DREAM
Danish Research Institute for
Economic Analysis and Modelling

GREEN REFORM

Development of the GreenREFORM model

Sharing learnings from development of the climate and energy-economic CGE-model GreenREFORM

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Preface

With growing international interest in the project, the aim of this paper is to share the experience and learnings from the development of the GreenREFORM model. The content is based on numerous presentations and discussions with people from the global policy and modelling community over the past few years.

We have aimed to strike a balance between making the text relevant and inspiring to a broad audience, while still providing food for thought for model developers and economists like ourselves. We would greatly appreciate any comments and recommendations for future revisions of the text.

The list of references at the end of the paper is primarily intended for fellow modellers. Unfortunately, some of the working papers and other materials are only available in Danish. We recommend using Google Translate to access these resources, as it typically does a good job of translating both websites and PDF documents.

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1. The story of GreenREFORM

The idea for creating the GreenREFORM model was first conceived in 2016 by Professor of Economics Peter Birch Sørensen. In his role as chairman of the Danish Council on Climate Change, he recognized an unresolved need for appropriate analytical tools that would facilitate the systematic integration of climate and environmental considerations into the design of economic policy. The goal was therefore to provide the Danish government, as well as think tanks and other organizations, with a new analytical tool that would enable the integration of economic policy with climate and environmental policy.

In collaboration with Peter Stephensen, a specialist in applied models and the research director at DREAM (Danish Research Institute of Economic Analysis and Modelling), Peter Birch Sørensen wrote the initial research grant application that would form the foundation of GreenREFORM (Stephensen & Sørensen, 2017). The timing was good, as DREAM was already in the early stages of developing a new macroeconomic model, called the MAKRO model, for forecasting and analysing economic policy on behalf of the Danish Ministry of Finance (MoF). The GreenREFORM research project therefore aimed to build upon this existing framework by incorporating considerations for natural resource use, pollutant emissions, and more detailed modelling of key sectors such as energy, transport, waste treatment, agriculture, fishery, forestry, and land use.

The research grant for the GreenREFORM project was awarded in 2017, and a research team was assembled, consisting of 2 PhD. students and an associate professor, in addition to Peter Birch Sørensen himself.

A conundrum quickly emerged: existing sector-specific models are typically formulated as discrete optimization problems, whereas macroeconomic models operate within a continuous problem space. It's evident these two frameworks don't readily align. Therefore, the primary challenge for the research team became how to reformulate the sector-specific models into a continuous space, enabling seamless integration with the macroeconomic model. The primary motivation behind this endeavour is the significant computational efficiency gained compared to an approach involving iterative processes between disparate model types.

In 2019, the MoF became involved and provided additional funding to establish a team of four dedicated model developers at DREAM. Up until that point, university researchers had been focused on developing individual sector-specific models without considering how they would integrate in the broader scheme. It became the responsibility of the new team at DREAM to construct the macroeconomic model and integrate the sector-specific models in a unified model framework in co-operation with the researchers.

At that time, the aforementioned MAKRO model was well underway in development at DREAM. MAKRO is built upon a new technical framework enabling a modular design approach, featuring a system of submodels that can be decoupled to operate independently when necessary. GreenREFORM adopts the same strategy and platform.

The researchers had developed submodels with significantly greater granularity than what standard national accounts offer. Convincing the various stakeholders was a considerable challenge, but eventually, Statistics Denmark was assigned the responsibility of constructing a new comprehensive experimental dataset to bolster the model. The focus at the initial stages was on internal consistency rather than absolute accuracy. Consequently, data gathering and pre-processing were outsourced, as these tasks can often consume a substantial amount of time that should be allocated to model development.

Another crucial aspect of the project has been the collaboration between DREAM, university researchers, and various stakeholders from both inside and outside of the government, facilitated through a project board chaired by Peter Birch Sørensen and a larger following group of potential future users of the model.. The initial two years were notably intense, characterized by monthly board meetings followed by discussions with the following groups. While this approach did demand significant resources, it also fostered a sense of urgency from the outset, which ultimately proved successful.

In 2021, a parliamentary agreement commissioned an expert group to propose new policies aimed at regulating industrial and agricultural emissions, with the goal of meeting the government's ambitious 2030 climate targets. When the expert group prepared its initial report (Svarer et al, 2022), GreenREFORM was not yet operational. However, in the second and final report of 2024 focusing on agricultural emissions (Svarer et al., 2024), GreenREFORM was extensively utilized by the expert group. This marks the first real-world application of GreenREFORM by the government, while other projects are already underway.

Peter Birch Sørensen's ambition from the outset was to make GreenREFORM open source. The version of the model utilized by the expert group has been released for download, enabling stakeholders and researchers to conduct their own analyses using the same model and set of assumptions employed by the expert group. Additionally, DREAM has established a server with all the required software, further enhancing accessibility to the model.

2. Project objectives

The original research proposal (Stephensen & Sørensen, 2017) outlines the project objectives as follows: The goal is to develop a modelling tool, which will allow the evaluation of economic and environmental policy within a unified conceptual framework that accounts for environmental as well as economic effects, thereby facilitating an integrated assessment of the two types of policy. GreenREFORM will expand on existing macroeconomic modelling capabilities in two ways:

1. Accounting for natural resource use and emissions of pollutants.
2. A more detailed modelling of key sectors. GreenREFORM will include a more detailed and disaggregated modelling of the following sectors which play a particularly important role in Danish environmental and climate policy: Energy, transport, waste treatment, agriculture, fishery, forestry, and land use more generally.

During the research period, the scope underwent some adjustments. Firstly, the primary focus remains predominantly on pollutants, while natural resource use is not yet described in much detail. Secondly, the researchers opted to concentrate on developing sector-specific models for energy, transport, waste treatment, and agriculture, while excluding fishery, forestry, and land use[1]. On the other hand, the scope was broadened to include the development of a general approach to modeling technological change across all sectors, known as the abatement model. Table 2.1 offers an overview of the various submodels.

The involvement of DREAM and the engagement with government administration since 2019 have introduced new priorities. For the Ministry of Finance, it was crucial that the baseline macroeconomic forecast and public finance forecast aligned with existing forecasts, ensuring consistency in both short and long-term dynamics, similar to the aforementioned MAKRO model. Likewise, the Ministry of Climate, Energy, and Utilities, responsible for forecasting energy balances, emissions etc., emphasized the importance of aligning the baseline statistics with existing forecasts. Significant resources are allocated to these calibration efforts. It's undeniably challenging to meticulously calibrate a model with forward-looking agents against a variety of external forecasts simultaneously. However, for the model's utility in government policy analysis, this work is indispensable. It ensures that the baseline can be swiftly adjusted as new forecasts become available.

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[1] The LULUCF-model as described in table 3.1 was developed later by DREAM.

Table 2.1
The submodels of GreenREFORM

Submodel	Description
CGE-model	The core of GreenREFORM is a dynamic computable general equilibrium model (CGE-model) describing a small open economy. The model features forward looking behaviour, a simple representation of overlapping generations, and various frictions to achieve credible short run dynamics. The CGE-model provides an a priori description of all sectors covered by the sector specific submodels. For further detail, see section 5.
Energy and emission accounts	Unlike the other submodels, the energy and emission accounts are integrated directly into the CGE-model. Currently, the model quantifies the supply and demand of 26 types of energy based on their energy content (joules). Additionally, the emission accounts describe 14 types of greenhouse gases and other pollutants using both national accounting standards and UNFCCC guidelines. For more details, see (Beck & Dahl, 2020).
Energy system	The energy system model is an intra-year dispatch model for district heating and electricity. It is based on plant-level data for Denmark and neighbouring price regions. The model operates within a continuous problem space and features decentralized decision-making, facilitating hard-linking with other submodels, much like the abatement model described in Section 6. To mitigate computational demands, dimensions are condensed through aggregation using clustering algorithms. Integrated with the CGE-model, the energy system model offers an alternative bottom-up depiction of demand for inputs in the production of electricity and district heating, including production quantities and prices. This information from the energy system model feeds back into the CGE-model through the recalibration of production functions, as outlined in Section 4. For more details, see (Berg, Eskildsen, & Kirk, 2020).
Agriculture	The agriculture model provides an alternative description of production in a total of 10 agricultural sectors. See section 8 and (Beck U. R., Berg, Christiansen, & Jørgensen, 2020) for further detail.
LULUCF	The LULUCF model computes emissions arising from land-use, land-use-change and forestry. It closely mirrors the methodology used in the National Emissions Inventory Report (NIR) submitted to the UNFCCC. The model is interconnected with the agricultural model, ensuring that shifts in land allocation by farmers correspond to NIR-consistent alterations in LULUCF emissions. This linkage extends to actions such as re-wetting carbon-rich agricultural soils and afforestation on agricultural land. For further detail, see (Berg, Eskildsen, & Kirk, 2020) and (Berg & Stewart, 2024).
Waste	The waste model describes production and treatment of waste across 17 different waste fractions (plastic, metal etc.). The model takes material consumption data from the CGE-model as input, detailing how material use leads to the generation of various waste fractions measured in tonnes. Additionally, the model outlines the treatment of generated waste within the economy, encompassing recycling, incineration, and other forms of material utilization, as well as import and export of waste materials. For further detail, see (Kruse-Andersen & Sørensen, 2020).
Carbon Leakage	The carbon leakage model calculates changes in foreign emissions resulting from policy changes in Denmark. For Instance, the implementation of a carbon tax in Denmark may decrease domestic production, potentially leading to increased production in other countries and consequently elevated emissions outside Denmark. This model relies on leakage factors, which delineate shifts in foreign emissions when Denmark alters its exports and imports of various commodities. These leakage factors are derived from computations conducted using a modified version of the GTAP-E model, which specializes in analysing global trade dynamics, energy utilization, and emissions. For further detail, see (Beck, Dahl, & Kruse-Andersen, 2021).
Transport	The transport model is a vintage based model for demand for vehicles. The vehicle fleet in a given year is divided into vehicle type, age, and fuel-type. The model feature endogenous network effects, which implies that optimal vehicle-investments depend on the stock of vehicles and existing fuel-infrastructure, and it is possible to compare subsidies for charging network versus subsidies for cars. When integrated, the demand for transportation is determined in the CGE-model, and the transport model determines the composition of the vehicle fleet, which feeds back into the demand for transport capital and energy for transportation in the CGE-model. For further detail, see (Eskildsen, 2020).
Abatement model	The abatement model enables approximate discrete changes in the input composition of energy input in any given industry, drawing on bottom-up information regarding the nature of alternative technologies. Further details can be found in Section 6.

For the Ministry of Taxation, providing a comprehensive description of relevant tax bases and tax incentives has been a key priority, along with the capacity to conduct economic welfare analysis using the model. To meet these requirements, Statistics Denmark was tasked with expanding the energy accounts to include an additional dimension called "tax-purpose," while the Ministry of Taxation supplied corresponding tables containing accurate tax rates. These rates directly influence the pricing of energy in the model (Kirk & Stephensen, 2022). Additionally, we have developed a welfare measure that aligns consistently with the model (Stephensen, 2024).

Reflecting on our experience engaging with various sector ministries, there is a persistent scepticism regarding the development of a new model with overlapping features already available in existing tools. On numerous occasions, proposals have been made to set boundaries for the model's scope. However, this contradicts the ambition of our research project. At DREAM, we believe that people have gradually come to appreciate that overlapping features should be viewed as a benefit. They facilitate mutual understanding of complex issues and streamline the transfer of specific evaluations from one model to another.

3. The data

When DREAM began its work in 2019, one of the initial challenges being addressed was the discrepancy between the level of granularity in the submodels developed by researchers and the standard provided by national accounts. For instance, the agriculture model detailed the production of feed and livestock across 13 agricultural sectors, whereas national accounts only feature a single aggregate sector. Similarly, the transport model aimed to segment the production of transport services into approximately 10-15 sectors, whereas national accounts encompassed only half that number.

As a strategic decision, the team opted to construct a comprehensive input-output system (IO system) covering production and demand for all goods and services outlined in the submodels, including a significant number of energy goods. Recognizing the magnitude of this endeavour, initial support was not readily forthcoming, as it would entail requesting additional funds almost at the project's outset. Moreover, Statistics Denmark, the institution responsible for constructing the new data, initially hesitated due to the scale of the task and concerns about data quality. Nevertheless, undeterred, Statistics Denmark was persuaded to develop an initial preliminary dataset with a focus on internal consistency rather than absolute accuracy. This provided DREAM with the foundational basis necessary to proceed, as detailed in Box 3.1. Presently, Statistics Denmark receives permanent funding to update the data annually, with dedicated resources allocated for enhancements and expansions.

While Statistics Denmark provides most of the data for supporting the base-year calibration of the model, the Danish Energy Agency (DEA) and the Ministry of Climate, Energy, and Utilities play a crucial role in supplying data for forming the baseline and information on costs and the adoption potential of future technologies. These agencies are responsible for establishing the official Danish forecast of energy balances and emissions. A significant portion of their work is based on the energy economic model IntERACT developed by the DEA. IntERACT integrates a static CGE model with the energy system model TIMES to simulate the interaction between the macroeconomy and technological advancements in producing so-called "energy services". The abatement model in GreenREFORM draws inspiration from the DEA's work and relies on the same dataset as the IntERACT model, as detailed in Section 6.

In a sense, GreenREFORM seeks to replicate what the DEA is already accomplishing, while relying on the DEA to provide the primary input to the model. Understandably, there has been some skepticism towards GreenREFORM. However, the ambition of GreenREFORM is not to supplant the work of the DEA, but rather to establish a connection between the bottom-up approach favored by the DEA and the top-down macroeconomic approach favored by the Ministry of Finance and the Ministry of Taxation. Presently, the DEA routinely provides updated data to GreenREFORM, as outlined in Box 3.2.

Box 3.1
Data from 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. In modelling projects like this, the collection and processing of data often consume a significant portion of resources allocated for model development. Outsourcing the collection and processing of data, and dedicating resources to it, has been crucial to the success of GreenREFORM.

The data provided by DST is made publicly available on a dedicated website, forming part of DST's collection of experimental statistics. Experimental statistics are not yet classified as official statistics, which allows for more flexibility in introducing new methods and gradually improving quality with each edition.

The core data consists of expanded input-output tables, energy balances, and emission accounts, which have been augmented to include a greater number of industries, increasing from 117 to 146. This disaggregation is tailored to meet the specific needs of the sector-specific submodels. Therefore, the emphasis is placed on providing a detailed description of the sectors that are most significant for climate and environmental policies.

Government regulations and available abatement options are influenced not only by the industry and type of energy but also by the specific technical or legal purpose for which the energy is used. This distinction is reflected in the tax system, where different taxes are applied based on the intended use of energy. For example, fuel used for transportation is subject to heavy taxation, whereas fuel used for heavy industrial processes has historically been largely exempt from domestic taxation until recent changes, as discussed in section 7. To accommodate these distinctions, the energy balances provided by DST are further categorized into six distinct "tax purposes."

Additionally, DST supplies various supplementary statistics, including data on vehicle stocks, detailed accounts of production-related taxes and subsidies, and statistics on the production and treatment of waste, among others.

Box 3.2
Data from the Danish Energy Agency

The Danish Energy Agency (DEA) and the Ministry of Climate, Energy, and Utilities firstly provide a forecast of energy balance accounts, emission accounts, and other statistics, which serve as the baseline for the dynamic calibrating of GreenREFORM, as outlined in section 2.

Secondly, the DEA supplies all data for the energy system model and most data for the abatement model (see table 3.1), drawing from inputs they utilize in their own electricity market model and the IntERACT model.

After preprocessing to align with the dimensions in GreenREFORM, the data for the abatement model describes a range of future technologies for each sector, tax purpose, energy type, and year, detailing the abatement potential and cost components of each technology. For example, 'heat pumps' may have the potential to reduce 50 pct. of the use of natural gas for heating purposes across industries and households, at a cost of 0.5 GJ of electricity and additional capital costs per 1 GJ of natural gas saved. Further details on the abatement model are provided in section 6.

4. A modular design approach

GreenREFORM owes much to its predecessor MAKRO, a model developed for forecasting and economic policy analysis commissioned by the Ministry of Finance. The team behind MAKRO, inspired by modern programming practices, adopted a modular approach to model design. GreenREFORM not only builds on the same technical framework as MAKRO but also extends the modular design approach further.

An essential enabling factor is a pre-processor to GAMS called GamY. GamY transforms custom macros into GAMS code, which is then processed by GAMS. GAMS, short for General Algebraic Modelling System, has been the preferred platform for building CGE models for decades. This preference stems from the similarity between the structure of defining variables and equations in GAMS and the formulation found in economic textbooks. Additionally, GAMS offers a suite of powerful algorithms, or "solvers."

For readers familiar with GAMS, the key feature of GamY is the so-called $Group and $Block statements, which enable batch operations on a set of variables (group) or equations (block). A model or module is thus defined as a group of endogenous variables and a block of equations. In GreenREFORM, we also maintain strict control over the set of exogenous variables, which are variables present in the block of equations but assumed to be exogenously determined in the particular model. For those interested, a small demonstration model has been made available for public download[2].

Combining modules often involves simply adding the respective groups and blocks together and allowing the solver to work on the combined system. When constructing the core CGE model, we aggregate several self-contained partial equilibrium models, as typically seen in textbooks. To solve the model, you begin by fixing the group of exogenous variables, releasing the endogenous variables, and then instructing GAMS to solve the block of equations.

Integrating the various submodels of GreenREFORM is a more complex task. A submodel may present an alternative representation of all or part of the production structure of firms in a particular sector, leading to some variables being endogenously determined by equations in both the CGE model and the submodel. In such cases, we basically aim to turn off those equations in the CGE-model. This can be achieved by either removing the specific equation from the model using a block statement, or, more commonly, by adding a scale parameter (defined as a variable in GAMS) to those equations in a group statement, thereby incorporating the submodel to inform a recalibration of the CGE model. This approach allows both models to coexist, enabling the possibility to run scenarios without the particular submodel at a later stage if necessary.

In some cases, the CGE-model and the submodels are not perfectly integrated. For example, the average price of electricity predicted by the energy system model might not perfectly align with the national accounts statistics upon which the CGE model is based. In such cases, we introduce a linkage equation with an error term between the electricity prices in the two models, allowing for the observed discrepancy to persist. For further details on integration between the CGE model and the energy model, please refer to (Stephensen, Berg, & Kirk, 2020).

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[2] Download of GamY demonstration model: https://github.com/MartinBonde/framework_model

5. 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). While GreenREFORM documentation consists of numerous dispersed working papers[3], a complete model documentation is not yet accessible.. Both models are available for download[4], and can be run by a powerful PC with a GAMS license and the CONOPT solver.

The CGE model of GreenREFORM shares similarities with MAKRO. However, certain aspects are more refined in GreenREFORM, while others are more developed in MAKRO, reflecting the varying importance of specific areas for the model's focus.

MAKRO is designed to merge short and long-term macroeconomic forecasts and to analyse economic policy for the Ministry of Finance. The core of the model is a standard structural dynamic CGE model with overlapping generations and perfect foresight. To ensure sound short-term dynamics, various nominal short-term rigidities are introduced, drawing inspiration from the Dynamic Stochastic General Equilibrium (DSGE) literature. The parameters of these rigidities are determined by fitting impulse response functions using S-VAR models, see (DREAM, 2021).

In GreenREFORM the overlapping generation model is simplified (Blanchard, 1985). Currently, only the most critical nominal rigidities are retained, including sluggishness in export demand, capital accumulation, wage adjustment (Phillips curve), and myopic behaviour of a portion of households. Through our experience, we have found that these features are essential for achieving realistic Keynesian multiplier effects in a model tailored 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, resulting in the production of a total of 81 products and services, including 26 types of energy. On the demand side, energy is categorized into 6 tax purposes to reflect differences in the tax system. Methodologies have been devised to accurately represent marginal tax rates on energy for each of these purposes, with adjustments made to taxes paid to account for discrepancies with national account statistics stemming from bottom-rate deductions or statistical errors (Kirk & Stephensen, 2022). Finally, a model consistent dynamic welfare measure has been developed (Stephensen, 2024).

5.1 Sectors

The CGE model is constructed based on the extended version of the national accounts provided by Statistics Denmark, as outlined in Table 3.1. As a standard, the national accounts include 117 sectors at the most disaggregated level. However, the extended version comprises 146 sectors. From this level, certain sectors, primarily service sectors, are aggregated to reduce the model's size.

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[3] www.dreamgruppen.dk [Danish] [English]

[4] GreenREFORM is available for download at www.Dreamgruppen.dk [Danish] [Google translate]

MAKRO is available for download on github: https://github.com/DREAM-DK/MAKRO/

5.2 Production and price setting

Each sector is represented by a generic CES-production function, with capital and energy modelled as complementary inputs. The energy usage of each sector is categorized into 6 tax purposes (transportation, normal process, etc.) and further divided into 26 distinct energy inputs. The complementarity between energy and capital is accounted for by the substitution between energy and capital, which is described by the abatement model, cf. section 6.

The production function determines the unit cost for each sector. Firms within each sector operate under monopolistic competition and set their market prices with a mark-up above the unit cost. Consequently, an increase in unit cost leads to a higher market price and a reduction in production due to decreased demand. In sectors related to energy production and agriculture, a CET- function is employed to allocate output between relevant energy and agricultural products, with any remaining output classified as residual *other output*.

In certain sectors being cement, refinery, fishery, and oil and gas extraction, we apply assumptions of regulatory restrictions or capacity constraints on production, along with fixed world market prices (Kirk & Hansen, 2023). In these cases, the level of production is dictated by external forecasts, and firms operate at variable profit margins rather than having a fixed mark-up as explained above. Currently, firms in these sectors are assumed to operate at the upper limit of production, thereby lacking an endogenous response to a significant drop in profits, as one would expect. See section 7 for further discussion on this matter.

5.3 Demand and households

In the economy, total demand is determined by firms themselves (due to material input in production), households, the government, and the outside world. The response to price changes on the demand side is crucial for the model's outcomes. Consequently, there has been significant empirical focus on the relationship between price changes and demand, particularly concerning exports, which typically experience the highest fluctuations as prices change.

The dynamic behaviour of households, such as savings decisions, is described partly by (i) forward looking households with an initial wealth and a savings decision that maximise their utility over a life cycle, and partly by (ii) credit restricted household without any initial wealth and incentive to use all of their disposable income in each period of time. The combination of these two types of households allows the model to generate realistic short-run responses and responses to future policy changes.

Both types of households allocate their total consumption in a given year in a similar manner. A CES consumption function governs households' willingness to substitute between different products as prices change. Additionally, the consumption function specifies how price changes in specific sectors translate into an overall change in households' utility. These changes in household utility drive adjustments in the welfare function of the model, enabling economic welfare analyses. The welfare change is disaggregated into changes in prices, income, and wealth due to fluctuations in the value of firms.

5.4 Calibration

The calibration process comprises both a static and dynamic part. The static calibration relies on detailed input-output data from Statistics Denmark (Table 3.1). Additionally, the dynamic calibration is based on official forecasts for macroeconomic development from the Ministry of Finance and official forecasts of energy balances and emissions from DEA and the Ministry of Climate, Energy, and Utilities (Table 3.2).

In the static calibration, every relationship between sectors, production inputs, consumption, and taxation is adjusted against empirical data. Each parameter in the production functions is determined to ensure that the model accurately replicates the actual utilization of input factors across different sectors, as well as the utilization of labour and capital. A similar procedure is applied to different types of consumption, taxation, and other interactions between the government, firms, households, and the rest of the world. Essentially, every aspect is calibrated to ensure that the model reproduces the observed data.

The calibration to macroeconomic development involves adjustments to underlying macroeconomic variables within GreenREFORM based on external factors sourced from the official forecast. Key external factors include demographic components such as population and labour force. Factors such as structural unemployment, growth and inflation rates, interest rates, and others are also implemented from the official forecast. Moreover, factors determining underlying productivity, consumption tendencies in production and consumption, and foreign demand are adjusted accordingly.

Through these adjustments, GreenREFORM is calibrated to mirror the same GDP development and underlying consumption components (private consumption, investment, government consumption, imports, and exports) as outlined in the official forecast from the Ministry of Finance. Finally, effective tax rates and transfer rates are fine-tuned to ensure that public finances evolve in line with the official forecast, with the exception of taxes on energy, where GreenREFORM's refinement is most evident (Andreasen & Kirk, 2020).

The energy inputs in production, energy production in each sector, household energy consumption, and energy involved in imports and exports are adjusted to align with the official forecast for energy balances, cf. table 4.2. This adjustment encompasses different types of energy and the purpose of energy use, achieved by modifying parameters in the production function and other relevant areas. Additionally, minor adjustments are made to emission coefficients to align with the official forecast for emissions.

The calibration process described above inevitably leads to various internal inconsistencies within the model. However, as GreenREFORM is now integrated into the yearly workflow of the government administration, every update of a particular forecast presents an opportunity for improvement. The high level of detail in GreenREFORM and its capability to generate alternative forecasts allow for challenging existing forecasts, fostering productive professional discussions about the underlying assumptions.

6. Bottom-up technology in a CGE-model

The most important submodel of GreenREFORM is the ‘abatement model’, facilitating approximate discrete changes in the composition of energy input in any given industry. This submodel is informed by bottom-up information on the characteristics of alternative technologies[5].

In many energy and climate economic CGE models, technological change is depicted through a sub-nest in the production function, allowing for substitution between 'brown' and 'green' energy or between capital and energy. In contrast, technological change in bottom-up energy system models occurs through discrete choices between specific technologies.

Even when based on the same underlying information, the two approaches can yield very different results in practice. To illustrate this, consider Figure 6.1, which depicts an inverse marginal abatement cost curve (MAC curve) in two scenarios. The red curve represents a top-down MAC curve with a constant elasticity of substitution between 'brown' and 'green' energy, while the blue curve depicts a bottom-up MAC curve with only a single 'green' technology, which becomes profitable at 75 EUR/t and reduces emissions by 30 percent. As shown, even if the top-down MAC curve is calibrated against bottom-up information, it is challenging to achieve a good fit across the entire spectrum. In this specific case, the top-down approach will overestimate emissions reductions at both small and large changes in carbon prices compared to the bottom-up approach.

The inspiration for the abatement model is drawn from existing energy system optimization models, such as the TIMES model developed by the DEA, as mentioned in section 4. TIMES is a discrete optimization model aimed at minimizing the total costs of producing a specific demand for 'energy services'. The DEA employs a soft-linking or iterative approach to couple TIMES with a static CGE model. In GreenREFORM, the ambition is to establish hard links between all sub-models, enabling the entire system of sub-models to be solved simultaneously.

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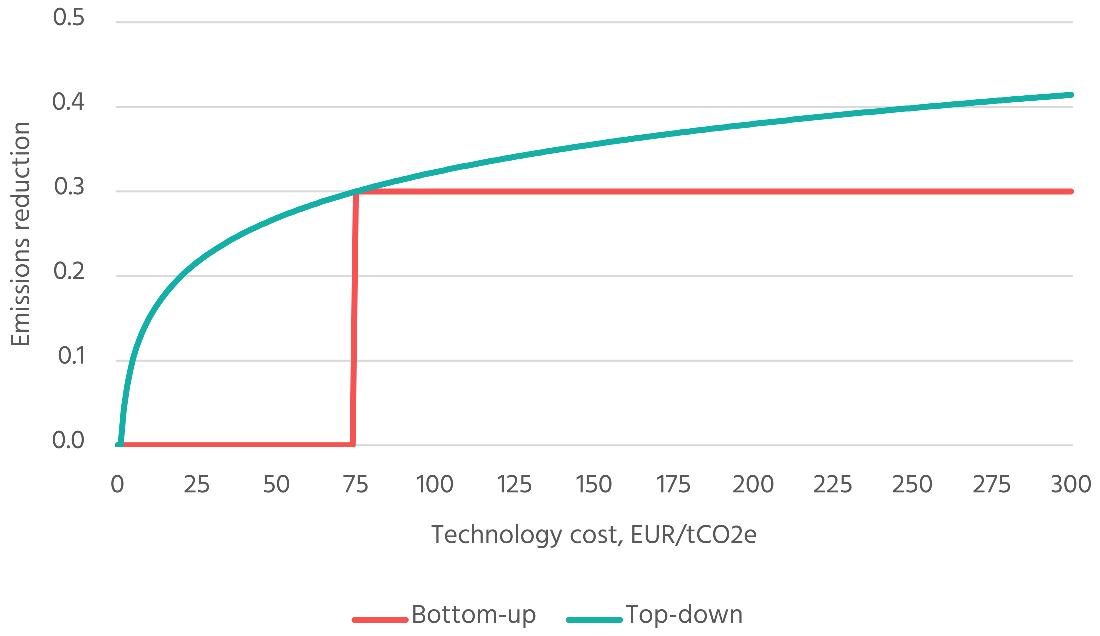
[5] See (Beck & Kirk, 2020), (Berg, Leisner, & Nielsen, 2020), and (Beck, Berg, & Stephensen, 2020) for early documentation. The methodology is currently undergoing revision.

Figure 6.1
Difference between bottom-up and top-down modelling



In the discrete optimization model, a central planner assigns the demand for 'energy services' to individual technologies to minimize total costs. In GreenREFORM, the abatement model and the energy system model replace this central planner with individual cost-minimizing behaviour. Thus, the representative firm of a given sector faces a discrete choice of adopting various alternative technologies. A technology is defined by its ability to substitute a share of input of a certain type of energy with an alternative set of inputs, typically a combination of another type of energy and machinery capital. Adoption of a technology occurs if the costs of adoption are lower than the costs associated with the baseline energy inputs. This decision is guided by a profitability indicator function. However, to facilitate a full integration with the CGE model, the profitability indicator function of the discrete model is approximated by a continuous function, resulting in the 'smoothed' lilac curve in Figure 6.2.

Box 6.1

Strategy for linking top-down and bottom-up models

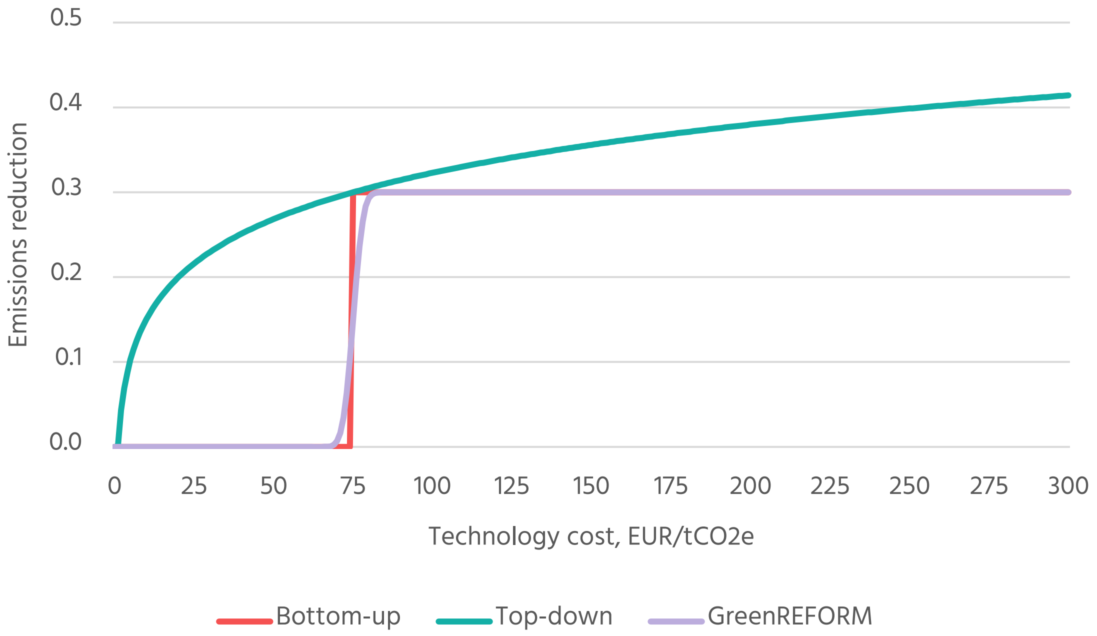
A central challenge in the project was integrating the economic model with various sector modules such as energy supply, transport, LULUCF, and abatement. An example of this challenge is linking macroeconomic models (e.g., CGE models) with energy system models, often referred to as linking top-down and bottom-up models (Fattahi et al., 2023). On one hand, there's a need to provide a top-down description of households' and firms' supply and demand, while on the other hand, there's a need to offer a detailed bottom-up description of the energy supply system, emissions, and abatement technologies..

The discussion often revolves around three approaches: soft-linking, hard-linking, and full integration (Wene, 1996; Holz et al., 2016; Fattahi et al., 2023). Soft-linking allows users to control information exchange between models. Hard-linking involves information exchange between a main model and a smaller reduced-form model. Integrated modelling, on the other hand, employs the same mathematical approach in both models. A well-known example of integrated modelling is (Böhringer & Rutherford, 2009), where mixed complementarity problems are utilized as the fundamental mathematical approach. With appropriate formulations, optimization problems of households and firms can be described similarly to the discrete problems typically associated with the energy supply system.

The advantage of soft-linking lies in its potential to connect a full macroeconomic model with a fully specified energy supply model. However, a drawback is that only a limited number of links can practically be established between the two models. In our case, we opted against soft-linking due to the considerable number of specialized modules that would need to be linked with the macroeconomic model. While soft-linking individual modules, such as an energy supply module, is feasible, doing so with numerous modules is not practical. Similarly, hard-linking was not suitable for us because we aimed for a high level of detail in all modules, including the economic model.

We chose to build a fully integrated system as it appeared to be the most robust solution for the many issues we need to analyse. Our approach differs somewhat from that of Böhringer and Rutherford (2009). While they describe economic agents using theory most naturally applied in the energy supply module (mixed complementarity problems), we chose the opposite strategy. We depict individual facilities of the energy system (as well as agents' abatement technologies) as small decentralized units that only operate when profitability is feasible. Each technology switches on or off based on economic viability. We add a smooth (or soft) version of this on/off mechanism, so that all modules can be described as part of the same large nonlinear equation system. It has been demonstrated that the system remains robust even when employing many thousands of such individual technologies.

Figure 6.2
Continuous approximation of bottom-up MAC curve



To facilitate the adjustment in inputs within the production structure of the CGE model, a (Leontief) subnest of energy input is incorporated into the CGE model. In this subnest, the share parameters are determined by the profitability indicator. Currently, in the baseline calibration, this feature is redundant because we calibrate energy demand against an official government forecast of energy balances without considering underlying changes in technology. However, in an experiment where an alternative technology becomes profitable, such as due to a tax on emissions, the profitability indicator of that technology will approach 1. Consequently, the share parameters of the subnest will shift energy input in production towards the new set of inputs. Section 9 presents results from analyses where this methodology is applied.

Box 6.2
Modelling of abatement technologies

See (Beck & Kirk, 2020), (Berg, Leisner, & Nielsen, 2020), and (Beck, Berg, & Stephensen, 2020) for documentation of the applied methodology. The methodology is currently undergoing revision, while the basic principles remain. An introduction is provided below:

Consider a technology that has the ability to save a share, θ_i, of current energy input, q_i, at a cost, c. Technology adoption will be profitable if the price of current energy use exceeds the technology cost

$$p_i > c \tag{1}$$

Initially, the use of (1) will lead to a discrete choice of either adopting technology or not

$$\Delta q_i = \begin{cases} -\theta_{i,i} & if\ p_i \geq c \\ 0 & if\, p_i < c \end{cases}$$

As the Non-linear programming (NLP) solver cannot solve discrete choice problems, we introduce a continuous approximation of the discrete indicator function. Specifically, we use the cumulative normal distribution function, Φ, to determine the adoption of technology i, $f_i \in [0,1]$.

$$f_i(t) = \Phi\left(\frac{p_i - c}{\sigma}\right) \tag{2}$$

where σ defines the standard deviation of the distribution. The larger the value of σ the greater the degree of smoothing will be.

Equation (2) implies that when a technology becomes profitable at time t it is adopted instantaneously. However, this may not be realistic because firms may have existing capital that needs to be worn out before it becomes profitable to adopt the technology. Hence, we introduce sluggish adoption together with a forward-looking mechanism.

The forward looking mechanism calculates preferred adoption, $\hat{f}(t)$ by weighing future preferred adoption with the instantaneous adoption rate with a scale parameter $\beta \in [0,1]$

$$\widehat{f_i}(t) = \beta \cdot \widehat{f_i}(t+1) + (1-\beta) \cdot f_i(t)$$

The sluggishness calculates actual adoption by weighing preferred adoption with the actual adoption of last period

$$\overline{f_i}(t) = a(x_t) \cdot \widehat{f_i}(t) + \big(1 - a(x_t)\big) \cdot \overline{f_i}(t-1)$$

where $a(x) = e^{-x^2}/\rho$, $x = \widehat{f_i}(t) - \bar{f_i}(t-1)$ and ρ determines how fast the function approaches 0 when the absolute value of x increase.

The change in energy use is then the reduction potential of a given technology scaled by the actual adoption rate

$$\Delta q_i = -\theta_{i,i} \cdot \bar{f_i}(t) \tag{3}$$

Finally, the technology cost c is detemined endogenously in the model by the investment cost on capital, p_t^I, and potentially the cost of other energy inputs, $p_{j,t}$, when relevant. This allows for the 'steps' on the MAC-curve to change place, when shocking the model.

$$c_{i,t} = g\left(p_t^I, p_{j,t}\right)$$

7. Reform of industrial emissions

GreenREFORM was not used directly in the first report of the expert group (see section 1), but the implications of the recommendations put forth by the expert group were subsequently simulated in GreenREFORM at a later stage. In this section, we discuss the insights gained from collaborating with the expert group on the initial report and present findings from the aforementioned simulations.

In the analysed proposal, which bears striking resemblance to a reform later endorsed by parliament, a general tax of approximately 100 EUR per ton CO_2e is proposed for most industries. However, lower rates are applied to the most emission-intensive sectors, such as refineries (50 EUR/t) and mineralogical firms (17 EUR/t), which are already encompassed by the ETS system. Importantly, this tax is supplemented by a subsidy scheme for CCS, whereby revenue generated from the €100/t tax is reinvested into incentivizing the adoption of green technology.

However, the 100 EUR/t tax doesn't generate significant revenue, nor does it have a substantial impact on curbing total industrial emissions. This is primarily because industrial emissions are highly concentrated among a few companies. By 2030, it was projected that approximately 35 percent of industrial emissions would be attributed to one cement factory and two refineries, which are subject to lower tax rates as previously mentioned. The concentration of industrial emissions poses challenges not only for the design of regulations but also for modelling the effects of such regulations.

GreenREFORM already incorporated a well-defined refinery sector, but the crucial cement company was grouped together with numerous less emission-intensive companies within the mineralogical sector. While the model adequately captures the emissions and technological changes prompted by the tax, the net effect on production costs and consequently on competitiveness is diluted due to aggregation. Currently, efforts are underway to segregate cement into its own sector, but similar challenges persist for other emission-intensive companies.

Hence, the analysis presented here relies on external assessments of the changes in production among the most important companies. Subsequently, we apply the methodology outlined in section 6 to forcefully introduce a shift in technology within the relevant sectors. For instance, the anticipated decrease in production at the cement company is modelled by substituting energy and non-energy-related emissions in the mineralogical sector with increased imports of materials. This approach implies that the cement company transitions from manufacturing cement to distributing imported cement.

In the case of the refinery sector, we also rely on external evaluations of the changes in production, even though the sector is well-defined in the model. Historically, the two refineries have operated at full capacity with fluctuating profits. Refineries compete internationally with other refineries for both raw oil inputs and global markets for refined oil products. Each refinery has little or no influence on either its input or output prices. Reflecting these observations, both production and the price of output are exogenously determined in the baseline in GreenREFORM. Hence, we also rely on external evaluations of changes in production in the refinery sector.

In the initial report on industrial emissions, the expert group adopted a methodology employed by the Ministry of Taxation: For specific tax bases, such as emissions from burning refinery gas, a simple partial model is established, incorporating a semi-elastic relationship between the tax base and the tax burden. Essentially, for every 1 EUR of tax imposed, there's an anticipated reduction in the tax base by a certain percentage. In the cases of refineries and cement, this reduction is interpreted as indicative of an increasing likelihood of companies shutting down as the tax rate rises.

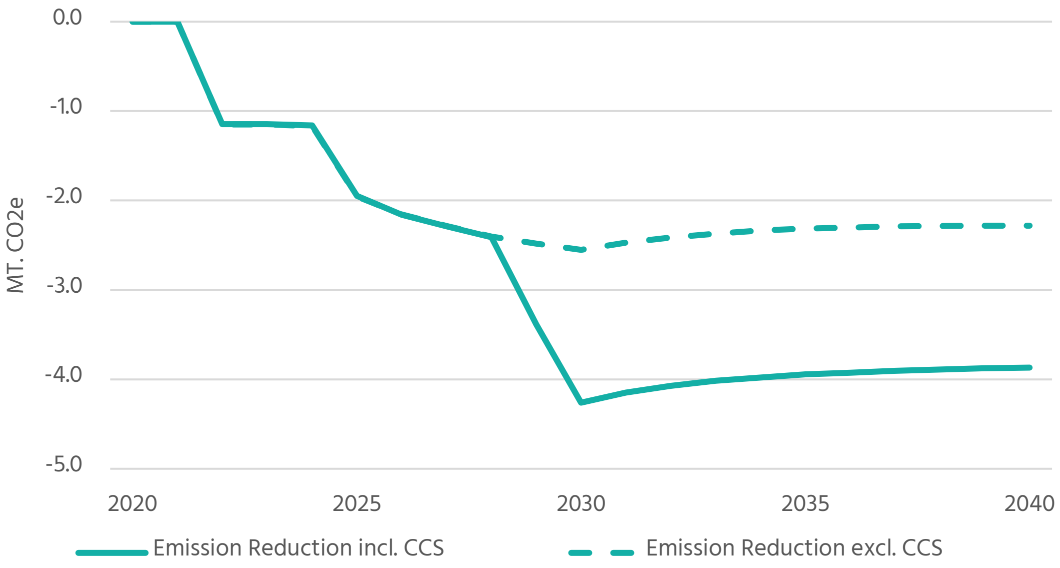
This approach offers the advantage of simplicity. It necessitates minimal information and facilitates supplementary welfare analysis. In situations where decision-makers have limited patience for the development of more sophisticated analytical tools, this approach comes well recommended.

The concern with this approach aligns closely with the discussion in section 6. If the actual response function is discrete, meaning firms continue operating at full capacity until the tax reaches a specific level, the top-down approach is prone to overestimating the change in production at lower tax levels. Despite this concern, to remain consistent with the work of the expert group, we rely on the evaluations provided by the expert group in the current analysis.

In summary, our experience has highlighted the significant impact of emissions concentration within industries. We have not had much focus on understanding industries except for their abatement options until now. While disaggregation would be ideal, it's often impractical. Our method of relying on external analysis and representing production changes as within-sector technical adjustments has proven effective. Additionally, we've recognized the potential superiority of a bottom-up approach for evaluating supply-side production changes compared to the top-down approach favoured by macroeconomists.

Figure 7.1

Change in emissions with and without subsidy to CCS

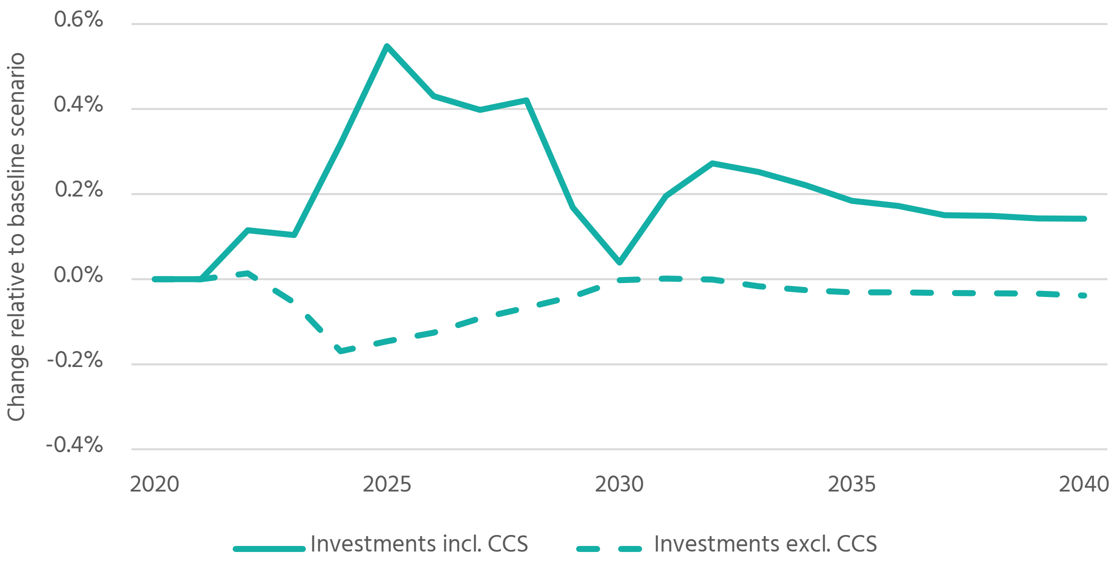


Turning to the results of the simulations, Figure 7.1 illustrates the relative importance of the subsidy scheme for CCS. The emission tax is progressively introduced leading up to 2030, with CCS implementation anticipated to occur discretely in 2030 within the cement and other industries. The gradual decline in emissions towards 2030 primarily stems from the projected decrease in production, cf. above.

CCS is modelled as an end-of-pipe technology, meaning that input of fossil fuels in production remains unchanged while emissions are reduced through increased capital use in production. The combination of the tax and the CCS subsidy provides the necessary incentive for this transition. The investments needed to build up the capital stock result in a net positive change in total investments in the years leading up to 2030, despite the adverse effect of the emission tax itself, as illustrated in Figure 7.2. In the scenario without a subsidy for CCS, there is a sharp decline in total investments in 2024, the year the tax is announced, due to forward-looking behaviour of firms in the model.

Figure 7.2

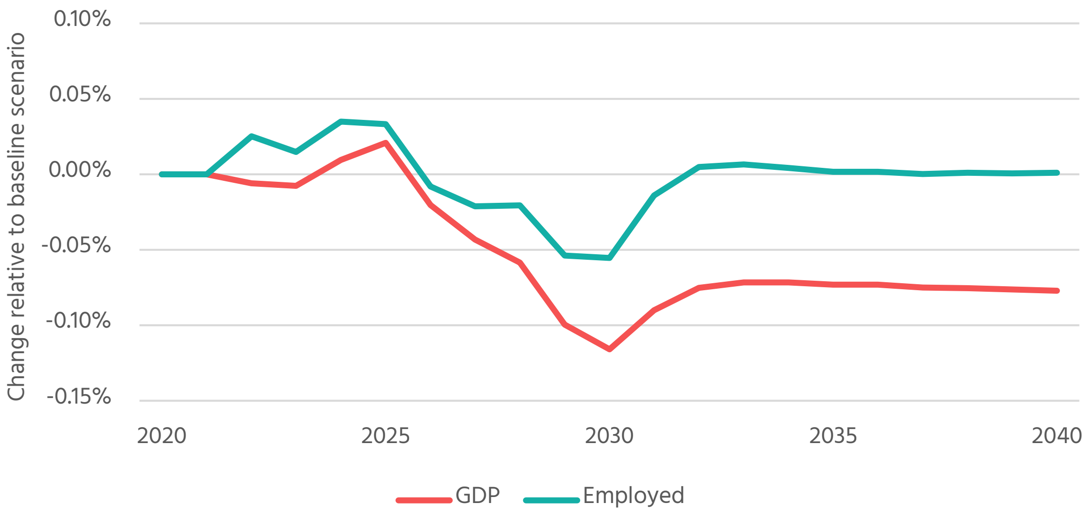
Change in total investments with and without subsidy to CCS



The increase in investment stimulates employment and GDP temporarily, as shown in Figure 7.3. This Keynesian multiplier effect is facilitated by the representation of a Phillips curve and various other frictions in the model, as discussed in section 6. In the long run, wages adjust to bring employment back to its structural equilibrium, and GDP experiences a depression, as expected. However, the depression is minimal, cf. Figure 7.3. The CCS subsidy, in particular, along with the tax, incentivizes substitution to capital in production, which has an offsetting positive effect on GDP. However, capital requires maintenance, leading to a net positive change in investments in the long run despite the drop in GDP. Consequently, a larger share of GDP is allocated to investments. This serves as a reminder that GDP is not a measure of welfare. At the time these simulations were conducted, we did not have a proper welfare measure in the model, as we do now, as discussed in section 8.

These simulations demonstrate the benefit of a dynamic model with forward looking behaviour and bottom-up technology. A dynamic recursive model employing a top-down approach would struggle to capture the transitional impact of climate policy in a comparable manner, while a static model would be of limited utility.

Figure 7.3
Change in GDP and employment with subsidy to CCS



8. Reform of agricultural emissions

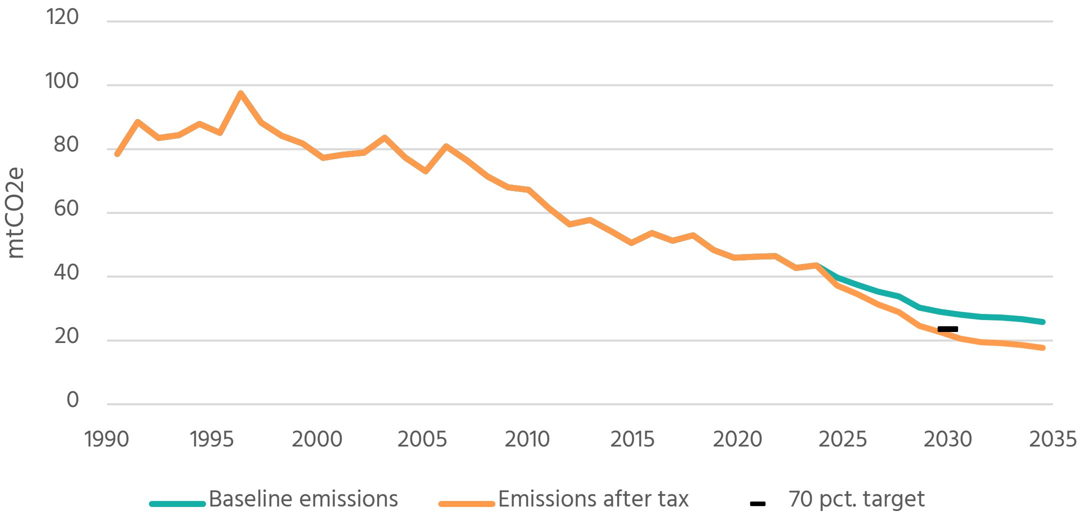
For its second report on agricultural emissions, published in February 2024 by the expert group (see section 1), GreenREFORM has been the central analytical tool. It is expected to be relied upon by the government in upcoming political negotiations. Agricultural emissions account for 50 pct. of Denmark's total emissions by 2030, and regulating them is therefore a crucial step toward achieving Denmark's climate target of reducing emissions by 70 pct. in 2030 compared to 1990.

The expert group established various scenarios involving different levels of carbon taxation on non-energy-related emissions from agricultural production, as well as subsidies for activities such as afforestation. In the scenario with the highest carbon tax, approximately 80 pct. of non-energy emissions from agricultural production are taxed at a rate of 100 EUR per tCO_2e, aligning it with the taxation of energy emissions from firms not covered by the ETS system. Additionally, subsidies are provided for afforestation, aiming to plant 250,000 hectares of forest by 2045, along with a tax on emissions from peatlands and subsidies for wetland restoration. Overall, this scenario is projected to reduce Danish emissions by 2.8 million tCO2e by 2030, thereby aligning with Denmark's climate target for that year, as illustrated in Figure 8.1.

In this section, we outline the key features of the agricultural model and discuss how they impact the results of the aforementioned scenario, which involves a carbon tax of 100 EUR per tCO_2e.

Figure 8.1

Denmark's total emissions before and after carbon tax



8.1 Agricultural sectors and emission intensities

The agricultural model provides a more detailed depiction of agricultural production and emissions compared to the CGE-model (Beck U. R., Berg, Christiansen, & Jørgensen, 2020). Agricultural production is segmented into 10 distinct sectors, with three sectors dedicated to crop and vegetable production, six sectors focusing on livestock production, and one sector dedicated to agricultural contractors who provide services to other sectors as a production input. Both crop and livestock production encompass conventional and organic sectors. Production quantities, prices, and emissions are calibrated based on forecasts provided by the DEA and the Ministry of Climate, Energy and Utilities (Stewart & Berg, 2023).

Non-energy related emissions represent the bulk of emissions from the agricultural sectors. These emissions are modelled to be proportional to emitting inputs. For instance, N_2O-emissions related to fertilizer use are modelled proportionally to the use of fertilizer (including both manure and inorganic fertilizer). Similarly, emissions from CH_4-emissions due to enteric fermentation in animals are modelled proportionally to the number of animals in production..

Table 8.1

Price and quantity change in agriculture and food industries, 2030

	Emission intensity, tCO_2e per million EUR	Mechanic price change (pct.)	Price change in equilibrium (pct.)	Quantity change in equilibrium (pct.)	Implicit own price elasticity
Agricultural sectors					
Crop and vegetable production, conventional	24	12.6	0.7	-10.4	-14.0
Crop and vegetable production, organic	19	10.0	-2.2	-5.7	2.6
Horticulture	1	0.3	-0.5	1.2	-2.7
Cattle, conventional	38	20.5	14.8	-21.2	-1.4
Cattle, organic	33	17.7	12.7	-16.1	-1.3
Pigs, conventional	13	7.2	5.0	-18.0	-3.6
Pigs, organic	8	4.1	2.6	-10.6	-4.1
Food industries					
Dairy	-	-	4.7	-15.9	-3.4
Bovine meat products	-	-	10.0	-32.9	-3.3
Pig meat	-	-	1.6	-14.1	-8.7
Poultry	-	-	0.0	-0.2	6.0
Bread products	-	-	0.0	-0.4	-9.0
Beverages and tobacco	-	-	0.0	-3.2	-87.0

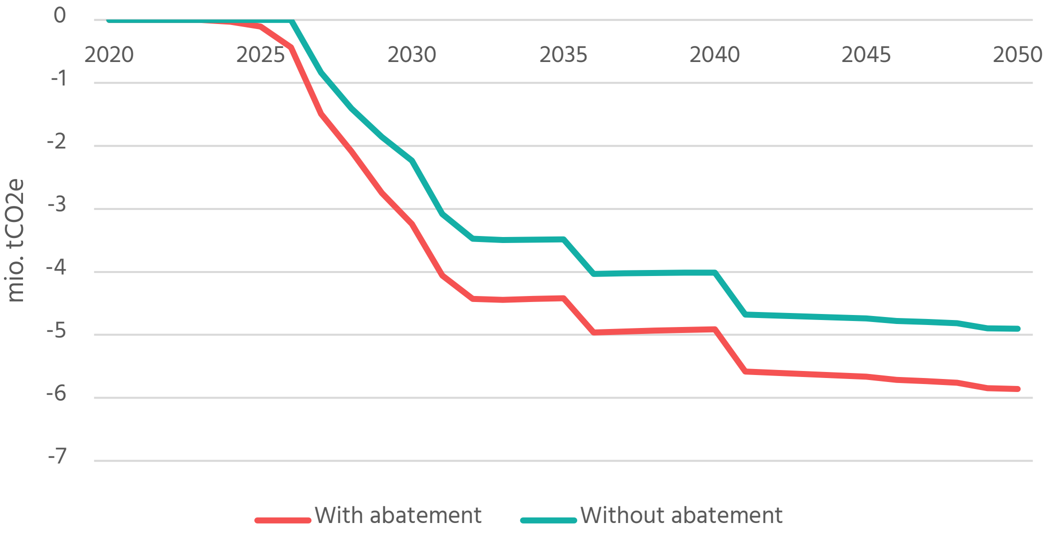
Note: Emission intensity is defined as taxed emissions per value of production. Some non-energy related emissions are not covered by the carbon tax and are therefore left out of the measure for emission intensity.

Emission intensities (emissions relative to production value) play a crucial role in understanding the impacts of a carbon tax. As indicated in table 8.1, emission intensities are highest in conventional and organic cattle production (column 1). Consequently, these sectors experience the most significant mechanical price change, which refers to the price change without behavioural effects (column 2). Generally, organic sectors exhibit lower emission intensities compared to conventional sectors. This difference is attributed, among other factors, to organic producers receiving higher output prices per quantity than conventional producers. It's worth noting that the difference between conventional and organic production was not addressed in the results presented by the expert group. This omission stemmed from uncertainties surrounding the projection of organic production prices and quantities.

8.2 Abatement technologies

Certain non-energy emissions from the agricultural sectors can be mitigated using technology. Implementing these technologies allows the sectors to reduce emissions at a cost lower than the carbon tax. Consequently, the utilization of technology results in a smaller increase in equilibrium prices for sectors such as cattle, compared to the mechanical price change (column 3 in table 9.1). As depicted in Figure 8.2, abatement technologies contribute to approximately one-third of the total reductions in emissions by 2030 (Stewart L. B., 2024). Other reductions, aside from abatement, primarily stem from afforestation efforts and decreased production.

Figure 8.2
Emission reductions of carbon tax, ktCO₂e



Note: The jagged emission reductions is a result of the forest model which runs on 5-year intervals.
Source

Abatement technologies in the agricultural sectors are modelled using a bottom-up approach, consistent with the methodology employed for abatement technologies elsewhere in the model (Beck and Kirk 2020 and Stephensen et al 2020). The fundamental concept behind this modelling approach is to represent technologies as discrete choices, akin to engineering models. This contrasts with the conventional top-down approach in CGE modelling, where technological adjustments are typically represented through substitution elasticities in the production functions.

Technologies capable of mitigating agricultural non-energy emissions are modelled as end-of-pipe technologies (Stewart & Kirk, 2024). These technologies entail retaining the emitting input in production while reducing the emission coefficient associated with it. For instance, feed additives can be used to decrease the amount of methane emitted from enteric fermentation in animals.

The costs associated with these technologies are integrated back into the model as increased demand from other sectors. While the standard assumption links technology costs to increased capital demand, this approach permits a more nuanced depiction of technology costs..

8.3 Endogenous amount of land

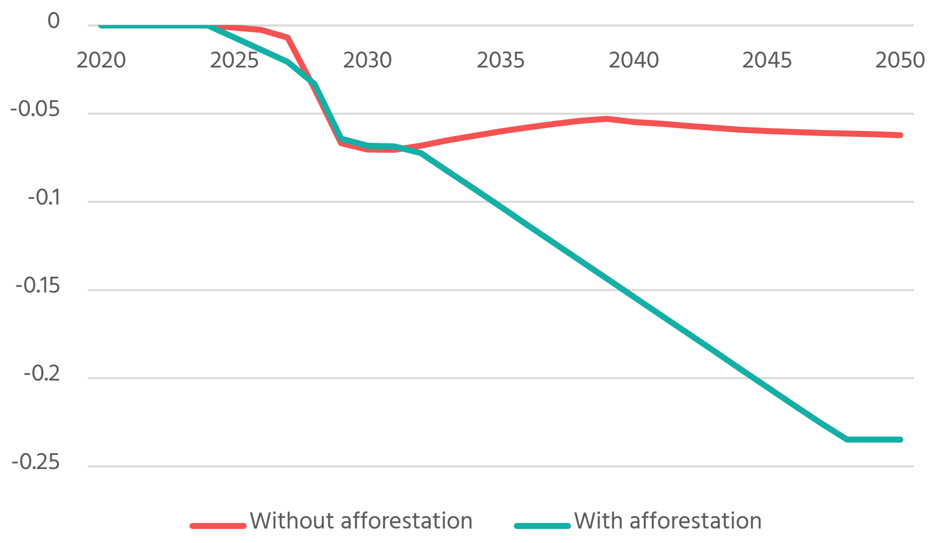
The GreenREFORM model stands out from other macroeconomic models used for policy analysis in Denmark due to its unique approach to modelling the land market. In this model, both the quantity and price of agricultural land are endogenously determined. Consequently, the implementation of a carbon tax results in a reduction in the amount of arable land and a decrease in the price of agricultural land. This, in turn, lowers the production costs of the crop sectors (Stewart & Kirk, 2024). Due to this feature, the equilibrium price changes are much smaller than the mechanical price change for crop and vegetable sectors (column 3 in table 8.1).

The imposition of the carbon tax also leads to a reduction in production quantities (column 4) due to the decrease in total agricultural area. This decline in agricultural area is significant, especially when subsidizing afforestation. However, even without this subsidy, the model predicts a decrease in the amount of agricultural land, as illustrated in Figure 8.3.

The modelling aims to incorporate knowledge of heterogeneity in factors such as geography and soil quality into a macroeconomic model that portrays each sector as an average farm. The identifying is that the productivity of agricultural land varies. Therefore, if a tax on emissions were to be imposed, some parcels of land would become unprofitable to maintain in production, while others would still profitable.

The land market is modeled through two interconnected (Stewart, Berg, & Kirk, 2023). Firstly, the total amount of agricultural land in production is determined by a "land withdrawal function" that considers heterogeneity in land productivity. Agricultural land will be withdrawn from production if alternative uses are more profitable (Berg & Stewart, 2024). These alternatives may include fallowing, afforestation, or flooding of carbon-rich soils. Secondly, the total amount of available land is allocated to the three crop sectors based on their relative willingness to pay for land.

Figure 8.3
Change in agricultural land, million hectares



8.4 Intra-farm deliveries

In the IO-table of the national accounts, the agricultural sectors produce goods that are utilized by all sectors of the model, including the food industries, other agricultural sectors, and final consumption. However, agricultural production also includes products that are not accounted for in the national accounts, following international guidelines. These include coarse feed and litter produced by the crop sectors, as well as manure produced by the livestock sectors.

We explicitly model these deliveries based on Agricultural Accounting Statistics, as they represent important linkages within agriculture. For instance, a decrease in the amount of livestock would decrease the supply of manure, leading to increased demand for inorganic fertilizer. Additionally, fewer animals would reduce the demand for animal feeds and free up land for other crop production. These interconnections within the agricultural sectors imply that a carbon tax on the livestock sectors would diminish the value of crop production, affecting the price and quantity of agricultural land, as discussed in section 8.3.

8.5 Food industries and market conditions

The IO tables of the National Accounts reveal a close interdependence between the agricultural sectors and the food processing industries, particularly evident in the livestock sectors and the dairy and meat processing sectors. The majority of output from the livestock sectors is supplied to the dairy and meat processing sectors, with these food industries relying minimally on imported agricultural products.

Consequently of this interdependence, the production response in the agricultural sectors closely mirrors that of the food industries (Stewart L. B., 2024). For instance, the reduction in production in the cattle sectors closely corresponds to the weighted average of the production decline in the dairy and bovine meat processing sectors (column 4 in table 8.1).

Hence, the impact of a carbon tax on agricultural emissions heavily relies on how the market conditions of the food industries are depicted. The market structure within the Green-REFORM model is constructed based on empirically estimated export elasticities. These estimates are derived from the BACI dataset, allowing for export elasticity estimation at a granular product level (Kronborg, Poulsen, & Kastrup, 2020). As an example, we estimate export elasticities on 20 different products (cheese, butter, milk powder etc.) which are then weighted into an average export elasticity for the dairy sector. While export elasticities are also estimated for the agricultural sectors, their impact on the model outcomes is comparatively less significant since the majority of production output is directed toward the domestic food industries.

The expert group chose to base their calculations on export elasticities estimated in an international study (Fontagné et al, 2022), as shown in Table 8.2. These export elasticities, employed by the expert group, are on average around 25 percent higher than those estimated using the methodology described above. However, these elasticities suggest that Danish food industries possess a certain level of market power when exporting food products. This implies that they may not experience a complete loss of demand in response to price increases—a contention often raised by opponents of a carbon tax on agriculture. Several factors may account for this empirical finding, with one potential explanation being the ability of Danish companies to engage in pricing-to-market (PTM) strategies. This strategy enables them to sell their products in markets where prices are higher (Stephensen et al 2023).

Table 8.2
Export elasticities for agriculture and food industry sectors

	Elasticity	Export share of production
Agricultural sectors		
Crop production, conventional	-5.36	21.5%
Crop production, organic	-5.36	21.1%
Horticulture	-7.50	17.2%
Cattle	-8.11	2.6%
Pigs	-6.41	26.9%
Poultry	-6.41	17.1%
Food industries		
Bovine meat products	-5,69	53.1%
Pig meat products	-12.10	61.3%
Poultry meat products	-5.84	27.6%
Dairy products	-5,46	50.7%
Bread and bakery products	-6.67	21.2%
Other food industries	-6.93	36.9%

Note: The table show the export elasticities used by the expert group based on (Fontagné et al, 2022).
Source: (Svarer et al., 2024)

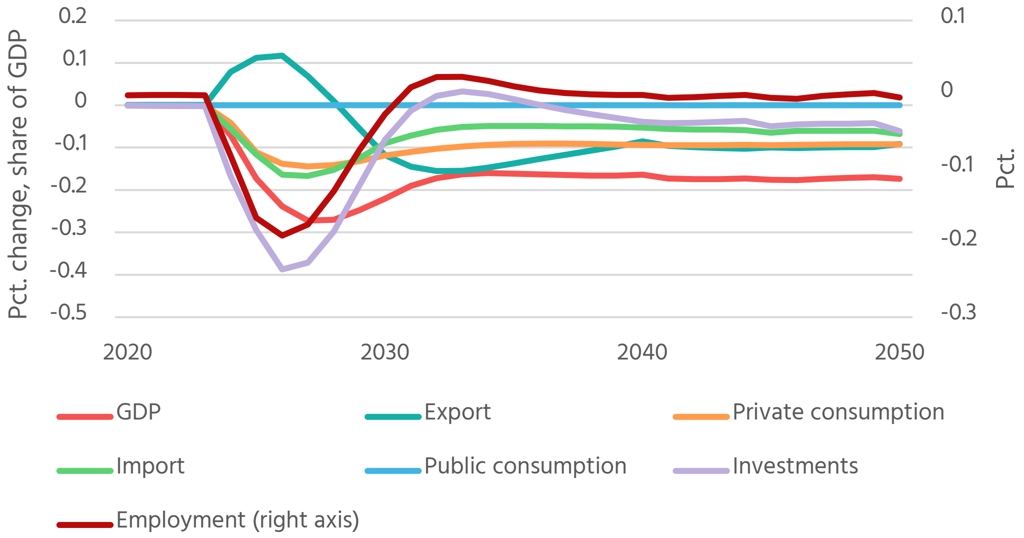
8.6 Macroeconomy and welfare

Overall, the carbon tax has a limited impact on the Danish economy, primarily because agricultural production constitutes a relatively small portion of Denmark's overall production, both in terms of employment and GDP. GDP decreases by 0.22 pct. in 2030 and 0.17 pct. by 2040, as depicted in Figure 8.1. Total investments decline upon announcement of the carbon tax, as the economy becomes less capital-intensive in the long run. Private consumption and imports also decrease, but to a lesser extent. Export experiences a short-term increase due to a lag in the adjustment of production capacity (buildings and machinery). However, in the long run, export decreases.

Employment declines by 0.2 pct. in the short run, as overall demand in the economy decreases. However, in the long run, total employment returns to its structural level, facilitated by declining wages. Consequently, individuals laid off in the agricultural and food industry sectors find employment in other sectors, primarily within the service sectors.

Figure 8.4

Change in GDP-components (quantities) and employment



The model calculates changes in household welfare based on the discounted flow of future income and changes in consumer prices (Stephensen P. , 2024). Welfare is measured as Equivalent Variation, signifying the compensation households would need today to be indifferent between the baseline and the after-tax scenario. In calculations conducted by the expert group, the change in welfare is adjusted to account for benefits not included in the model, such as positive health effects from reduced ammonia emissions and the recreational value of forests. Dividing the change in welfare by changes in emissions yields the shadow cost of reducing emissions. The calculations reveal an average shadow cost of 20 EUR per tCO_2e reduced, indicating that the cost of reducing emissions is significantly lower than the marginal tax rate of 100 EUR per tCO_2e.

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