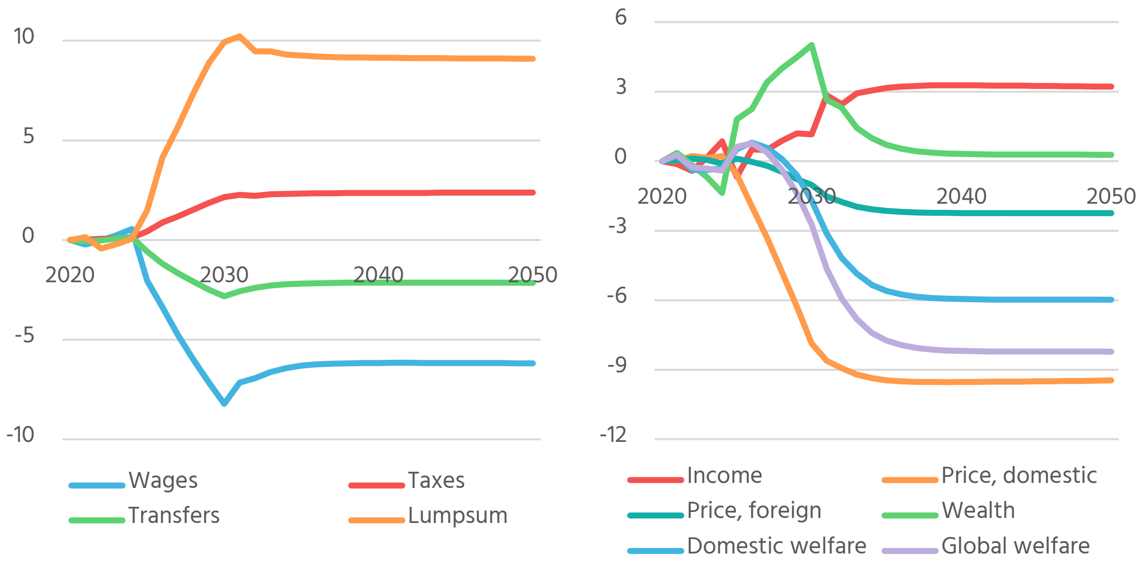
4.5 Welfare economic effects

The model quantifies the effects of the CO_2e tax on private economic welfare by measuring the change in households' consumption possibilities. Additionally, it considers how such a policy impacts foreign households and their consumption capabilities. The welfare measure comprises three main effects: income changes, price changes, and alterations in initial wealth.

The income effect includes changes in wages, transfers, taxes, and lump-sum payments. While wages, transfers, and taxes decrease, the lump-sum transfer contributes to an overall increase in income, as illustrated in Figure 4.4.

Figure 4.4

Welfare economic effects, absolute changes, bn. DKK



Note: Left figure is a decomposition of the income effect.
Source: Simulations on GreenREFORM EU

Changes in consumer prices directly impact domestic households, while shifts in export prices influence foreign households. As domestic prices rise due to the tax, household consumption is adversely affected.

Changes in future earnings affect the value of industries. Consequently, the wealth of the owners fluctuates when the tax impacts future earnings. The wealth effect is positive in the short term, owing to a temporary decline in investments, which results in an increase in dividend payouts.

5. Effects of a CO_2e-tax - with abatement model

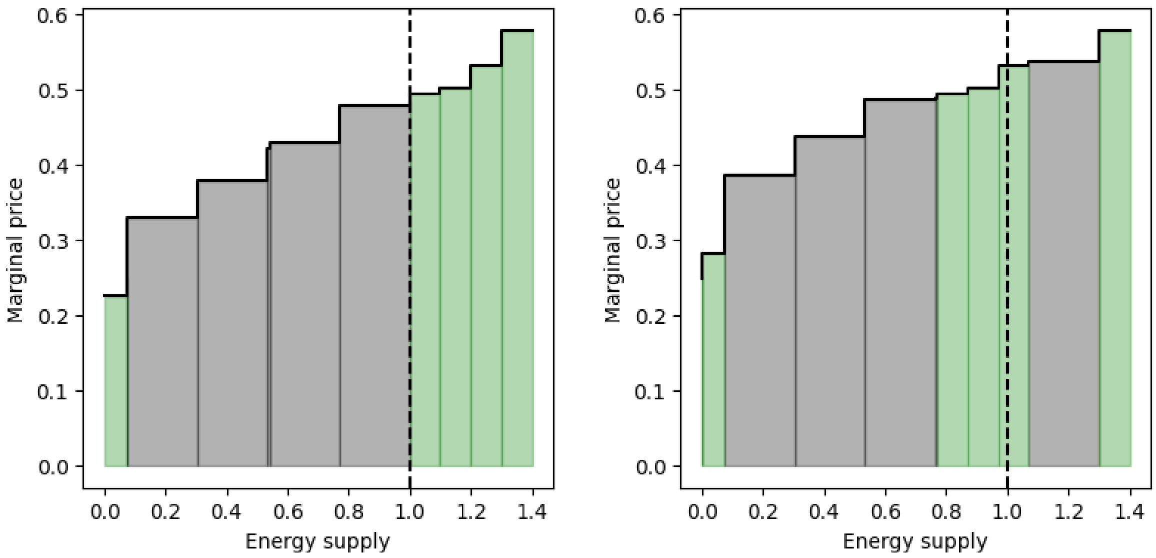
This section presents the effects of an increase in the CO_2e tax, when incorporating the abatement model into the overall model system. The policy scenario is otherwise consistent with that outlined in Section 4, specifically a €100 increase in the CO_2e tax in 2030.

The abatement model describes near-discrete changes in the energy inputs of industries based on specific technology data, as detailed in Section 2.8. Therefore, the increase in the CO_2e tax affects the merit order of energy-producing technologies, due to changes to the relative prices of these technologies.

Consider, for example, the technology choices in the domestic road freight transportation industry. In the baseline scenario, the most cost-effective technologies predominantly utilise fossil fuels. This is illustrated in the left-hand side graph of Figure 5.1, where fossil fuel technologies are represented in grey, while non-emitting technologies are shown in green. The dotted line in the figure indicates the equilibrium point, where energy supply equals the demand for energy services. Therefore, only technologies to the left of the dotted line are employed in the baseline. In the baseline scenario, approximately 88% of total energy demand in the freight transport industry is satisfied by diesel fuel.

Figure 5.1

Example of supply curve of energy in the abatement model in baseline (left) and policy scenario (right)



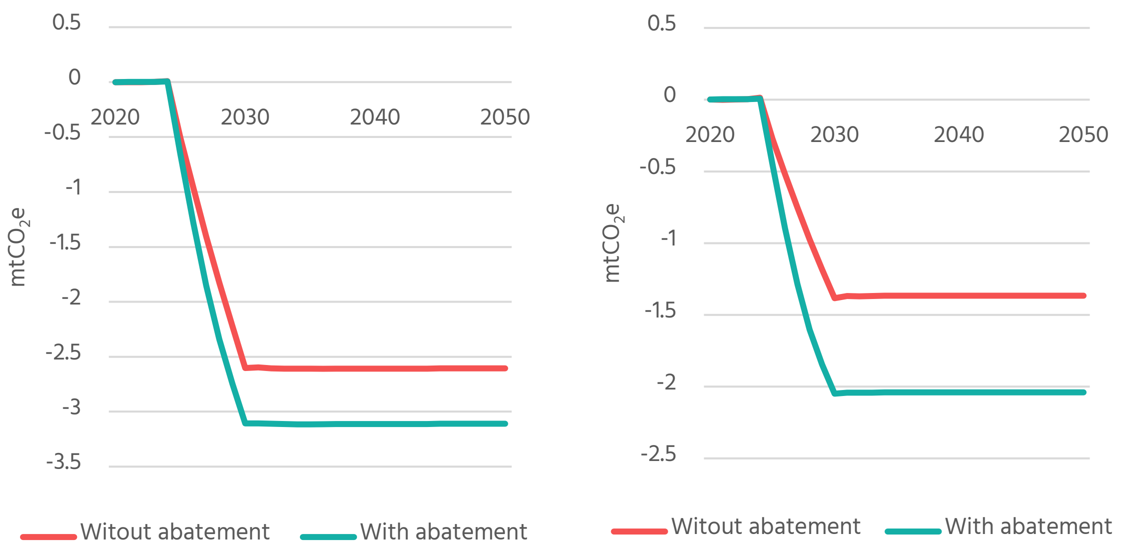
Source: Simulations on GreenREFORM EU

In the policy scenario, fossil fuel technologies become more expensive due to the increase in the CO_2-tax. This renders “green” technologies more attractive, thereby altering the cost ranking on the supply curve, as illustrated in the right-hand graph of Figure 5.1. In this scenario, one of the fossil technologies (a diesel technology) is replaced by “green” alternatives. Consequently, only 70% of the energy demand is met by diesel, while the use of electricity rises from 4% to 22% of total energy demand.

As illustrated in Figure 5.2, the impact on emission reductions across the overall economy is greater when the abatement model is included.

Figure 5.2

Changes in emissions, total (left), and industry energy use (right), absolute change relative to baseline



Source: Simulations on GreenREFORM EU

The abatement model introduces flexibility in the composition of energy inputs, which differs from the standard assumptions in the CGE-model. Without the abatement model, there is still a shift away from more expensive fossil fuels towards green energy; however, this shift is less pronounced than when the abatement model is included. The flexibility provided by the abatement model mitigates the cost increases of energy services resulting from the higher CO_2e tax. As a result, production costs rise less when the abatement model is integrated into the overall model.

5.1 Macroeconomic effects

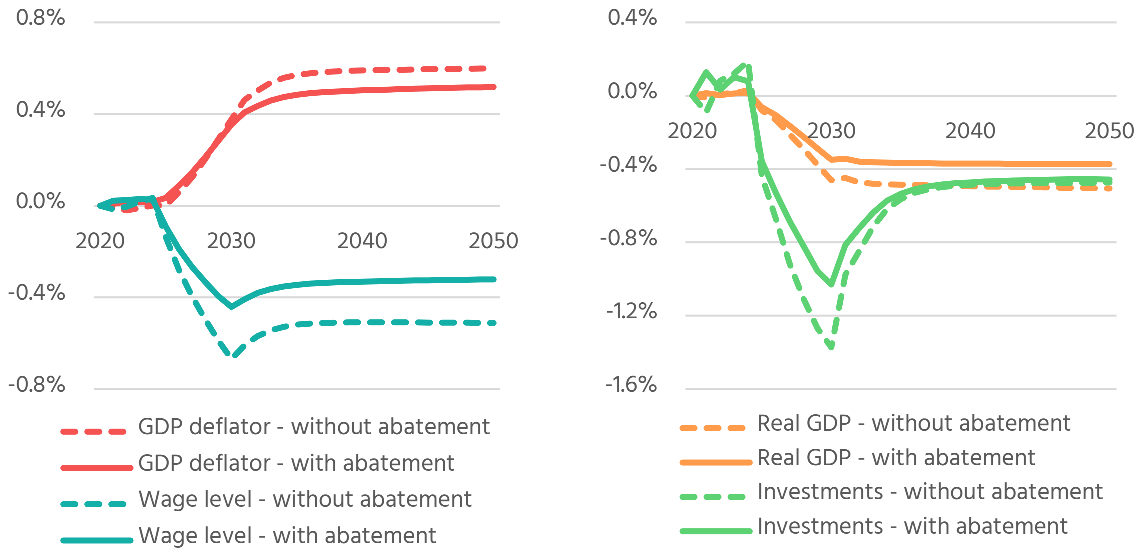
Incorporating the abatement model mitigates the impact of the CO_2e tax on macroeconomic indicators compared to the findings presented in Section 4. Firstly, wages do not decline as significantly as they would without abatement technologies, as illustrated in Figure 5.3. This is because production can be maintained at a higher level in industries where abatement is feasible, thereby alleviating the negative effects on labour demand. Furthermore, the demand for abatement technologies leads to an increased demand for labour in sectors that specialise in providing these technologies.

The overall GDP deflator does not increase as significantly as it would in the absence of abatement technologies. This is because industries can mitigate their rise in total production costs by utilising abatement technologies, as explained above. While the smaller decline in wage levels would, in isolation, exert upward pressure on the GDP deflator, the initial effect of the reduced tax burden is more pronounced.

The overall decline in real GDP is less pronounced with the inclusion of abatement technologies, as the shift towards labour-intensive industries does not occur at the same rate. Additionally, investment in abatement technologies mitigates the decline in overall investments.

Figure 5.3

Macro economic effects with and without abatement, % change compared to baseline



Source: Simulations on GreenREFORM EU

5.2 The effect on public finances

The direct effect of abatement on public finances is a lower revenue from the CO_2e tax on industries, as shown in Table 5.1. Additionally, the shift in energy inputs leads to further declines in other energy-related duties. Together, these two effects result in reduced revenues when abatement technologies are available.

Wage declines are less pronounced with the inclusion of abatement, as previously described, resulting in a smaller decrease in direct taxes and household transfers. Overall, this leads to an improvement in public finances; however, the effect is less substantial compared to the impact of reduced energy consumption. Consequently, public finances improve to a lesser extent with abatement, as evidenced by a reduction in lump-sum transfers.

Table 5.1

Public finances with and without abatement technologies, changes in 2040, bill. kr.

	Without	With		Without	With
Expenditures	**6.5**	**6.3**	**Revenues**	**6.5**	**6.3**
Government consumption	-0.1	0.0	Direct taxes	-2.4	-1.4
Household transfers	-2.1	-1.4	Indirect taxes	8.5	7.4
Government investments	0.0	0.0	*CO2 tax, industries*	*4.2*	*3.5*
Other expenditures	-0.5	-0.3	*CO2 tax, households*	*5.4*	*5.4*
Lump-sum transfers	9.1	8.1	*CO2 tax, non-energy*	*0.8*	*0.8*
			Duty on energy excl. CO2	*-1.9*	*-2.6*
			VAT on energy	*0.8*	*0.8*
			Other indirect taxes	*-0.9*	*-0.6*
			Other revenues	0.4	0.3

Source: Simulations on GreenREFORM EU

5.3 Welfare economic effects

The introduction of abatement technologies impacts welfare costs through a series of opposing effects, rendering the overall effect on total welfare costs complex. On one hand, welfare costs diminish because wages do not decline as significantly, and consumer prices show a smaller increase. On the other hand, the greater reductions in emissions achieved through abatement technologies lead to a decrease in tax revenue generated from the CO_2e tax. This, in turn, results in reduced lump-sum transfers to households, which increases welfare costs. Consequently, the net effect on welfare costs remains ambiguous due to these opposing influences.

A crucial factor affecting several of these outcomes is the price of abatement technology relative to the tax burden. If the cost of abatement technology is significantly lower than the tax burden, the adverse price effect will be mitigated more effectively. Simultaneously, the structural effects and the associated decline in wages will be less pronounced. Conversely, if the price of abatement technology is very close to the tax rate, the wage and price effects will resemble those observed without abatement, and the lost revenue from the CO_2e tax will outweigh the overall welfare loss, resulting in increased welfare costs.

In the specific calculations, a range of inexpensive abatement technologies is introduced, leading to a reduction in the overall welfare loss; however, this is solely a consequence of the assumptions made regarding the abatement technologies.

A. Description of the action

Appendix A presents extracts from the 'Description of Action' section of the project grant agreement of TSI project 101195159 GreenREFORMEU.

A.1 Needs analysis and specific objectives

From a technical modelling perspective, participating Member States face similar challenges despite using diverse models. Currently, all five rely on either partial equilibrium models or aggregated Computable General Equilibrium (CGE) models. CGE models, which are dynamic models that estimate how an economy reacts to policy, technology, or other external factors, can capture macro-economic effects but at the expense of aggregating specific technology information and coarsely modelling technology choices. On the other hand, partial equilibrium models allow for technology-specific policies but lack feedback to the rest of the economy. Both approaches carry the risk of over- or under-estimating the effectiveness and impact of different measures, leading to sub-optimal decision making.

To overcome these limitations, it is proposed that a CGE model be complemented by bottom-up technology data, such as the GreenREFORM model developed by the Danish Research Institute for Economic Analysis and Modelling (DREAM). This combination will provide Member States with a robust tool to accurately model the macroeconomic costs of their Net Zero transition and meet their NECP requirements.

The project will involve 2 study visits to Copenhagen, where training will be provided to the BA's modelling teams. The joint deliverable of the project will be a workhorse model ready for use in different member states.

The host will conduct an online opening plenary session to present the project plan, and the model in general terms to teams from different member states. The presentation will focus on the theory behind the model, practical modelling challenges, and data requirements.

After the opening session, member states can choose to follow a track leading to the construction of a simplified workhorse model based on the GreenREFORM philosophy. Member states with existing modelling capacity can proceed with this option. Other member states can choose to follow up on the progress made.

For the BAs, this involves preparing a dataset (supply and use / io tables / income accounts) that will serve as the basis for building the model. For DREAM, this involves preparing a workhorse CGE model that is simplified for use outside the specific Danish context.

During the first study visit, DREAM will host a series of workshops in Copenhagen. The technical framework for the model will be presented, based on a much simplified version of the final model. During the workshops, DREAM will share experience of stakeholder management of the GreenREFORM project and expand on the themes discussed during the opening session, ie. theoretical underpinnings of the GreenREFORM model, introduction of emission abatement technology curves into CGE models, and practical data collection considerations.

Between the two study visits, DREAM will develop the ‘work horse model’ and do remote support of the BA’s in their efforts to collect and prepare data for the model. The support of collection and preparation of data will be partly subcontracted to Statistics Denmark.

Statistics Denmark (DST) serves as the national statistical office in Denmark and is entrusted with compiling Danish official statistics, including the national accounts and environmental-economic accounts. All data used for calibrating the base year of GreenREFORM is provided by DST, which is responsible for ensuring accuracy and internal consistency.

Data collection and calibration efforts should first focus on national accounts statistics, energy balances and emissions accounts. In the early stages, the workhorse model will run on artificial technology catalogues.

Depending on the progress of the BA’s, the second visit may focus on specific data requirements, particularly technology catalogues. But ideally, technology data should be collected and prepared prior to the second study visit, to meet the project objectives. These catalogues should ideally provide an exhaustive list of emission bases, potential emission reductions, and costs for each sector and abatement technology. However, in practice, there are multiple issues, such as non-exhaustive catalogues from different sources.

A.2 Impact and ambition

In the short and medium term, the BA's will acquire a customised "workhorse" CGE model using their own national datasets. This will enhance their ability to identify, assess, and select the most efficient and effective policies and investments for the green transition. It will also enable them to forecast energy balances and emissions.

In the long term, the model can be expanded to include additional sector-specific sub-models and more detailed descriptions of national regulations, similar to the approach taken in Denmark. However, it is important to note that these extensions will add complexity to the model and require additional data. Therefore, they should only be implemented once users are familiar with the model and a solid data foundation has been established. In Denmark Statistics Denmark has dedicated funding for yearly updates and ongoing development of the core data for GreenREFORM. This project can also serve as a blueprint for other countries to develop their own customised models based on their specific data and needs. Building models on a common framework can offer significant advantages.

A.3 Complementarity with other actions and innovation — European added value

DREAM has extensive experience in building macroeconomic models, specifically CGE-models. They initially developed the "Danish Rational Economic Agents Model," a complex structural CGE-model that incorporates overlapping generations and rational agents with perfect foresight. DREAM is also based on National Accounts and includes households, firms, and a public sector, allowing for the assessment of fiscal sustainability.

In recent years, DREAM has been asked to develop models for the Danish Ministry of Finance, namely MAKRO and GreenREFORM. MAKRO, in contrast to DREAM, bridges the gap between the medium-term and long-term, allowing for meaningful medium-term behaviour. GreenREFORM serves as an analytical tool for assessing the environmental and climate impact of economic policies, as well as the economic effects of environmental, energy, and climate policies.

Additionally, DREAM excels in projecting educational and labour market attainment, providing a vital input for all of the aforementioned models. For more information, please visit www.dreamgroup.dk.

Over the past four years, DREAM has also developed model systems for the Greenland Ministry of Finance and the Fiscal Council of Slovenia. These models draw on the experience gained from DREAM's diverse range of economic models but are simpler and more comprehensible. Simplicity, without compromising representativeness, is considered a necessary condition when introducing a system of models to clients who may be unfamiliar with such a framework.

A.4 Concept and methodology

The workhorse model will be developed using the latest version of GAMS, which has introduced a new technical framework that facilitates integration between GAMS itself and Python. This new integration allows for the application of a modular approach to model design, which aligns with the method previously employed in the models GreenREFORM and MAKRO. However, the current models depend on 'gamY', a software developed in-house by DREAM. Given gamY's limited user base and lack of support from a larger organisation, a shift to the new GAMS-Python framework is proposed. This shift requires the model to be built from scratch but presents a significant benefit: it ensures a more future-proof model reliant on consistent updates and support solely from the GAMS corporation, rather than both GAMS and gamY.

Relying on current research, a new and more advanced version of the abatement module found in GreenREFORM is expected to be implemented in the workhorse model. The abatement module enables bottom-up integration of technology information and endogenous (approximately) discrete choice of technology similar to what is found in energy systems models like TIMES.

The text below describes the CGE-model and the abatement module of GreenREFORM in Denmark, which will be the key elements in the workhorse model developed in the current project.

The CGE-model

The core of GreenREFORM is a dynamic computable general equilibrium model (CGE-model), similar to the model MAKRO, for which a full documentation is available (Bonde et al., 2023). For GreenREFORM, documentation consists of a rather large number of disparate working papers, while a complete model documentation is not yet available. Both models are available for download and can be run on a powerful PC with a license for GAMS and the solver CONOPT.

The CGE-model of GreenREFORM is similar to MAKRO. Some aspects are more evolved in GreenREFORM and vice versa, reflecting the importance of specific areas for the focus of the model. MAKRO is built for marrying short and long-term macroeconomic forecasts and for analysis of economic policy at the Ministry of Finance. The core of the model is a standard structural dynamic CGE model with overlapping generations and perfect foresight. Sound short-term dynamics are achieved by introducing various nominal short-term rigidities inspired by the DSGE-literature, with determining parameters fitted using match impulse response functions of estimated S-VAR models (DREAM, 2021).

In GreenREFORM, the overlapping generation model is simplified (Blanchard, 1985) and only the most important nominal rigidities are currently maintained, i.e., sluggishness in export demand, capital accumulation, wage adjustment (Phillips curve), and myopic behaviour of a share of households. Based on our experience, these are the key features for achieving realistic Keynesian multiplier effects in a model for a small open economy.

In other respects, GreenREFORM is much more complex than MAKRO. GreenREFORM expands the number of sectors from 9 to 52, which produce a total of 81 products and services, including 26 types of energy. On the demand side, energy is divided into five so-called tax purposes to reflect differences in the tax system. Methodology has been developed to represent correct marginal tax rates on energy for each of these purposes, with adjustment in taxes paid due to discrepancies with national account statistics due to bottom rate deductions or statistical error. Finally, a model-consistent dynamic welfare measure has been developed.

Production and price setting

Each sector is represented by a generic CES-production function, wherein capital and energy are considered complementary. The energy usage of each sector is categorised into six purposes (transportation, normal process, etc.) and further divided into 26 distinct energy inputs. The complementarity between energy and capital is explained through the abatement model, as mentioned in section 7. The production function determines the unit cost for each sector. Firms within the market compete under monopolistic competition and establish their market price by adding a mark-up to the unit cost. Consequently, an increase in unit cost leads to higher market prices and reduced production due to decreased demand. In energy-producing sectors and agriculture, a CET-function is utilised to divide output into energy and agricultural products, along with a residual output. For sectors such as cement, refinery, fishery, and oil and gas extraction, regulatory restrictions or capacity constraints on production are assumed, along with fixed world market prices. In such cases, the level of production is determined by external forecasts, and firms operate with variable profit margins instead of a fixed mark-up as explained earlier. Currently, firms in these sectors are assumed to operate at the maximum level of production, hence there is no inherent response from firms in the event of a significant decline in profits, which would be expected.

Demand and households

Households, government, and the outside world all contribute to total demand in the economy. The response to price changes on the demand side is crucial for the model's outcome. Therefore, there has been significant empirical research exploring the relationship between price changes and demand, especially in relation to exports, which tend to have the highest fluctuations in prices.

The dynamic behaviour of households, including their savings decisions, can be described in two ways. First, there are forward-looking households with initial wealth who make savings decisions to maximise their utility over their lifetimes. Second, there are credit-restricted households without any initial wealth, who have an incentive to use all their disposable income each period. Incorporating both types of households allows the model to capture realistic short-term responses and responses to future policy changes. These two types of households divide total consumption in a given year in the same manner.

A CES-consumption function determines how willing households are to substitute between different products as prices change. Furthermore, this function determines how price changes in specific sectors translate to overall changes in household utility. Changes in household utility, in turn, affect the welfare function of the model, which can be used to conduct economic welfare analyses. The welfare change can be attributed to changes in prices, changes in income, and changes in wealth resulting from changes in the value of firms.

The abatement model

The most important submodel of GreenREFORM is the 'abatement model'. This model allows for approximate discrete changes in the energy input composition in any particular industry based on bottom-up information on the character of alternative technologies. In many energy and climate economic CGE models, changes in technology are represented by a subnest in the production function that allows for substitution between 'brown' and 'green' energy, or between capital and energy. In bottom-up energy system models, changes in technology occur through discrete choices between specific technologies. Even if based on the same underlying information, these two approaches can lead to very different results in practice.

The inspiration for the abatement model is found in existing energy system optimisation models like the TIMES model of the Danish Energy Agency (DEA). TIMES is a discrete optimisation model that aims to minimise the total costs of producing a certain demand for 'energy services'. The DEA uses a soft-linking or iterative approach to couple TIMES with a static CGE model. In GreenREFORM, the ambition is to hard-link all submodels so that the complete system of sub-models can be solved simultaneously.

In the discrete optimisation model, a central planner allocates the demand for 'energy services' to individual technologies in order to minimise total costs. GreenREFORM's abatement model and the energy system model replace the central planner with individual cost-minimising behaviour. Thus, the representative firm in a given sector is presented with a discrete choice of adopting a range of alternative technologies. A technology is defined by its ability to replace a share of input of a certain type of energy with an alternative set of inputs, typically a mix of another type of energy and machinery capital. The technology will be adopted if the costs of adoption are lower than the costs of the baseline energy input. This is determined by a profitability indicator function.

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C. Documentation of the abatement model

Appendix C presents a rigorous documentation of the abatement model of GreenREFORM EU.

Documentation of the Abatement Model of the GreenREFORM EU Model

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June 2nd, 2025

1 Foreword

This note provides preliminary documentation of the abatement model of the GreenREFORM EU model. Section 2 offers a brief introduction to the CGE model of GreenREFORM EU, with which the abatement model interacts. This serves as the foundation for the introduction to the abatement model in Section 3, which discusses the key design features of the model. Section 4 presents the three core equations of the model, emphasizing intuitive understanding rather than mathematical rigor. A comprehensive theoretical documentation is provided in Section 10. Section 5 offers a brief presentation of various supplementary outputs. Section 6 discusses various issues related to the statistical properties of the log-normal distribution. Section 7 provides a brief introduction to a separate model used for tracing supply curves. Section 8 introduces the Excel-based data input module, which allows the model to be scaled flexibly according to the properties of the provided data. Finally, Section 9 offers a brief introduction to residual reporting variables.

2 The CGE Model

GreenREFORM EU is a dynamic CGE model with forward-looking expectations and fully integrated energy and emissions accounts. Energy goods are represented in physical units of energy content. Energy is used as an input into production in each industry or for household consumption. Energy input can be divided into various purposes, which may represent tax brackets and/or different technical applications of energy use. Furthermore, input of energy is complemented by a quantity of machinery capital. For each purpose, the aggregate of energy and capital is referred to as an 'energy service'. In the CGE model, production is described by standard nested CES demand functions, including the aggregation of energy and machinery capital to 'energy services'. Energy-related emissions in the CGE model are linked to energy input through exogenous emission coefficients.

GreenREFORM EU is a single-country model designed to be adopted in any given country and can be further tailored as needed. The number of industries, energy services, and types of energy inputs and emissions represented depend on the data available for any specific country. A benchmark dataset has been developed for Denmark. Building on this data, the Danish version of the GreenREFORM EU model features 53 industries, 29 types of energy inputs, 5 tax purposes, and 11 types of emissions.

3 Introduction to the Abatement Model

The abatement model provides an alternative description of the production of energy services, where the demand for energy input as well as emission coefficients can change discretely based on exogenous information about available technologies. The abatement model can function in full integration (hard-linked) with the CGE model or as a standalone partial model. In the latter case, the abatement model describes the cost-minimizing technology mix at given input prices and given demand for energy services. When integrated with the CGE model, the demand for energy services and input prices are endogenously determined by the CGE model and provided to the abatement model, while the price of energy services and the demand for inputs (energy and capital) are determined by the abatement model and provided to the CGE model. Changes in input prices during simulation compared to baseline assumptions thus alter the merit order of technologies simultaneously, and changes in the price of energy services concurrently affect the demand for energy services.

The abatement model is inspired by energy system models such as TIMES. Indeed, the ambition is to bridge the gap between the top-down approach of CGE models and the bottom-up approach of energy system models. The abatement model has two distinct technical features that set it apart from energy system models, which are crucial for achieving full integration with the CGE model, allowing both models to be solved by the same solver.

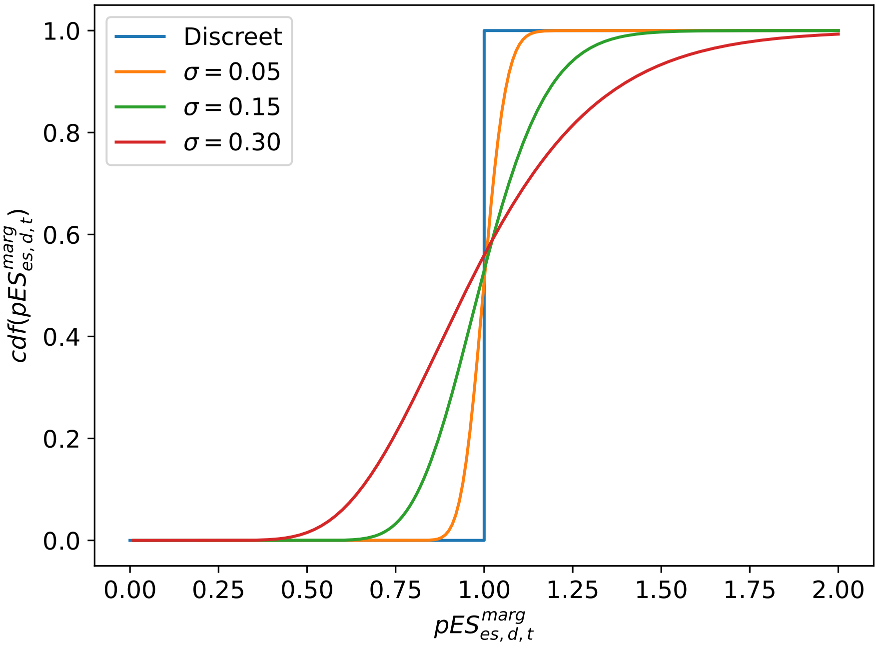
1) First, in the tradition of CGE models, optimization is decentralized to the respective agents of the model. This contrasts with energy system models like TIMES, which feature centralized cost minimization. In the abatement model, representative agents for firms and households adopt all cheaper technology options at their respective potentials until the price point where demand for energy service is exactly satisfied. Mathematically, this is expressed as

$$sqT_l = \begin{cases} sqT_l^{Potential} & \text{if } pT_l \leq pES^{marg} \\ 0 & \text{otherwise} \end{cases}$$

where sqT_l is production of energy service by technology l and $sqT_l^{Potential}$ is potential production. Both in relative terms to demand. pT_l is the unit cost, and pES^{marg} is the price point where supply equals demand for energy service.

2) The true discrete choice of energy system models is replaced by a continuous approximation: The costs of variants i of a technology l are assumed

Figur 1: Continous approximation of discrete choice



to be log-normally distributed. The share of variants that meet the criteria $pT_l^i \leq pES^{marg}$ can then be described in continuous form by the cumulative distribution function (cdf) of the unit costs pT_l^i.

The production by technology l is thus

$$sqT_l = sqT_l^{potential} \cdot cdf\left(pES^{marg}\right) \tag{1}$$

Figure 1 pictures the cumulative distribution function with an arbitrary expected value of pT_l^i equal to 1. Depending on the variance of the distribution (σ^2), if the marginal price of energy service is higher than 1 the technology will be fully adopted, and otherwise not.

As illustrated, if the variance of the distribution is set close to zero, the approximation to the discrete form is very close. This is optimal in the case that only one variant of a technology exists. In energy system models, technologies are often separated into many variants to capture variations in costs. In the abatement model, this can instead be captured explicitly by adjustment of the variance of the distribution, potentially reducing the computational size of the model substantially.

In the current version of the abatement model, the variance is not in the unit costs of a technology but specifically in the underlying capital intensity. This is to ensure that the energy intensity of technologies is determined directly by exogenous data, which makes intepretation of model results easier. It is also done to avoid a caveat, that dividing a technology into many variants with variation in energy effeciency may result in unrealistic implicit assumptions about the energy efficiency of both low-cost and high-cost variants.

It does however also make the model slightly more complex than portrayed above, cf. section 4.

4 The Core Equations Explained

In this section we present three core equations and three variables of the model in the same form as in the GAMS-code itself, while also striving to provide further intuition.

A technology is a means of producing an energy service (es) such as heating, cooling, or propulsion in a given industry (d) in a given year (t) by a specific quantity of energy of various types (e) and machinery capital. Each technology has the potential to supply a fraction $sqT^{potential}_{l,es,d,t}$ of any given amount of energy service. For each technology l, there exists a subset of variants i. Each variant differs only by its capital intensity of production; that is, all variants of a technology have the same energy efficiency. For intuition, consider all heat pumps within a given category having equal energy efficiency, while costs of installation and maintenance may differ depending on specific circumstances.

All variables of the abatement model are defined on (es, d, t). To simplify the presentation, we suppress this, so that for example $sqT^{potential}_{l,es,d,t}$is presented as $sqT^{potential}_{l}$.

We start by defining the marginal price of energy services pES^{marg} as the price point at which the supply of energy service equals demand. In the model, pES^{marg} is implicitly determined by the previously mentioned market equilibrium, which in relative terms is

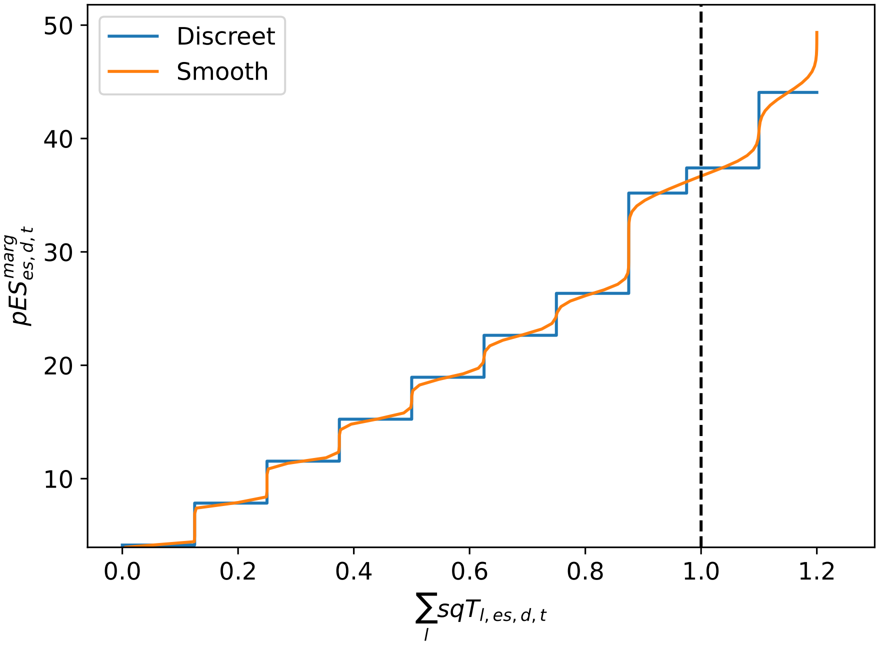
$$1 = \sum_{l} sqT_l \tag{2}$$

where sqT_l is the share of demand for energy service produced by technology l.

Figure 2 pictures the sum of supply by technologies relative to demand on the x-axis at different price points on the y-axis. The dotted line represents total demand, and the intersection equilibrium. As in Figure 1, the supply curve in discrete form is pictured as a blue curve for comparison. Again, the approximation to the discrete form is close, if the variance is close to zero.

The unit cost of variant i of technology l is a function of the underlying capital intensity, or in mathematical terms $pT^i_l\left(utk^i_l\right)$, where utk^i_l is the capital intensity drawn from a random variable $UTK_l$with cumulative distribution function *cdf* and probability distribution function *pdf* We further assume that input ratios are fixed (Leontief production), such that the cost (or price) per unit of energy service produced by variant i of technology l is

Figur 2: Market equilibrium



$$pT_l^i\left(utk_l^i\right)=\sum_e\left(uTE_{l,e}\cdot pTE_e\right)+utk_l^i\cdot pTK_l \tag{3}$$

where $uTE_{l,e}$ is the energy intensity, pTE_e is the price of energy input, and pTK_l is the price of capital.

Now, as explained before, variant i will produce only if the unit cost is lower than or equal to the marginal price of energy service, i.e., if

$$pT_l^i\left(utk_l^i\right)\leq pES^{marg}$$

By combining the two equations above and rearranging, it can be shown (see Section 10) that this effectively places a restriction on the capital intensity of technology variants, such that only variants with capital intensity lower than a threshold value $uTK^{marg}{}_l$ will produce. Formally, $uTK^{marg}{}_l$ is defined as

$$uTK^{marg}{}_l\equiv\frac{pES^{marg}-\sum_e uTE_{l,e}\cdot pTE_e}{pTK} \tag{4}$$

The share of variants i of technology l with capital intensity lower than $uTK^{marg}{}_l$ can be found using the cumulative distribution of UTK_l, i.e., $\mathit{cdf}\left(uTK_l^{marg}\right)$.

Finally, the production by technology l relative to the demand for energy service is restricted to $sqT_{l,es,d,t}^{potential}$. It is assumed that the potential is uniformly distributed across variants. This allows us to complete the model by defining the supply function at the technology level as

$$sqT_l=sqT_l^{potential}\cdot\mathit{cdf}\left(uTK_l^{marg}\right) \tag{5}$$

The core equations of the model are 2, 4, and 5. Together, they solve for the core variables sqT_l, pES^{marg}, and uTK_l^{marg} at exogenous values of the remaining variables and a well-defined distribution UTK_l. Specifically, we assume a log-normal distribution with mean value uTK_l^{exp} and standard deviation σ, both of which are also exogenously determined.

5 Supplementary Output

The demand for energy in the production of energy services $qESE_{l,e}$ is the average energy intensity of technologies $uTE_{l,e}$ weighed by their respective share of energy service demand sqT_l times total energy service qES, ie.

$$qESE_{l,e}=qES\cdot\sum_l sqT_l\cdot uTE_{l,e} \tag{6}$$

While the energy intensity of technologies is exogenously determined, the capital intensity is endogenously determined in the model. Observe that uTK_l^{exp} is the unconditional expected capital intensity. In the case where only a subset of variants are adopted, the average capital intensity of these will be lower. In the continuous form of the model, this measure, which we call uTK_l, is captured by the conditional expectation of UTK_l with respect to an upper threshold of

${uTK^{marg}}_l$, as only variants with realizations of UTK_l lower than or equal to ${uTK^{marg}}_l$ are adopted, or mathematically

$$uTK_l = E[UTK_l | utk_l^i \leq {uTK^{marg}}_l] \tag{7}$$

The demand for machinery capital in the production of energy services $qESK$ is thus

$$qESK = qES \cdot \sum_l sqT_l \cdot uTK_l \tag{8}$$

Note however, that the expression for $qESK$ in the GAMS-code is slightly different, cf. section 6 and specifically equation 12.

The costs of producing an energy service vES (v for value) is

$$vES = \sum_e (qESE_{l,e} \cdot pTE_e) + qESK \cdot pTK$$

Finally, the price of energy services pES is simply the value divided by the quantity of energy service:

$$pES = \frac{vES}{qES}$$

6 Issues Related to the Log-Normal Distribution

We assume that UTK_l follows a log-normal distribution as follows:

$$log(UTK_l) \sim N\left(log\left({uTK^{exp}}_l\right) - \frac{\sigma^2}{2}, \sigma^2\right)$$

This formulation guarantees that the expected value of UTK_l is ${uTK^{exp}}_l$.

It follows that the cumulative distribution can be formulated as follows

$$cdf\left({uTK^{marg}}_{l,es,d,t}\right) = \Phi\left(\frac{log\left(uTK^{marg}\right) - log\left(uTK^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right) \tag{9}$$

, where Φ is the cumulative distribution of the normal distribution.

The partial expected value of UTK_l with respect to an upper threshold ${uTK^{marg}}_l$ is

$$E^{partial}\left(uTK_l^{marg}\right) = uTK_l^{exp} \cdot \Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2} - \sigma^2}{\sigma}\right) \tag{10}$$

Finally, the conditional expectation of UTK_l with respect to an upper threshold ${uTK^{marg}}_l$ is the fraction between the partial expectation and the cumulative distribution, i.e.:

$$
\begin{aligned}
E^{conditional}\left({uTK^{marg}}_l\right) &= E[UTK_l | utk_l^i \leq {uTK^{marg}}_l] \\
&= \frac{E^{partial}\left(uTK_l^{marg}\right)}{cdf\left(uTK_l^{marg}\right)} \\
&= \frac{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2} - \sigma^2}{\sigma}\right)}{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right)}
\end{aligned}
\tag{11}
$$

In the practical implementation of the model, the conditional expectation has been prone to lead to 'division by zero' errors in GAMS. To avoid this, we only calculate uTK_l after the model is solved in the reporting section of the model. uTK_l only enters in equation 8. By inserting from equation 5 into equation 8, we can avoid an explicit representation of uTK_l:

$$
qESK = qES \cdot \sum_l sqT_l^{potential} \cdot cdf\left({uTK^{marg}}_l\right) \cdot \frac{E^{partial}\left(uTK_l^{marg}\right)}{cdf\left(uTK_l^{marg}\right)}
$$

which simplifies to

$$
qESK = qES \cdot \sum_l sqT_l^{potential} \cdot E^{partial}\left(uTK_l^{marg}\right) \tag{12}
$$

The domain of the log-normal distribution is restricted to positive values. If, for a particular technology, the costs of energy input in production ($\sum_e uTE_{l,e} \cdot pTE_e$) exceed the marginal price of energy pES^{marg}, the marginal capital intensity in equation 4 will be negative. This presents the problem that the cumulative distribution function cannot be evaluated outside the domain of the distribution.

The practical solution is to distinguish between an unbounded version (labelled 'unbounded' in GAMS) expressed by equation 4, and a bounded version called uTK_l^{marg}, which enters in its place in all other equations. The bounded version is restricted to values above 0 by continuous approximation. We also introduce an upper bound at 5 standard deviations above ${uTK^{exp}}_l$. This limits the potential production of technologies ever so slightly while helping the solver converge in some cases.

In the abatement model GAMS code, all of the above functions are represented by macro functions with '@' as prefix and similar names as in this text. The functions themselves are defined in the file 'functions.gms'. This is also the case for the function used to set bounds on ${uTK^{marg}}_l$.

7 The Energy Service Supply Curve

The abatement model provides a singular point on the energy service supply curve, i.e., at a given level of energy service demand. To facilitate a better understanding of the model, it is useful to be able to trace the entire supply curve, as illustrated in figure 2. This is done in the file 'supply_curves.gms', where a supply curve simulation model is defined and simulated. Technically, it is quite involved, but the underyling principles are simple enough: Building on the core variables and equations in Section 4, we first replace the market clearing condition (equation 2) with an exogenous threshold price pES^{marg}. Next, we expand all core equations and variables with a extra set dimension n in this exposition. This allows us to solve the model for $sqT_{l,n}$ for a range of price prices pES_n^{marg} simultaneously. Finally, summing across technologies l provides a measure $sQES_n$ of the total supply of energy service relative to demand, i.e.

$$sQES_n = \sum_l sqT_{l,n} \tag{13}$$

The supply curve model is obviously useful for making illustrations like the above. More importantly, it can be used to discover unusual errors in the input data and to help understanding why the solver fails to converge in a particular experiment.

The supply curve simulation model is also used as a pre-model to gain good initial values for the core variables of the abatement model. When used as a pre-model, the supply curve model is simulated, and initial values are picked from n, where $sQES_n \cong 1$.

8 Excel-Based Input Module

The partial abatement model is based on an excel-based data module in the file 'Abatement_dummy_data.xslx'. In the input module, the user determines the scope and scale of the model (e, es, d, t) as well as the energy demand, technology characteristics (l), energy prices etc. The input module consists of six different data sheets:

1. Model sets: Definition of set elements of the model. Note, that the set elements do not have to be consistent with the CGE-model as long as the abatement is used as stand-alone. The sets that is used by the model are:
   (a) TechID: Technology names
   (b) e: Energy input
   (c) es: Energy service
   (d) d: Industry
   (e) t: Year
2. Technologies: Determines the technology characteristics. A technology has to be assigned an element in each of the above mentioned sets. A technology is defined through three parameters:
   (a) Potential: Translate into $sqT_l^{potential}$, which defines the share of the energy service that the technology can supply.

   (b) Energy intensity: Translate into uTE_l, which defines the amount of energy input required to supply one unit of energy output.
   (c) Capital intensity: Translate into uTK_l^{exp}, which defines the amount of capital required to supply one unit of energy output.

3. Energy price: Determines the base price of the different energy inputs, which translate into pTE^{base}.
4. Energy tax: Determines the tax on the use of energy input, which translate into pTE^{tax}. Together with the energy price this makes up the total price of energy input.
5. Capital cost index: Determines a cost index for capital costs.
6. Energy service: Determines the amount of energy service demanded by the specific industries.

9 Report Variables

[Document reporting variables in output]

10 Appendix: Rigorous documentation of the Core Model

We assume that the quantity produced qT_l^i is a Leontief production function of inputs:

$$qT_l^i = min\left\{\frac{qTE_{l,1}^i}{uTE_{l,1}}, ..., \frac{qTE_{l,E}^i}{uTE_{l,E}}, \frac{qTK_l^i}{utk_l^i}\right\}$$

where $qTE_{l,e}^i$ is energy input e and qTK_l^i is capital input in the i-th variant. Note that we assume that $uTE_{l,e}$ is identical for all variants, but that utk_l^i differs.

In optimum, this implies that:

$$qTE_{l,e}^i = uTE_{l,e} \cdot qT_l^i \tag{14}$$

$$qTK_l^i = utk_l^i \cdot qT_l^i \tag{15}$$

The price of output by variant i of technology l is as follows:

$$pT_l^i\left(utk_l^i\right) = \sum_e uTE_{l,e} \cdot pTE_e + utk_l^i \cdot pTK_l \tag{16}$$

where pTE_e is the input price of energy, and pTK is the user cost of capital (the same for all variants).

The quantity of variant i is restricted by:

$$qT_l^i \leq sqT_l^{Potential} qES \tag{17}$$

where $sqT_l^{Potential}$ is the relative potential of variant i (the same for all variants) and qES is the total use of the energy service.

The user of the energy service (a firm or a consumer) seeks to minimize their costs, given a fixed level of energy service qES, and will thus choose to adopt all lower price variants until demand is satisfied.

Total costs vC is given by:

$$vC = \sum_l \int_0^\infty pT_l^i \left(utk_l^i\right) \cdot qT_l^i \left(utk_l^i\right) \cdot pdf \left(utk_l^i\right) dutk_l^i$$

where $qT_l^i \left(utk_l^i\right)$ is qT_l^i given utk_l^i (a policy function), and where $pdf \left(utk_l^i\right)$ denotes the probability density function of UTK_l.

The total costs should be minimized under the restrictions (17) and the restriction:

$$\sum_l \int_0^\infty qT_l^i \left(utk_l^i\right) \cdot pdf \left(utk_l^i\right) dutk_l^i = qES \tag{18}$$

where qES is the total use of the energy service. For this purpose, we define a Lagrange function:

$$\begin{aligned} L = & \sum_l \int_0^\infty pT_l^i \left(utk_l^i\right) \cdot sqT_l^i \left(utk_l^i\right) \cdot pdf \left(utk_l^i\right) dutk_l^i \\ & - pES^{marg} \left(\sum_l \int_0^\infty sqT_l^i \left(utk_l^i\right) \cdot pdf \left(utk_l^i\right) dutk_l^i - 1 \right) \end{aligned}$$

where

$$sqT_l^i \left(utk_l^i\right) \equiv \frac{qT_l^i \left(utk_l^i\right)}{qES}$$

and pES^{marg} is the shadow price of the restriction. Observe that we have normalized with qES. We should minimize the Lagrange function under the additional restrictions:

$$sqT_l^i \left(utk_l^i\right) \leq sqT_l^{Potential}$$

We can re-write the Lagrange function:

$$\begin{aligned} L = & \sum_l \int_0^\infty \left(pT_l^i \left(utk_{l,}^i\right) - pES^{marg}\right) sqT_l^i \left(utk_l^i\right) \cdot pdf \left(utk_l^i\right) dutk_l^i \\ & + pES^{marg} \end{aligned} \tag{19}$$

From (19) it is clear that the policy function is given by:

$$sqT_l^i \left(utk_{l,}^i\right) = \begin{cases} sqT_l^{Potential} & \text{if } pT_l^i \left(utk_l^i\right) \leq pES^{marg} \\ 0 & \text{otherwise} \end{cases}$$

or equivalently from (16):

$$sqT_l^i\left(utk_l^i\right) = \begin{cases} sqT_l^{Potential} & \text{if } utk_l^i \leq uTK_l^{marg} \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

where

$$uTK_l^{marg} \equiv \frac{pES^{marg} - \sum_e \left(uTE_{l,e} \cdot pTE_e\right)}{pTK} \tag{21}$$

The market clearing condition is given by

$$\sum_l sqT_l = 1 \tag{22}$$

where from (20):

$$\begin{aligned} sqT_l &\equiv \int_0^\infty sqT_l^i\left(utk_l^i\right) \cdot pdf\left(utk_l^i\right) dutk_l^i \\ &= sqT_l^{Potential} \int_0^{uTK_l^{marg}} pdf\left(utk_l^i\right) dutk_l^i \\ &= sqT_l^{Potential} cdf\left(uTK_l^{marg}\right) \end{aligned} \tag{23}$$

where *cdf* is the cumulative distribution function. Observe that this expression is identical to equation 5.

The average price of energy service pES is given by:

$$\begin{aligned} pES \equiv \frac{vC}{qES} &= \sum_l \int_0^\infty pT_l^i\left(utk_l^i\right) \cdot sqT_l^i\left(utk_{l,}^i\right) \cdot pdf\left(utk_l^i\right) dutk_l^i \\ &= \sum_l \left(\sum_e uTE_{l,e} \cdot pTE_e\right) \cdot \int_0^\infty sqT_l^i\left(utk_l^i\right) \cdot pdf\left(utk_l^i\right) dutk_l^i \\ &+ pTK \cdot \sum_l \int_0^\infty utk_l^i \cdot sqT_l^i\left(utk_{l,}^i\right) \cdot pdf\left(utk_l^i\right) dutk_l^i \\ &= \sum_l \left(\sum_e uTE_{l,e} \cdot pTE_e\right) \cdot sqT_l^{Potential} \cdot cdf\left(uTK_l^{marg}\right) \\ &+ pTK \cdot \sum_l sqT_l^{Potential} \cdot \int_0^{uTK_l^{marg}} utk_l^i \cdot pdf\left(utk_l^i\right) dutk_l^i \\ &= \sum_l \left(\sum_e uTE_{l,e} \cdot pTE_e\right) \cdot sqT_l^{Potential} \cdot cdf\left(uTK_l^{marg}\right) \\ &+ pTK \cdot \sum_l sqT_l^{Potential} \cdot cdf\left(uTK_l^{marg}\right) \cdot E\left[UTK_l | utk_l^i \leq uTK_l^{marg}\right] \end{aligned} \tag{24}$$

as

$$E\left[UTK_l|utk_l^i \leq uTK_l^{marg}\right] = \frac{\int_0^{uTK_l^{marg}} utk_l^i \cdot pdf\left(utk_l^i\right) dutk_l^i}{cdf\left(uTK_l^{marg}\right)}$$

Inserting from 23 in 24 and rearranging leads to

$$pES = \sum_l \left(sqT_l \sum_e \left(uTE_{l,e} \cdot pTE_e\right) + pTK \cdot E\left[UTK_l|utk_l^i \leq uTK_l^{marg}\right] \right) \tag{25}$$

, which can be observed to be consistent with equation 3 and 7 combined.

We now make the specific assumption that UTK_l follows a log-normal distribution as follows:

$$log(UTK_l) \sim N\left(log\left(uTK_l^{exp}\right) - \frac{\sigma^2}{2}, \sigma^2\right)$$

This formulation guarantees that the expected value of UTK_l is uTK_l^{exp}.

It follows that the cumulative distribution can be formulated as follows, where Φ is the cumulative distribution of the normal distribution:

$$cdf\left(uTK_l^{marg}\right) = \Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right) \tag{26}$$

It can be proven that:

$$E[UTK_l|utk_l^i \leq uTK_l^{marg}] = \frac{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) - \frac{\sigma^2}{2}}{\sigma}\right)}{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right)} uTK_l^{exp} \tag{27}$$

From (25) we then have that:

$$pES = \sum_l \left(sqT_l \sum_e \left(uTE_{l,e} \cdot pTE_e\right) + pTK \cdot \frac{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) - \frac{\sigma^2}{2}}{\sigma}\right)}{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right)} uTK_l^{exp} \right) \tag{28}$$

From (23) we have that:

$$qT_l = sqT_l^{Potential} \cdot \Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right) \cdot qES$$

From (14) we have that:

$$qTE_{l,e} = uTE_{l,e} \cdot qT_l$$

which can be observed to be consistent with equation 5 and 6 combined.

And from (15) and (27):

$$\begin{aligned}
qTK_l &\equiv \int_0^{\infty} qTK_l^i pdf\left(utk_l^i\right) dutk_l^i \\
&= \int_0^{\infty} utk_l^i \cdot qT_l^i \cdot pdf\left(utk_l^i\right) dutk_l^i \\
&= qT_l^{Potential} \cdot \int_0^{uTK_l^{marg}} utk_l^i \cdot pdf\left(utk_l^i\right) dutk_l^i \\
&= qT_l^{Potential} \cdot \Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right) \cdot \frac{\int_0^{uTK_l^{marg}} utk_l^i \cdot pdf\left(utk_l^i\right) dutk_l^i}{\Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right)} \\
&= qT_l^{Potential} \cdot \Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) + \frac{\sigma^2}{2}}{\sigma}\right) \cdot E[UTK_l | utk_l^i \leq uTK_l^{marg}] \\
&= qT_l^{Potential} \cdot \Phi\left(\frac{log\left(uTK_l^{marg}\right) - log\left(uTK_l^{exp}\right) - \frac{\sigma^2}{2}}{\sigma}\right) \cdot uTK_l^{exp}
\end{aligned}$$

which is consistent with equation 12.