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MSG-TECH: Analysis and documentation of a general equilibrium model with endogenous climate technology adaptations

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Foreword

This report describes and illustrates the use of the computable general equilibrium model MSG-TECH, which is a version of the MSG model in Statistics Norway with endogenous climate technology investments. It was first used in the macroeconomic analyses performed by Climate Cure 2020, an expert group commissioned to explore ways to meet climate policy targets set by the Norwegian Parliament in 2008. Climate Cure 2020 delivered their report in February 2010. This report is commissioned by the Ministry of Finance as part of the MSG contract 2012/2013. While carrying out this research, the authors have been associated with the Oslo Centre for Research on Environmentally friendly Energy (CREE). CREE is supported by the Research Council of Norway. The report is also published in the Report series of Statistics Norway (47/2013).

Summary

To meet the global challenge of climate change, shifts in industrial structures and consumption patterns will have to be accompanied by technological adaptations. Analytical tools for projecting effects of ambitious climate policies cannot be based on historical data and current technology characteristics, alone, but need to represent technological innovations that have not yet emerged. This is the background for the development of the *hybrid* model MSG-TECH, which builds on the *computable general equilibrium* (CGE) model MSG6, but resembles *energy system models* in its inclusion of anticipated future technological options. The information on technological options is collected from bottom-up calculations and is exploited to model a wider range of possibilities in the optimisation by households, firms, and public institutions than in traditional CGE models.

The significance of the modelling innovations is illustrated by introducing a uniform carbon price to achieve the same climate policy target – a cut of 10 million tons CO2 equivalents by 2020 - in the MSG-TECH model and the original MSG6 model, respectively. When technological adaptations are accounted for, over one half of the necessary reductions take place by choosing other technological solutions. When these options are left out, marginal abatement costs more than triple and welfare costs more than quadruple, and the cost increase for the traditional manufacturing industries is particularly severe. The intuition is that a model that fails to account for a large part of the expected future abatement alternatives reflects an unrealistically inflexible and inefficient economy. The corresponding characteristic would apply to traditional bottom-up models that include technological abatement, but fail to account for reduced economic activity and new industrial patterns.

Sammendrag

Skal verdens klimautfordring løses, vil det kreve såvel nye nærings- og forbruksmønstre som nye teknologiske løsninger. Analytiske verktøy for studier av fremtidens klimapolitikk kan ikke bygges på historiske og nåtidige observasjoner, alene. De må også ta innover seg teknologisk utvikling som ennå ikke har funnet sted. Dette er bakgrunnen for at modellen MSG-TECH er utviklet. Den er en hybrid modell bygget på den generelle likevektsmodellen MSG6, men som i likhet med energisystemmodeller representerer teknologiske muligheter utover dem som eksisterer i dag. Den teknologiske informasjonen er hentet fra detaljerte beregninger av potensialet til enkeltteknologier og utnyttet til å modellere flere valgmuligheter for husholdninger, og private og offentlige næringer i modellen.

Rapporten illustrerer betydningen av å modellere klimateknologisk innovasjon ved å analysere samme utslippstak – 10 millioner tonn CO2 ekvivalenter – ved bruk av uniform karbonpris i modellene MSG-TECH og MSG6. Når klimateknologiske tilpasninger er mulig, vil over halvparten av reduksjonene skje ved innovasjoner. Uten slike opsjoner vil marginal rensekostnad tredobles og velferdskostnaden firedobles. Kostnadene øker særlig for den eksportrettede, utslippsintensive industrien. Intuisjonen er at en modell som utelukker en stor andel av de tilgjengelige tiltakene er urealistisk rigid og ineffektiv. Tilsvarende vil gjelde for tradisjonelle energisystemmodeller, som kun endogeniserer valg av teknologier og utelukker omallokeringer mot mindre utslippsintensiv bruk av ressursene.

Contents

1 Introduction

To meet the global challenge of climate change, shifts in industrial structures and consumption patterns will have to be accompanied by technological adaptations. The costs of abatement will critically depend on whether technological options are present and triggered by political incentives. Among policy makers and analysts there is a large demand for analytical tools that can represent how and at what cost mitigation can take place and how adaptation occurs under different economic and technological conditions.

Traditionally, two main types of model tools have dominated in mitigation studies. In so-called *bottom-up models* competing energy technologies are represented, irrespective of whether they are currently in use or at present only known on paper. These models can describe radically different technological scenarios. A predominant example is the MARKAL model[1], which is extensively used in studies of societal responses to global warming. However, with their focus on the energy system, in isolation, bottom-up models tend to suffer from a partial perspective that fails to count in macroeconomic feedbacks and the endogeneity of demand and factor prices. As a consequence, responses in scales and compositions of economic activities are ruled out of the analysis.

The *top-down* approach to climate policy analyses mostly use computable general equilibrium (CGE) models. CGE models predict the development of the economy, energy use, and emissions based on micro-economic behaviour and the resource constraints and long-run conditions that restrict the opportunity set of agents and economies. They are empirically pinned down by use of historical data on the responsiveness of agents, and by use of current information on the technology specifications of production and consumption. Thus, their technological responses do not exceed observed practice.

By nature, these conventional approaches, top-down as well as bottom-up, tend to underestimate the potential for emission reductions. While top-down analyses exclude important profitable technology

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[1] See ETSAP (2004) for a central documentation.

substitutions and systemic shifts, bottom-up analyses exclude important flexibility of economies by neglecting profitable downscaling of supply and demand and shifting of costs among market agents. This dilemma has inspired analysts to develop synthesis models. Several amendments of the MARKAL model has been made, aimed at introducing main macroeconomic characteristics; among pioneering works, see Hamilton et al. (1992) and Loulou and Lavigne (1996). An impressively ambitious, recent approach departing from a bottom-up basis is that of Bataille et al. (2006).

Other recent contributors have used CGE modelling as a point of departure and supplemented it with technology details; see e.g. Böhringer et al. (2003), Laitner and Hanson (2006), and Bosetti et al. (2006). This enables a good representation of technological richness, while simultaneously ensuring advanced status quo characteristics of CGE models like intertemporal dynamic behaviour and the facilitation of a consistent welfare measure.

This report documents the amendments of a widely used CGE model of the Norwegian economy, *MSG6*, made in order to include present and future technological possibilities. The significance of the modelling innovations is illustrated by comparing the outcome of the same climate policy introduced in the extended model, *MSG-TECH*, and the original MSG6 model, respectively.

By integrating abatements within and beyond existing technologies in a common framework, model analyses will capture how these responses interplay. While most hybrid models in the literature have focussed on technological adaptation possibilities within energy supply, MSG-TECH also represents options of energy demanding sectors, both within energy-intensive manufacturing and within transportation, the latter affecting abatements of households, firms and public service sectors. Our modelling procedure is relatively simple, but at the same time capable of representing, with good proximity, a variety of potential technological measures.

In chapter 2 we present the model MSG-TECH and elaborate on the amendments of the original model MSG6. While the first part of the chapter gives a short overview of the main structures of the model, the second part gives a detailed description of the modelling of technological abatement options. In chapter 3 a model comparison is performed in order to identify the qualitative and quantitative significance of accounting for technological adaptations. Chapter 4 concludes on the experience with the MSG-TECH model, discusses some caveats, and suggests some paths for future refinements of the model.

2 The MSG-TECH model

2.1 General features

The MSG-TECH builds on the model MSG6[2] developed in Statistics Norway. The model gives a detailed description of the structures of economic policy, production, and consumption in the Norwegian economy. The model specifies 66 commodities and 42 industries, classified to capture any substitution possibilities with environmental implications. The model version MSG-TECH has integrated data on technological substitution opportunities today and for the next decades.

As the Norwegian economy is relatively small, and the exchange rate is normalized to unity, all agents face exogenous world market prices and real interest rates. Thus, financial capital is perfectly mobile across borders. Real capital and labour are perfectly mobile within the economy. As in most CGE models, supply equals demand in all markets every year.

The input–output structure is calibrated against the Norwegian National Accounts. This is supplemented with the Norwegian energy accounts in order to quantify energy flows. The present version is calibrated for 2004.

2.2 Behaviour

2.2.1 The consumers

The consumer side is modelled as one representative household, which allocates time between labour and leisure and its budget among 39 different consumer goods and services in order to maximise its utility in each period. Utility in each period originates from material consumption and leisure

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[2] Heide et al. (2004) and Bye (2008) give more detailed descriptions of the MSG6 model, its empirical fundament, and applications.

consumption, and is specified by an origo-adjusted Constant Elasticity of Substitution (CES) function. Its nested origo-adjusted CES structure is documented in Aasness and Holtsmark (1995); see figure A.2 in Appendix A. The origo adjustment allows the income elasticities to vary among goods. This structure reflects relevant price-induced substitution possibilities between commodities, and the consumption activities have different emission profiles; se section 2.3. Three energy commodities are specified: electricity, fuel oils, and transport oils (petrol and diesel). Electricity is used for household machines and apparatuses for heating, with different substitution possibilities. Various polluting and non-polluting forms of transportation can substitute for use of own cars. The transportation forms are split into short and long travels. Own car use can also avoid climate emissions by investing in new vehicle types with alternative technologies. The modelling of these choices is explained in section 2.4.

The welfare measure of the model is defined as the sum of discounted period-specific utilities. These are measured by a money-metric volume indicator for consumption measured in utility units, derived by deflating the current consumption expenditure by a consistent costs-of-living index. External effects, in particular environmental repercussions on the utility of the household, are not modelled.

2.2.2 The firms

The production side of the model specifies 42 firms and 66 products, which are classified with a view to displaying differences in emissions and substitution possibilities among goods. Each firm produces its own product variety different from others'; this implies a certain degree of market power in separated domestic market niches. Firms maximise the current value of the cash flow in setting production levels and composition of factor inputs, including one type of labour, different types of capital, goods, services, and energy goods, among them fossil fuels. It is assumed that capital goods are malleable and can be incrementally increased and decreased according to profitability assessments. As for households, firms may also choose to invest in different climate technologies; see section 2.4. Increasing production increases unit costs (diminishing returns to scale). Production within an industry can also expand through entry of new firms and varieties. A wider variety range increases utility and productivity of the goods (love of variety).

Norwegian firms compete with foreign suppliers in the domestic market and abroad. As the Norwegian economy is small, the world market prices are set externally. In the case of most commodities there is room for different price developments of Norwegian and foreign commodities on the domestic market (the Armington hypothesis). It is also allowed for domestic market prices to develop differently from export prices, modelled by the cost to firms of switching between the domestic and export markets within a Constant Elasticity of Transformation model.

The electricity supply is modelled in particular detail, and engineering data are explored to represent technologies. The current Norwegian supply of electricity is based on hydropower. Gas power capacity is phased in as a back-stop technology when the marginal willingness to pay for electricity equals or exceeds the long-run marginal cost of expanding the gas power. The Norwegian electricity market is part of a Nordic competitive market.

There are some exemptions to the general modelling of firms outlined above. Relatively homogenous raw materials like oil, natural gas, fish, agricultural products, and electricity are specified at the industry level rather than the firm level. They obtain the same price in domestic and world markets, and the model determines trade in net terms, only. Because of heavy policy regulations, production within agriculture, forestry, fisheries, offshore oil and gas exploration, and public servicing, are set exogenously.[3]

2.2.3 The government

The government collects taxes, distributes transfers, and purchases goods and services from the industries and abroad. Overall government expenditure is exogenous and increases at a constant rate. The model incorporates a detailed account of the government's revenues and expenditures. The modelled potential instruments for conducting climate policy include taxes on Kyoto gases, uniform or differentiated, national and international emission permit trading with auctioning or free allocation, as well as subsidies and compensation schemes to firms and households. In the presented policy experiments, it is required that the nominal deficit and real government spending follow the same path as in the baseline scenario, implying revenue neutrality in each period; see chapter 3.

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[3] In the version used in the analyses below, power production, its technology, and the Nordic market price are exogenous.

2.3 Emissions

All six greenhouse gases embraced by the Kyoto Protocol are included in the model: CO_2 (Carbon Dioxide), CH_4 (Methane), N_2O (Nitrous oxide, commonly known as laughing gas), and the fluorine compounds SF_6, CFC and HFC. The emissions are measured in CO_2-equivalents according to their global warming potentials (GWP). In addition, six air pollutants with regional and local effects are included: SO_2 (Sulphur Dioxide), CO (Carbon Monoxide), NO_X (Nitrogen Oxides), NMVOC (Non-Methane Volatile Organic Compounds), NH_3 (Ammonia) and PM (Suspended Particulates). Table 2.1 provides an overview of the specified air pollutants and their main sources in 2004.

Table 2.1: Emission compounds and main emission sources (2004)

Gas	Main emission sources
CO_2	Extraction of crude oil and natural gas, Manufacture of metals, transportation (misc.)
CH_4	Other private services (landfills), Agriculture
N_2O	Agriculture, Manufacture of industrial chemicals (fertilizers)
SO_2	Manufacture of metals, Manufacture of industrial chemicals
NO_x	Transportation (misc.), Extraction of crude oil and natural gas
CO	Transportation (misc.), Households (heating)
VOC	Extraction of crude oil and natural gas
NH_3	Agriculture

Emission coefficients link various activities within households and firms to their emissions to air based on the Norwegian Emissions Inventory. The emission-generating activities include energy use, material input, consumer goods and services, production processes, and waste deposits. For activities where technological alternatives are specified, the emission coefficients are endogenous. This modelling is described in section 2.4.

2.4 The modelling of technological options – a stylised representation

A distinct feature of this version of the model, MSG-TECH, is that households, firms, and public institutions can choose to invest in completely new technologies with lower emission intensities. Thus, in their optimisation they face a wider range of possibilities than in traditional CGE models. They compare the marginal costs of three options and choose the cheapest: Paying for polluting another, infinitesimally small, unit, abating the same amount through technological adaptation, or avoiding it through other adaptations, which in the model involves scaling down output or substituting for emitting production factors.

For a stylised presentation of the endogenisation of technological adaptations, assume the production function for a relevant industry is given by:

(1) $$X = \left(\frac{V}{\varepsilon} \right)^{\rho} ,$$

where X is the production, V is the factor input, ε is the factor productivity and ρ is the scale elasticity. $0 < \rho \leq 1$, implying decreasing returns to scale. Assume, further, that production generates emissions, *U*, according to:

(2) $$U = \mu \cdot X ,$$

where μ is the emission intensity. Emissions are measured in tonnes of CO_2-eqivalents. The government further imposes a tax on emissions at a given rate τ. The taxation revenue then amounts to:

(3) $$T = \tau \cdot U = \tau \cdot \mu \cdot X$$

By using (1) and (3) the profit for the industry can be expressed as:

(4) $$\pi = B \cdot X - C - T = B \cdot X - P^{V} \cdot \varepsilon \cdot X^{1/\rho} - \tau \cdot \mu \cdot X ,$$

where B is the price (index) of the output, P^V the price (index) of the input and C is the cost of inputs (excluding tax). Assuming that the industry can be represented by a representative firm, maximising profits, π with regard to output, X, gives the following first order condition:

(5) $$B = \frac{P^V}{\rho} \cdot \varepsilon \cdot X^{\left(\frac{1}{\rho}-1\right)} + \tau \cdot \mu \, .$$

Note that the emission intensity, μ, appears in three contexts; in determining emissions (eq. (2)), tax revenue (eq. (3)), and prices (eq. (5)).

2.4.1 Solution without technological adaptation

In the case without technological abatement, let $\varepsilon=\varepsilon_R$, where ε_R is exogenous and calibrated to 1. According to eq. (1) input is then, for a given X, given by:

(6) $$\mathrm{V_R} = \varepsilon_\mathrm{R} \mathrm{X}^{1/\rho}$$

Note that increased factor productivity, i.e. lower factor use for given output, can be modelled by setting $\varepsilon_R < 1$.

In this case without endogenous abatement $\mu=\mu_R$ is exogenous. Emissions will, in accordance with eq. (2), be:

(7) $$U_R = \mu_R \cdot X \, ,$$

The model without technological abatement define the endogenous variables B, V_R, U_R, and T for given exogenous variables X, ε_R, μ_R, τ, and P^V and parameters ρ. X is here regarded as exogenous (defined elsewhere), while B is endogenised. This choice is made by convenience. The equations (3), (5), (6) and (7) determine the endogenous variables.

In this model reduced emissions can only come true by reducing X or μ_R exogenously.[4]

2.4.2 Solution with abatement technologies

We now proceed by adjusting the model to account for abatement technologies, which introduce additional *costs* in terms of investments, operation and maintenance and *benefits* in terms of reduced unit emissions. We do this by endogenising the emission efficiency parameter, μ, and the factor productivity, ε.

The first step is to model the technological opportunities. This is done by defining marginal abatement costs, *c*, as a function of abatement through technological adaptations, *D*.

$$c = f(D) \tag{8}$$

In a cost-efficient solution, firms will invest in abatement technology until the marginal abatement cost equals the marginal cost of emitting:

$$c = \tau \tag{9}$$

Accounting for technological abatement, the emissions, *U*, now develop according to:

$$U = U_R - D, \tag{10}$$

where U_R are emissions before the abatement efforts and *U* are emissions after technological abatement. The endogenous emission intensity μ is given by equation (2) above as *U/X*. As long as abatement takes place, $U < U_R$ and $\mu < \mu_R$.

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[4] An industry is an aggregate of numerous firms, and changes in *U* through changes in the composition of firms and production processes can be represented by changes in μ_R.

The next step is to endogenise the productivity parameter, ε. To do this we first need to define the total technological abatement costs, E , which is the integral of marginal abatement costs in eq. (8):

(11) $$E = \int f(D)dD \, .$$

Introducing abatement with positive costs implies that the factor use V will increase from the level without technological abatement, V_R, with the amount E, which represents factor use involved in the technological adaptation*:*

(12) $$V = V_R + E$$

The resulting ε will be determined by equation (1) above:

(1) $$X = \left(\frac{V}{\varepsilon}\right)^{\rho} \Leftrightarrow \varepsilon = \frac{V}{X^{1/\rho}} \, .$$

The interpretation is that the input use needed for a given output increases when technological adaptation takes place, i.e. ε will endogenously increase above ε_R.

To sum up, the case with endogenous abatement can be defined by the 4 equations in the model without abatement: (3), (5), (6) and (7), along with the following 7 equations: (1), (2), (8), (9), (10), (11), and (12). The corresponding 11 endogenous variables are: B, ε, μ, c, T, U, U_R, D, V_R, V, and E. The exogenous variables are X, P^V , τ, ε_R , μ_R , while the parameter ρ is still given. Note that as long as $\tau = 0$, c, D, and E are all zero, and the solution for ε and μ will be $\varepsilon = \varepsilon_R$ and $\mu = \mu_R$ as in the original model without abatement technologies. If U_R= 0, then $\varepsilon = \varepsilon_R$ and $\mu = 0$.

This modelling solution avoids reprogramming of the model. Among the 11 equations, (1), (2), (3), and (5) are part of the original model and correspond to equations in the CGE model, MSG6. The remaining seven equations, (6) - (12), are novel and inserted into the new model MSG-TECH in order to determine technological abatement and the corresponding costs. The new equations added to the MSG6 model to account for technological adaptations are reproduced in Appendix A.

2.4.3 Empirical basis and detailed modelling issues

We have modelled technological abatement opportunities in the process manufacturing industries (sector 27, 34, 37 and 43; see the list of industries in Table A.1 in Appendix A), in the petroleum industry (sector 66), and for road transportation in firms, households and the public sector. Along with households, the industries land transportation (sector 75) and other private servicing (sector 85) are the largest users of road transport.

We have collected documentation on the emission reduction potential and costs of different specified technologies. In absence of historically observed data, as the technologies are new or not yet used on a wide scale, we have sought to explore the engineering information that is available and constructed hypothetical data on abatement costs.[5] We have, as far as possible, made calculations and definitions comparable across abatement measures.

The data originate from various published articles and reports. The main sources of information are the sector studies of Climate Cure 2020 (2010)[6], which have put effort into using consistent price data, discounting, and calculation methods across measures and sectors. For each industry we have merged information on various technologies and conducted OLS regressions, as an alternative to model several parallel abatement cost functions. The approach, thus, imply that each technology's detailed cost compositions and firm-specific/process-specific characteristics are abstracted from. We present the data sources, modelling procedures, and estimation details for each sector in section 2.4.3, before we close the chapter in 2.4.4 by commenting on some general methodological and modelling issues.

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[5] The method resembles the so-called engineering approach to economic production functions (Chenery (1949), Sav (1984)) in that we use engineering information directly in the absence of statistical data on the abatement functions.

[6] Climate Cure (Klimakur) 2020 is an expert group consisting of public agencies and directorates that were commissioned by the Ministry of the Environment in 2008 to assess the Norwegian climate policies towards 2020.

2.4.3.1 *Process manufacturing*

The abatement cost curve for the process manufacturing industries is based on information on technological abatement options for the following manufacturing processes: cement production (in sector 27), production of industrial chemicals (in sector 37), production of aluminium, iron, steel and ferroalloys (in sector 43) and production of pulp and paper (in sector 34).

The technological adaptations investigated include different ways of converting to bioenergy, process optimisation, as well as post-combustion CCS technologies. The following sources were used for collecting data on costs and abatement potentials for various technological measures: SFT (2007) SINTEF (2009), TELTEK (2009) and Climate Cure 2020 (2010) Table 2.2 lists the assessed measures and their corresponding abatement potentials and costs. The costs include investment and operational costs and represent added costs of production faced by the firm, thus including changes in VAT and other taxes.[7] They are measured as yearly costs by annuities.

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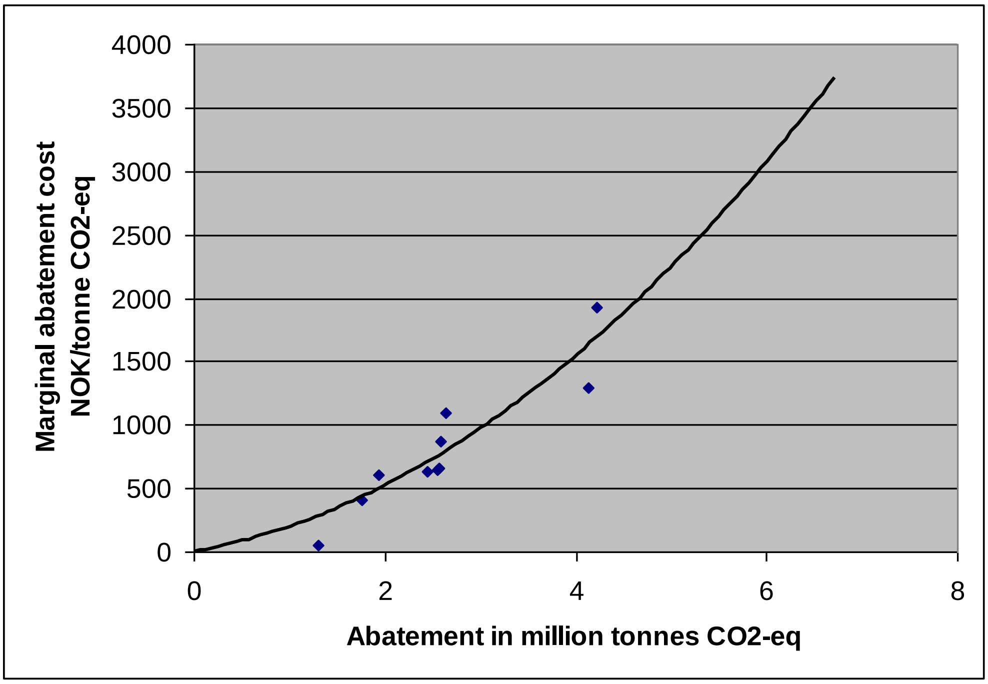
[7] The CCS information, quantified by NPI (2010)), reflects social costs; no separate private cost estimates are provided. Social costs tend to underestimate the private costs, if there are reasons to expect coordination problems or that other forms of market failures are present. Alternatively, one can interpret the government as a participating agent in the project.

Table 2.2: Abatement costs and potentials in process manufacturing, by measure

Abatement measure	**Annuity** (NOK/tonne CO2-eq)	**Abatement** (tonne CO2-eq)
Silicon Carbide prod: charcoal substitute for coke	868	0.02
Petrochemical industry: process optimisation	666	0.02
Metal industry: process optimisation	50	0.50
Ferrosilicon prod. – level 1: <40% charcoal for coke	415	0.45
Ferrosilicon prod. – level 1: <80% charcoal for coke	634	0.50
Ferromanganese prod: <20% charcoal for coke	611	0.19
Pulp industry: energy efficiency and substitution	50	0.29
Cement and mineral manufacture: substitution of bio	50	0.16
Chemical industry: energy efficiency and substitution	50	0.04
Metal industry: energy efficiency and substitution	50	0.30
Cement production – level 2: substitution of bio	645	0.10
Pulp and paper – level 2: substitution of bio	1931	0.09
Anode production: substitution of bio	1092	0.07
Fertilisers production: CCS	1300	0.69
Cement production: CCS	1300	0.79
Total manufacturing industries		4.21

If we arrange the measures according to cost annuities and position them in an (X-Y) diagram, where accumulated emission reductions are plotted along the X axis and the cost of the marginal technology along the Y axis, we can estimate a marginal abatement cost curve. A criterion we emphasise, besides good fit, is reasonable extrapolation outcomes in both ends. More precisely, we want to avoid that abatement costs for small potentials ever fall below zero and that the abatement cost always increases with increased, accumulated abatement potential. Figure 2.1 depicts the outcome of the estimation procedure for the process manufacturing industries as a whole.

Figure 2.1: Marginal abatement cost curve, process manufacturing



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100 NOK =12.5 €

The corresponding marginal abatement cost function (in NOK/tonne) for process manufacturing is specified by:

(13) $$f_M(D) = 62.744D^2 + 134.81D,$$

where D is abatement measured in million tonnes CO_2-equivalents and $f_M(\cdot)$ in NOK/tonne CO_2-equivalents. $f_M(\cdot)$ corresponds to the $f(\cdot)$-function in equation (8). Subscript M denotes process manufacturing. Note that in the numerical model, D is scaled proportionally to the pre-abatement emissions, U_R. This is made in order to account for that U_R develops along the time paths, and it is a reasonable assumption that the abatement potentials develop accordingly. This adjustment is identifiable in the model equations listed in Appendix B.

R^2 for the estimation is 0.85, which indicates a fairly good fit. Marginal costs increases continuously with accumulated abatement, and the estimated curve avoids any positive abatement potential at negative costs. The curve is convex, with marginal costs rising sharply in the higher part.

We assume that all technologically abatable emission sources within process manufacturing face the marginal abatement cost function defined in eq. (13). In the model this means that the four manufacturing industries mentioned earlier (sector 27, 34, 37 and 43, see table A.1 in Appendix A) have the abatement function specified by $f_M(D)$ in equation (13). Within each of the industries, j, emissions can be abated from different activities, k. The different emission generation activities consist of input of fuels, F, other inputs, V, and production, X; the latter applies to process emissions that are directly linked to the output volume. This detailed modelling of abatement makes up another reason for scaling D in proportion to the pre-abatement emissions, U_R. Since the various model industries and emission-generating activities vary in volume, so do their emissions. This should be reflected in their respective abatement potentials.

In MSG-TECH the marginal cost curve is implemented for the emissions sources $k=V, X$ in sector j=27, 37 ,43 and $k=X, V, F$ in sector j=34 (see Appendix A and Appendix B). Accordingly, eq. (10) and (11) in the stylised exposition are specified in the amended model for the same process industries, j, and the corresponding activities, k.

E_j now represents the annual extra cost for industry j, measured as an annuity, of abating the accumulated volume, and is defined as the sum of all E_{jk}:

$$E_j = \sum_k E_{jk} \tag{14}$$

$$E_j = \sum_k E_{jk} \tag{14}$$

Also here the scaling factors adapt the accumulated abatement volumes at each source k to its initial (pre-abatement) emissions. E_j is added to the aggregate input costs of each process industry as in eq. (12), and the industry-specific productivity parameters, ε, in eq. (1), are endogenous. The effect of a reduced ε is reduced profits and induced activity scale-down.

Eq. (2) in the stylised exposition is substituted by:

$$\mu_{kj} = \frac{U_{kj}}{A_{kj}} \quad (15)$$

where A_{kj} is industry and source-specific activity.

2.4.3.2 The petroleum sector

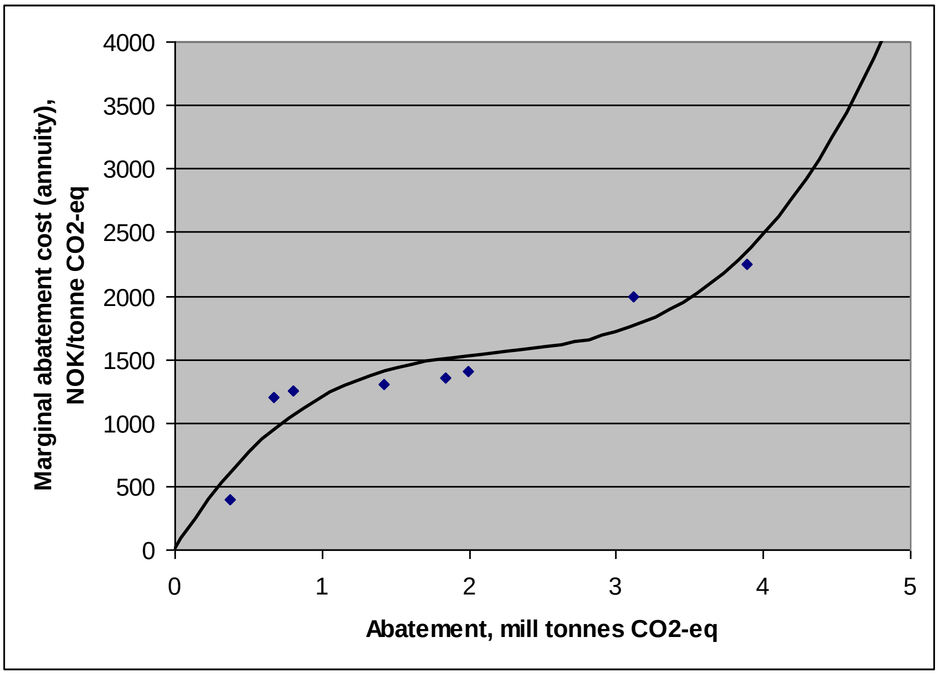
The petroleum sector corresponds to sector 66 (Extraction of crude oil and natural gas, including pipeline transport) in Table A1 in Appendix A. Abatement measures in the petroleum sector were assessed by Klimakur 2020's offshore group (Climate Cure 2020, 2010), under the leadership of the Norwegian Petroleum Directorate (NPD, 2010). The abatement measures include power efficiency improvements, several electrification projects with power transfer from mainland, and CCS deployment on mainland processing installations. The different measures, with accompanied costs and abatement potential, are presented in table 2.3.

Table 2.3: Abatement costs and potentials in the petroleum sector, by measure

Abatement measure	**Annuity (NOK/tonne CO2-eq)**	**Abatement (tonne CO2-eq)**
Energy efficiency offshore	400	0.2
Electrification Melkøya -1	400	0.17
Electrification Melkøya 2	1250	0.13
Electrification new site	1400	0.15
Electrification Melkøya 3	1200	0.3
Electrification North Sea south	1350	0.42
Mongstad processing CCS	1300	0.62
Electrification North Sea north	2000	1.13
Kårstø processing CCS	2250	0.77
Total		3.89

Based on the data in table 2.3, an OLS-regression was conducted. The observations and the estimated trend line are depicted in figure 2.2:

Figure 2.2: Marginal abatement cost curve, petroleum industry



100 NOK =12.5 €

The corresponding marginal abatement cost function for the petroleum sector is given by:

$$f_P(D) = 120{,}61D^3 - 796.01D^2 + 1873D \qquad (16)$$

where D is abatement measured in million tonnes CO_2-equvivalents and $f_P(\cdot)$ in NOK/tonne CO_2-equvivalents. D is scaled proportionally to the pre-abatement emissions, as for the process manufacturing industries. $R^2 = 0.88$ for this regression, indicating a fairly good fit. The marginal abatement cost curve is concave in the lower part of the curve, and for low abatement potentials the costs rise sharply. There is a relatively large potential at medium costs between 1000 and 2000 NOK/tCO2eqv., but at the high end costs do, again, increase sharply with accumulated abatement and the curve becomes convex.

The marginal abatement cost curve for the petroleum industry is implemented for the emissions sources $k=V, X$ in model sector $j=66$ (see Appendix A and Appendix B). The modelling is identical to that of the manufacturing industries. The extra annual cost, E_j, for the petroleum industry reduces profits. As exports, as well as production investments, are exogenously set in the model for this sector, output is hardly affected. Rather, social costs will appear as less revenue from the emissions pricing and taxation of the resource rent.

2.4.3.3 Road transport

Table 2.4 presents the abatement potential and costs of different abatement measures in road transport. The data is collected from two sources: SFT (2007) and Kanenergi/INSA (2009). In addition to improving efficiency of passenger cars and commercial vehicles, the measures within road transport comprise private and public zero-emission vehicles, fuel intermixture of ethanol and biodiesel, and measures to coordinate land planning. Our sources assess sensitivity to costs and potentials for the sequence in which the measures are phased in. In our data basis, the medium estimates are used, and the cheapest measures are assumed to be introduced first. Both data sources estimate the social costs of the measures. Whether there are wedges between the social and private costs (other than in their valuation of climate effects, which should not be included in the costs measured per unit of abatement) is uncertain and not adjusted for in the data.

Table 2.4: Abatement costs and potentials in road transport, by measure

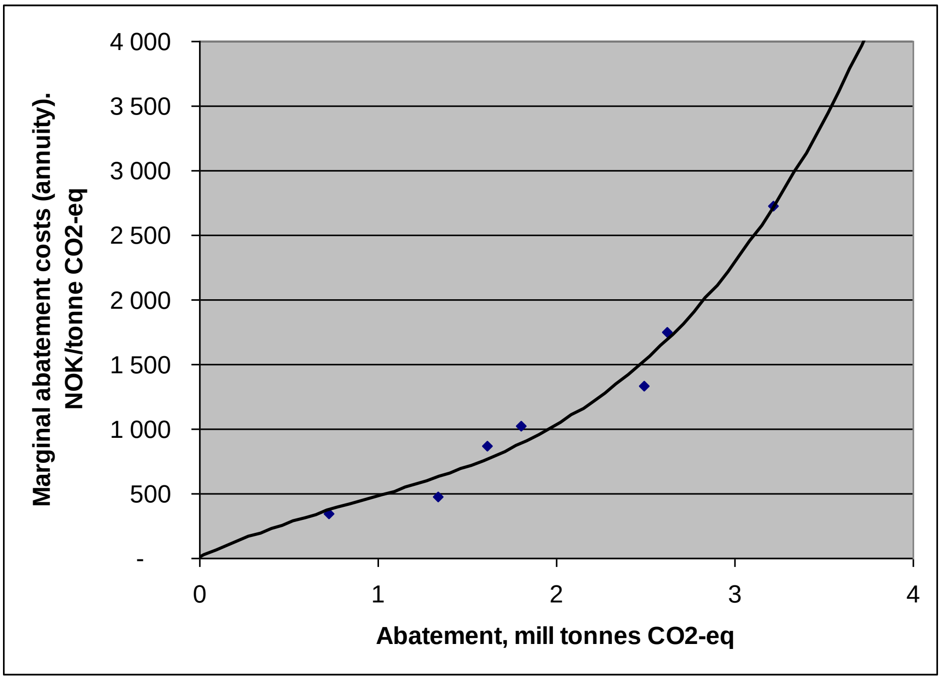
Abatement measure	**Annuity (NOK/tonne CO2-eq)**	**Abatement (tonne CO2-eq)**
Efficiency improvements private cars– level 1	350	0.72
Efficiency improvements private cars– level 2	480	0.62
Zero emissions vehicles– private and public	870	0.27
Intermixture of ethanol E5, E10, E20	1752	0.13
Intermixture of 1. generation biodiesel	1331	0.69
Intermixture of 2. generation biodiesel	2727	0.59
Intermixture of ethanol E85	1022	0.19
Total		3.21

Based on the data in table 2.4, the following marginal abatement cost function is estimated:

(17) $$f_T(D) = 106.48D^3 - 284.38D^2 + 656.17D,$$

where D is measured in million tonnes CO_2-equvivalents and $f_T(\cdot)$ in NOK/tonne CO_2-equvivalents. The data points and the estimated cost curve is depicted in Figure 2.3.

Figure 2.3: Marginal abatement cost curve, road transport



100 NOK =12.5 €

The regressed curve approximates the data very well, with an R^2 of 0.98. The marginal abatement cost curve is rather flat for lower abatement volumes, but becomes convex with sharp increases of marginal costs for high abatement volumes.

When implemented in the MSG-TECH model, we assume that all users of road transportation vehicles are subject to the same marginal abatement cost function, given in eq. (17). Road transportation takes place in all private and public industries (see table A in Appendix A), as well as in households. The scaling of the abatement potentials to the pre-abatement emission levels ensures that abatement potentials are proportional to the size of the emission source, i.e. the period-specific emissions from the use of road vehicles in the respective sector before abatement.

The modelling of real costs of abatement in transportation deviates from the previous sectors. The aggregate cost, corresponding to E in eq. (11) in the stylised model, is modelled as an increase in the price of vehicles. All vehicles are imported, so that

$$(18) \quad PI = PI_R + \frac{E}{I - E},$$

where PI is the import price of vehicles, PI_R is the initial price before abatement, while I is the total imports of vehicles.

2.4.4 General modelling issues

The information on the abatement projects' costs and abatement potentials apply to 2020, based on anticipated prices and technological opportunities. The need for updating in occurrence of new information is a continuous issue. Some updating can be easily met by our modelling approach. For instance, new information on emission levels from various sources will affect estimates on the corresponding technological abatement potentials. As explained above, the modelling automatically adjusts to new emission levels by proportionally adjusting the abatement potentials. This ensures that potentials are updated to new base years, along with time paths and according to the aggregation level of emission sources. However, in cases where the proportionality assumption is misleading, this must be manually taken care of. New information on abatement methods and cost components will change the data set and call for new estimations of abatement cost curves. As soon as new data in terms of (base year) potential and costs are calculated, the updating procedure as described above is relatively simple.

The basic data are, by nature, uncertain. Many of the technologies included in the material are not yet implemented or even tested out. The cost estimates vary with respect to which cost components are tentatively quantified, and information on possible gaps between private and social costs is lacking. For some measures we have distinguished between social and private costs by accounting for tax wedges, but no market imperfections have been identified or modelled. The ranking of the measures is made with respect to costs. In some cases, measures are directed towards overlapping emissions sources, so that abatement costs among projects affect each others or some projects exclude others. It has been necessary to make extra assumptions in order to conclude on a ranking of projects.

Added to these sources of uncertainty comes the abstraction of the abatement projects into abatement curves that are based on very few data points. The risk that the abstractions misrepresent abatement opportunities is particularly high in the extrapolated areas. Reasonable extrapolation outcomes in both ends avoid that abatement costs for small potentials ever fall below zero and that abatement potentials always increase with marginal costs. The steepness in extrapolations at high abatement levels is crucial for the results of analyses of ambitious climate policy targets. Flat technological marginal abatement cost curves implies the assumption that the last/most costly measure in the data material can be duplicated to the same cost as the previous. This could be a plausible characteristic for imported abatement technologies. A steep curve would indicate that, irrespective of the marginal willingness to pay, practically no technology exist that could abate another unit. In general, we cannot conclude on the plausibility of neither form. For most emission sources the truth is somewhere in between.

Also the interpolations can severely depart from real costs. One reason is that to be able to represent continuous abatement opportunities, we need assumptions on the average abatement costs within each project. We have assumed them to be constant. Ranking would not be possible if some projects were characterised by increasing returns to scale.

The modelling of abatement costs is made with regard to capturing that the projects have real costs, not to what these costs consist of, in detail. For example, when the costs of switching to new road vehicles are represented as an increased import price of vehicles, i.e. an investment cost, the modelling disregards that parts of the expenses are actually associated with other components, like maintenance or fuels. Indeed, some technologies would involve completely different inputs, as would e.g. measures that convert energy to biofuels or electricity. Likewise, the abatement cost modelling within the petroleum and manufacturing industries increases all (effective) input prices proportionally, which is not an accurate description of the projects' real input structures. This implicitly assumes that the climate technology projects in the industry have the same input composition as has its production technology. As the projects generally require dissimilar resources, an accurate representation would call for detailed modelling of each project, which is too comprehensive and which we have deliberately tried to avoid in this macro model approach.

The main shortcoming of the inaccurate abatement cost representations is that the input-output effects on the markets for capital, labour and intermediates are not consistent with data. Nevertheless, the model captures that costs for the sectors and for the economy as a whole will increase when multiple projects are carried out simultaneously because of increased input prices. Two other important limitations should, however, be noted in this respect. First, because the model has only one, unified labour market for the entire economy the costs will not reflect that some labour market segments might be particularly affected by the projects. For instance, it is realistic to anticipate some segments of the market for engineers to be particularly squeezed by multiple advanced energy-technology projects. Second, the incremental modelling of investments suppresses that early periods will be more affected by multiple investment projects than later periods, when most capital is installed and ready for use. The costs will be more evenly spread in the CGE model. These two limitations owe to the more general limitations of the CGE approach.

3 Computing the significance of accounting for technological adaptations in climate policy studies

3.1 Design of the analysis and main assumptions

3.1.1 Introduction

We analyse and compare two different shift scenarios with the same policy assumptions, but deviating with respect to the range of options available to reduce emissions. In scenario I, emissions can be reduced by investing in new abatement technology, scaling down output or substituting for emitting production factors. In scenario II, emission reductions through technological adaptations are excluded as options, hence the range of possibilities is narrower. Scenario II replicates how abatement challenges are traditionally modelled in the CGE literature, where all measures are defined within existing technologies. Thus, comparing the two scenarios help identifying the difference between applying a hybrid model approach and a traditional CGE method.

The policy shift in this illustration is the most cost-efficient fulfilment of the so-called Climate Agreement (Klimaforliket) among most parties in the Norwegian Parliament by January 2008 on emission targets for 2020.[8] The expert group Climate Cure 2020 interpreted the content of the agreement into specific domestic, European, and global targets for the years up to 2020. The policy assumptions in this analysis are based on these operationalisations. In the two scenarios, we study the

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[8] The Climate Agreement is available at www.regjeringen.no (in Norwegian, only).

effects of introducing the domestic target in Climate Cure 2020 (2010) compared to a reference path that only take the European and global emission targets into consideration, along with existing and decided climate policies.

While European and global contribution targets are allowed to be met by purchases of allowances in the EU ETS market or by Clean Development Mechanisms (CDM), the domestic abatement not conducted as a result of the EU ETS regulations, will have to be met by additional unilateral climate policies. We impose a uniform emission price on all emission sources exactly capable of meeting the domestic cap. This implies that the existing, differentiated CO2 tax system is replaced by uniform emission price (tax), while domestic emission sources that are today regulated by the EU ETS, will have to pay an additional price to Norwegian authorities over and above the European permit prices exactly sufficient to render their total emission price equal to the uniform tax faced by the rest of the economy.

3.1.2 The reference path

The reference path is based on realistic developments in economic variables and technologies for the next decades[9]. Main driving forces are the demographic development, natural resources forecasts, where a continuing growth in oil and gas production is anticipated, as well as a projected productivity growth of between 1 and 1½ per cent annually. Some energy efficiency improvements exceed these general assumptions, particularly within transportation.

Policy assumptions are based on current practice and resolutions. When it comes to the climate policy, in particular, the Norwegian differentiated system of CO_2 taxes in 2004 is included and prolonged throughout the reference path. The rates vary between 0 and 50€/tonne, with petrol and emissions

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[9] The reference path resembles scenario C published in Klimakur 2020 (2010), but with some adjustments. One of the most important amendments is that the allowance prices have been adjusted downwards to what have proved to be more realistic levels. In addition the technological marginal abatement cost functions have been re-estimated. We refer to Climate Cure 2020 (2010) and Fæhn et al. (2010) for a comparison.

from offshore production of oil and gas at the highest rates, see table 3.1. In the gas power industry, CCS is assumed installed already in the reference path from 2014, in accordance with the plans of The Government. Thus, no abatement potential is left in this industry. [10]

Table 3.1: CO_2 tax rates in the reference scenario, €/ tonne (2004 prices)

	Rate
Maximum taxes by fuels	
- Gasoline	50
- Coal for energy purposes	24
- Auto diesel and light fuel oils	22
- Heavy fuel oils	19
- Coke for energy purposes	18
Taxes by sectors and fuels	
North Sea petroleum extraction	
- Oil for burning	42
- Natural gas for burning	48
Pulp and paper industry, herring flour industry	10
Ferro alloys, carbide, and aluminum industries, production of cement and LECA, air transport, foreign carriage, fishing and catching by sea, domestic fishing, and goods traffic by sea	0

Source: Statistics Norway

Norway's international commitments in the Kyoto Protocol and the EU-ETS since 2008 are included in the reference path. For the period 2008-2012 the EU ETS participation implies that crude oil and

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[10] After the construction of the reference path, these plans have been postponed until 2018. The gas power generation in Norway is in any case of small significance, so the influence of this assumption is minor.

natural gas producers, manufacturers of chemical and mineral products (including cement), pulp and paper commodities, chemical raw materials (including fertilisers), refined oil products, gas power generation, and parts of the metallurgical industries are quota regulated, embracing about 40 per cent of current Norwegian climate gas emissions. From 2013 the rest of the metallurgical industries are also included.[11]

Total Norwegian allowances in the EU-ETS amount to 75.2 million metric tonnes, capped at 15 million metric tonnes annually over the first five years, while it gradually declines until 2020, when it reach 79 per cent of the 2005 emissions, according to the EU ETS specifications. In the first period, 87 per cent of the allowances allocated to the firms affected are free of charge with the exception of the petroleum sector, which has no free allowances. Since the corresponding allowance subsidy follows from historical emissions, it is modelled as a lump sum transfer to the firms from the public budgets. Firms will be allocated up to 100 per cent of their allowances free of charge when production competes with manufacturers outside of the EU ETS. This is estimated to embrace approximately two-thirds of the operations within EU ETS-regulated firms.[12]

The global contribution targets within the UNFCCC framework include an over-fulfilment of the Kyoto commitments by 10 per cent. Norway has also reported to UNFCCC a self-imposed pledge of contributing to global mitigation corresponding to a 30 percent reduction from the national 1990 emission level. In order to meet these targets, it is assumed that the government can supplement the EU-ETS instruments and the remaining CO_2 tax system with use of the flexible Kyoto mechanisms. The most prevalent mechanism to date is the Clean Development Mechanism (CDM), which permits the purchase of emission reductions from projects in developing countries.

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[11] These include sector 27, 34, 37, 43, 66, and 70 in Table A.1 in Appendix A.

[12] In addition, a separate allowance market connected to EU ETS is introduced for air transport from 2012. The calculations do not include the aviation market.

The over-fulfilment of the Kyoto Agreement implies a total emissions ceiling of 225 million tonnes CO_2 equivalents in the five years 2008–12 or a maximum annual global emission contribution of 45 million metric tonnes CO_2 equivalents for each of the five years. The self-imposed global target for 2020 is equivalent to a ceiling of 38 million tonnes CO_2 equivalents from 2020, when forest credits are accounted for[13]. In the period between 2012 and 2020, the annual Kyoto ceiling is kept constant, as an assumption.

Allowance prices for the EU-ETS and the flexible mechanisms are assumed to develop exogenously as depicted in Figure 3.1. They are determined internationally and unaffected by domestic actions. The EU ETS price increases to 20€ within 2020, in accordance with the low estimates in Climate Cure 2020 (2009). The flexible mechanism have so far remained significantly below the EU-ETS price and is assumed to stay below during the whole simulation period.

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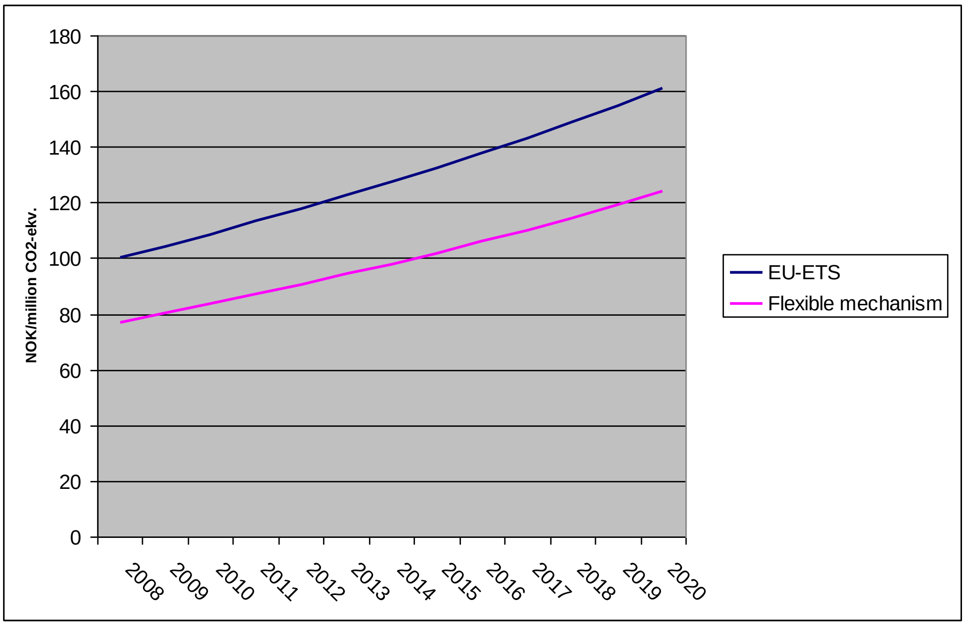
[13] Credits received from changes in forest carbon inventories amount to 3 million tonnes in 2020 in the reference path.Note that changes in the forest regulations adopted at the climate meeting in Durban in 2011 implies that Norways's credits from forest carbon inventoris will be reduced and consititue 1.75 million tonnes in 2020 instead of 3 million tonnes.These newly updated regulations are not accounted for in the reference path.

Figure 3.1: Allowance prices, NOK/tonne CO_2 equivalents, 2004 prices



100 NOK =12.5 €

In the reference scenario (blue curve), total emissions amount to 56.9 million tonnes in 2020. Figure 3.2 shows that Norway's committed emission cap for the EU ETS –regulated sources (purple curve), as well as the target for global contributions in the Kyoto protocol and beyond (yellow curve), both lie below the respective reference scenario levels along the whole path. These deviations will have to be met by permit purchases. As depicted in figure 3.3, Norwegian EU ETS-regulated firms purchase about half of the needed allowances in the years before 2020, while the government will assumedly trade the rest as CDM quotas. In 2020, when the global contribution target is tightened, the need for CDM quotas almost doubles. All in all, allowance purchases constitute 19 million tonnes CO_2 equivalents in 2020, equal to a cost of about 3.5 billion NOK.

Figure 3.2: Reference path emissions (total and in EU ETS sector), European , global and domestic caps; million tonnes CO_2 equivalents. 2008-2020

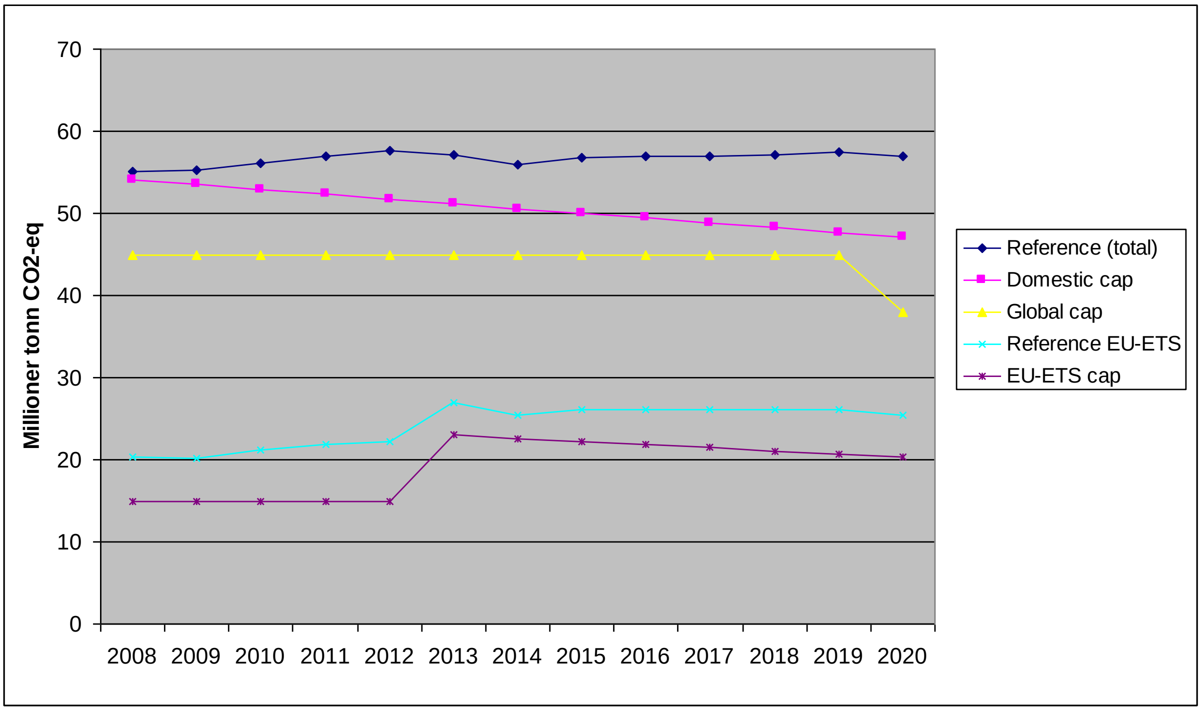
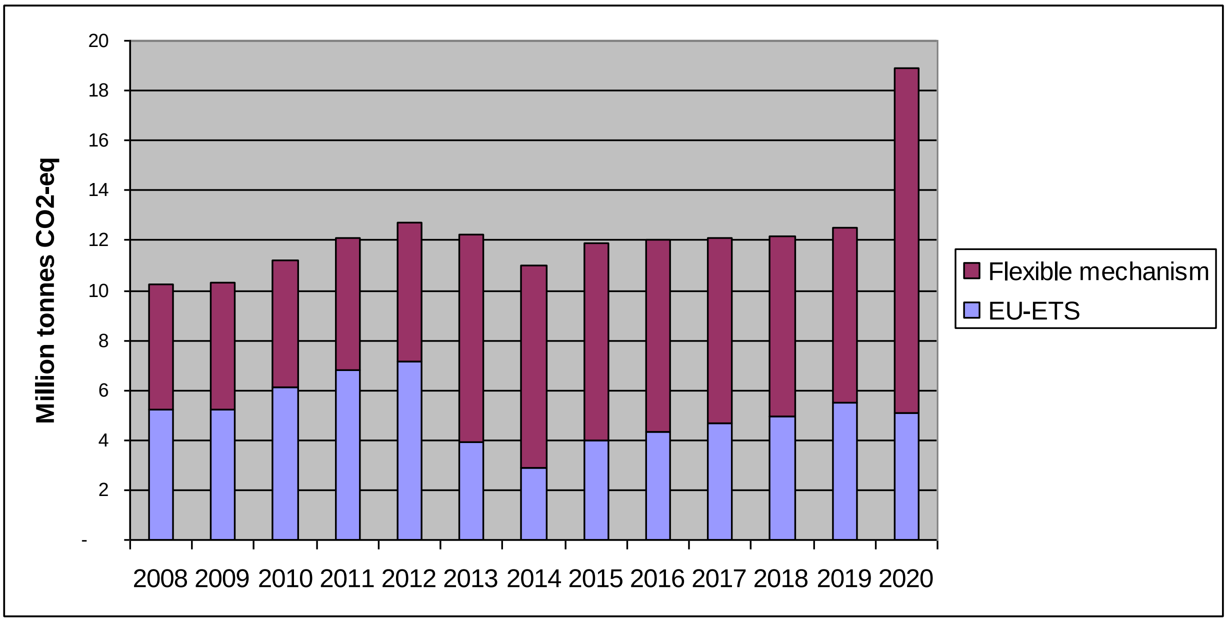


Figure 3.3: Reference path: Allowance purchases abroad, in million tonnes CO2 equivalents. 2008-2020



3.1.3 Policy assumptions in the climate policy scenarios

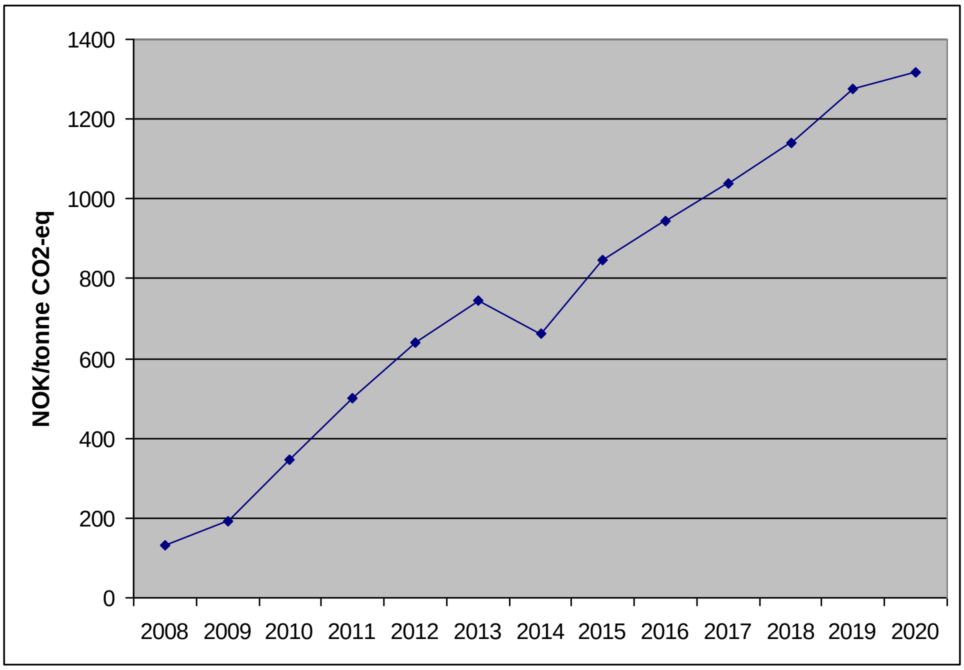
The domestic cap in the policy scenarios are also illustrated in figure 3.2 (pink). It corresponds to reserving at least half of the global reduction ambition in 2020 for domestic measures. We assume that this 2020 goal is approached gradually from the 2008 level. The domestic cap lies below the reference path in every period. The figure also shows that on top of paying the uniform emission price to fulfil the domestic cap, private agents or the government will have to buy allowances amounting to the gap between the pink and the yellow caps, in order to meet the global pledges.

3.2 Results Scenario I: Domestic cap and technology options

3.2.1 Impact on domestic emissions and allowance trading

To comply with the domestic target, the uniform emission price rises to 1300 NOK – equivalent to around 165€ - per tonne of CO_2 equivalents within 2020; see Figure 3.4.

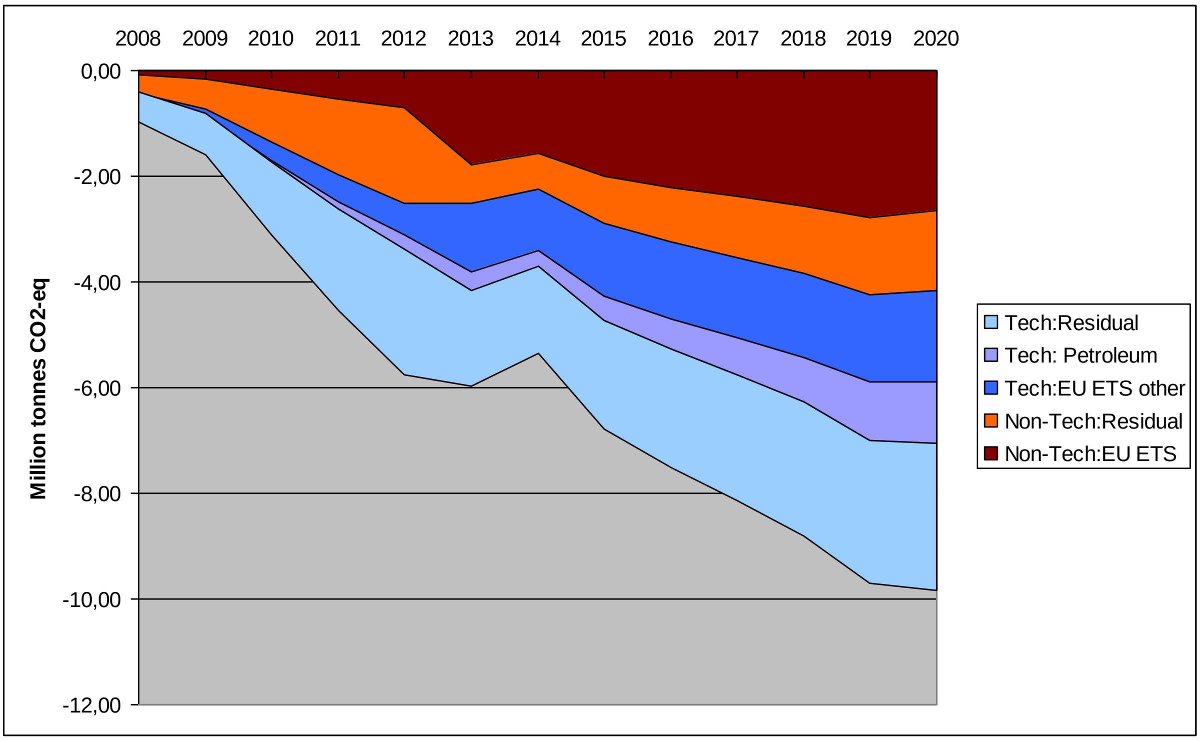
Figure 3.4: Scenario I: National emission price curve; NOK/tonnes of CO_2 eqv. (2004 prices)



100 NOK = 12.5 €

Figure 3.5 depicts changes in emissions from the reference path triggered by the domestic emission pricing. During the first 5 years the main reductions take place in sectors outside the EU ETS (residual sector), before the main reductions gradually move towards the EU ETS sector, which dominates by 2020. Both technological adaptation (labelled Tech in figure 3.5) and other adjustments like down scaling and substitution (labelled Non-Tech in the same figure), take place. Investments in abatement technology are found to be the most important abatement response throughout the period, and in 2020 technology adaptations account for around 60 per cent of emission reductions.

Figure 3.5: Scenario I: Changes in emission from the reference path, by category

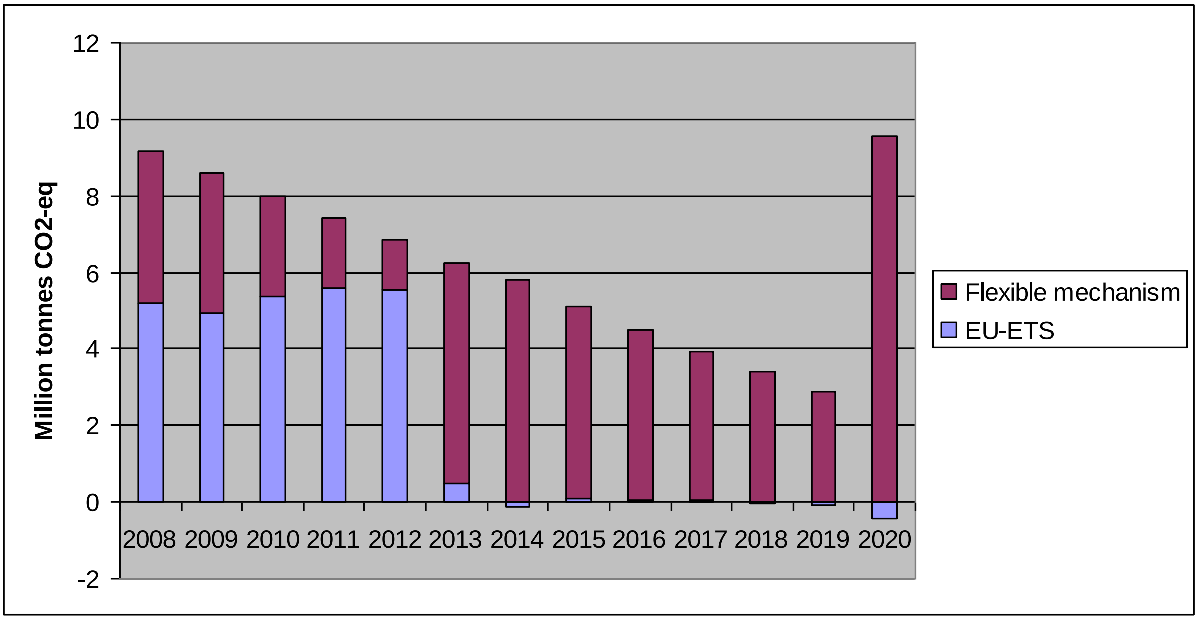


Of the total emission cuts of 10 million tonnes CO_2 equivalents by 2020, 5.5 million tonnes are carried by the EU ETS sector, consisting of the manufacturing industries as well as the petroleum sector. Technological adaptations account for 2.9 million tonnes of these; 1.2 million tonnes in the petroleum sector and 1.7 million tonnes in the manufacturing industries. Down-scaling of the manufacturing industries accounts for the remainder; the model assumes exogenous activity in the petroleum sector. The residual sector cuts 4.3 million tonnes CO_2 equivalents. Here, per assumption, only road transportation can abate emissions by technological adaptations, and this is found to contribute with

2.8 million tonnes CO_2 equivalents. The remainder comes from downscaling emitting transportation activities, most prominently within domestic shipping.

The international commitments and pledges over and above the domestic abatements will be met by allowance purchases abroad. Figure 3.6 depicts the evolution of allowance purchasing in the EU–ETS markets and via the flexible mechanisms.

Figure 3.6: Scenario I: Allowance purchases abroad, in million metric tonnes CO_2 equivalents



The estimates show that up until 2014 the domestic cuts made by EU-ETS-regulated firms will be too small to fulfil EU ETS commitments and they purchase permits in the ETS market. After that time, however, domestic reductions will more than meet commitments. In certain years after 2013 Norwegian firms will even be in a position to sell permits on the ETS market. Norway’s target for global contributions requires, however, more substantial cuts than provided by the national cap. The simulations indicate that the government need purchasing via flexible mechanisms in every period, and intensively so in 2020. Then, the target tightens while the EU ETS firms sell permits, which must also be compensated by the government’s CDM involvements. Compared to the reference, however, purchases do approximately bisect.

3.2.2 Macroeconomic effects

The social costs of fulfilling the national target equal a cut in welfare of 0.2 per cent from the reference scenario. Welfare is measured as the discounted utility of leisure and consumption.[14] This is equivalent to around NOK 378 annually per person. The dominating cost component in this scenario is the costs associated with the efforts within firms and households to cut domestic emissions. The marginal cost of these changes is represented for each year by the difference between the estimated domestic emission price and the emission pricing costs in the reference scenario. Reduced allowance purchases compared to the reference path compensate for some of the extra abatement costs.

Since the emission prices paid by the firms for residual emissions will rise considerably, significant government revenue will be generated in this scenario. This additional revenue is fed back into the economy through reduced pay roll tax rates of around 30 per cent compared with the reference path. This helps bring about lower wage costs which are shifted on to higher real wages. As a consequence, labour supply rises by 0.5 per cent. As initial tax distortions are considerable in the labour/leisure choice, these adjustments contribute to improve social efficiency and welfare.

Another positive effect on welfare result from the climate policy’s interaction with existing favourable industrial policy arrangements within energy-intensive manufacturing. Industries like production of *Metals* (sector 43) and *Chemicals* (sector 27) reduce production, and this, in isolation, benefits the economy as a whole, because their marginal productivity at the outset is lower than average. Their outputs contract by 22 and 32 per cent, respectively. This releases resources for activities with relatively higher macroeconomic marginal returns.

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[14] The social utility costs post 2020 are not simulated, but approximated by assuming they stabilise at the 2020 level to infinity.

3.3 Results Scenario II: Domestic cap and absence of technology options

3.3.1 Impact on domestic emissions and allowance trading

The emission price reaches far higher levels in absence of technological abatement options. The estimated development is depicted in Figure 3.7. In 2020, it reaches 4200 NOK/ tonnes of CO_2 equivalents, which is more than three times higher than in scenario I.

Figure 3.7: Scenario II: National emission price curve; NOK/tonnes of CO_2 eqv. (2004 prices)

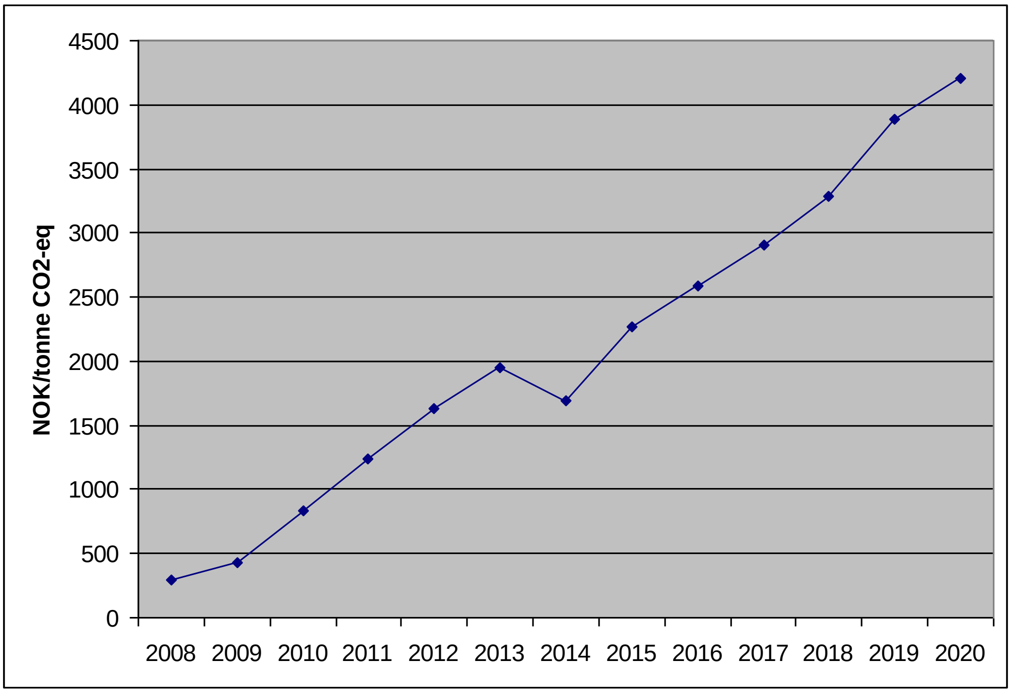
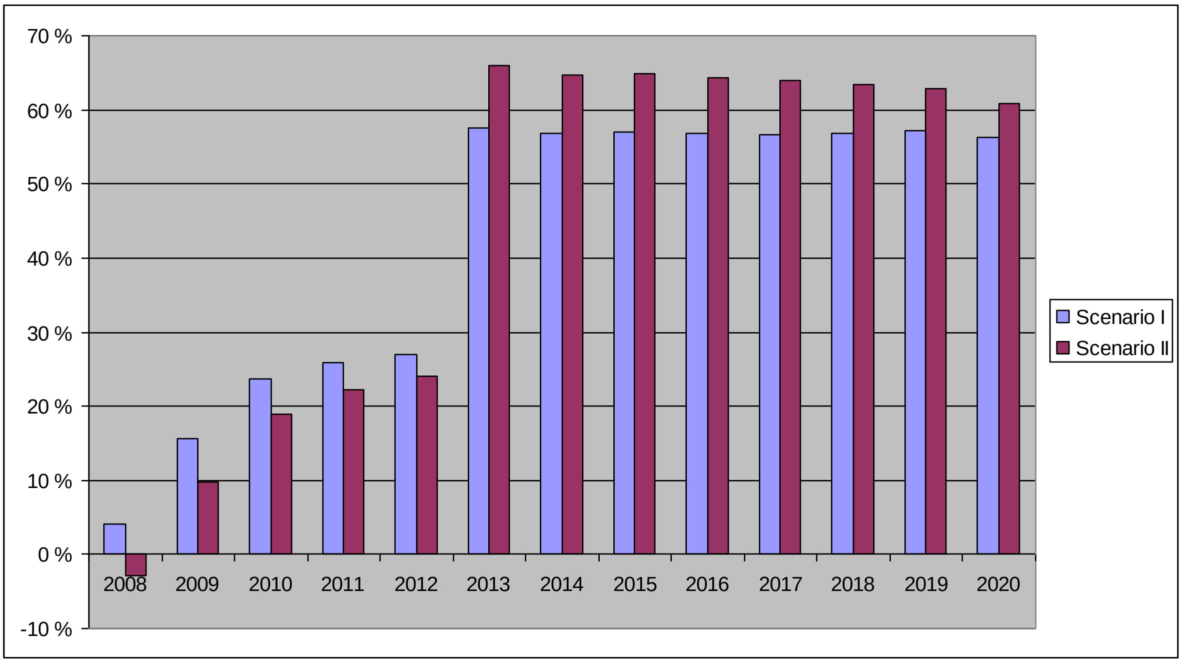


Figure 3.8 illustrates the change in the distribution of emission cuts from scenario I, where technological adaptations are available, to scenario II, where incentives for technological measures are absent. We see that abatement in the EU ETS sector increases after 2012; the share of total abatements increase by 8 percentage points. The internal composition of the cuts within the sector shifts from emission sources in the petroleum industry, where opportunities consist, by assumption, only of technological investments, to the process industries. Reductions within production of metals and of chemical raw materials predominate. These industries take more of the burden, since their production is highly cost elastic due to high export shares and negligible opportunities for cost shifting within the

world markets. Since the metal industry is part of the residual sector before it enters EU ETS in 2013, the abatement within the residual sector also increases from scenario I to II during the first years.

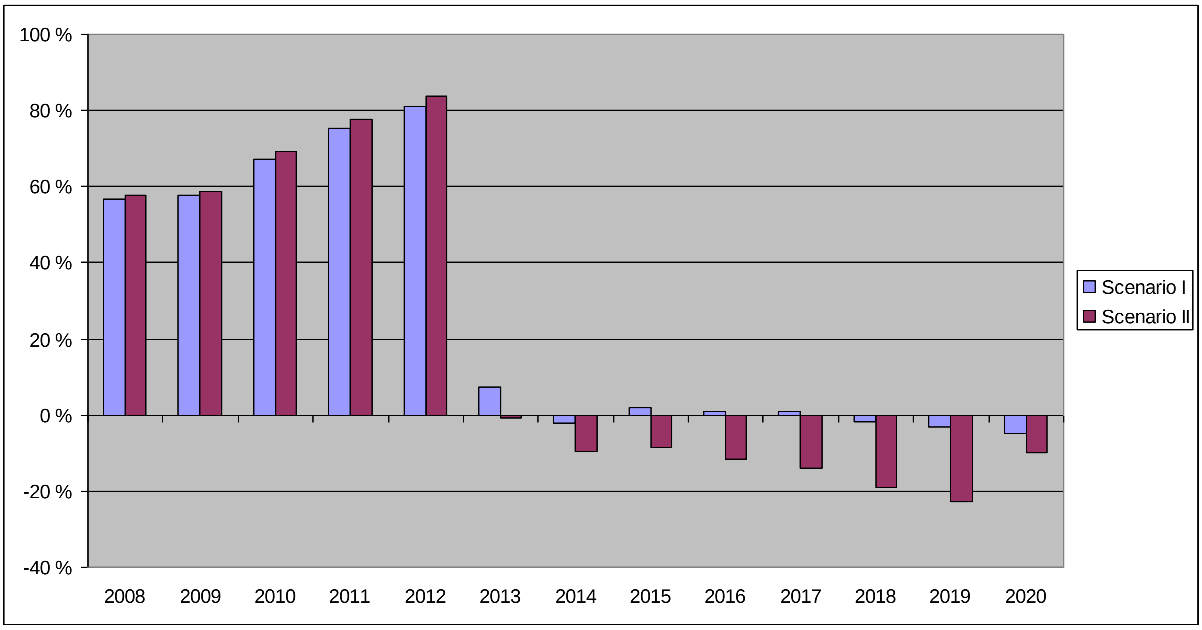
Figure 3.8: Scenario II vs. I: Shares of domestic abatement undertaken by the EU ETS sector



The activities within the residual sector are less elastic. This translates into a lower abatement share for the residual sector after 2012. Service production is more oriented towards the home markets, where costs to a higher degree can be passed on to the consumers. Road transportation is typically little price elastic. Thus, less car driving hardly compensates for the absence of technological opportunities in scenario II. GHG emissions from road transport inevitably rise. Domestic shipping does, however, adjust more elastically and takes a significantly larger share of the burden.

The EU ETS allowance trading mirrors the increased abatement efforts within the EU ETS sector post 2012, which reduces the need for allowances. The overall international trading of allowances will be the same and determined by the domestic and global targets (see Figure 3.2). Figure 3.9 illustrates the shares of European allowance purchases in scenario I and II. It shows the stronger bias towards use of the flexible Kyoto mechanisms after 2013. Actually, all the years in this period are characterised by *net sales* of EU ETS quotas.

Figure 3.9: Scenario II vs. I: Shares of European allowance purchases in total purchases



3.3.2 Macroeconomic effects

Failing to trigger technological adaptations quadruples the welfare costs of the policy. Higher domestic abatement costs explain most of this. Replacing technological measures by far costlier contractions of consumption and production activities will more than triple of *marginal* domestic abatement costs, defined by the emission price. Allowance purchases become slightly cheaper because of the compositional change away from the more costly EU ETS allowances.

As in scenario I revenue from carbon pricing is recycled through reduced pay roll tax rates, which are 78 per cent lower than in the reference scenario in 2020. This alleviates the labour tax burden and contributes positively to welfare through the reallocation towards more labour supply at the expense of leisure. Compared with the reference scenario, received wages increase by 1.8 percent and labour supply by 2 per cent in 2020.

Production in the EU ETS-regulated manufacturing industries is cut drastically. Compared to the reference scenario, production of *Metals* (sector 43) and production of *Chemicals* (sector 37) contract by 62 and 79 per cent, respectively. *Commercial road transport* (sector 75) and *Domestic sea transport* (sector 79) also cut services substantially, by 8 and 32 per cent, respectively. The industrial pattern shifts markedly towards service industries that are labour intensive and low-emitting. While the consumption is only reduced by 1.4 percent, we see a shift towards services other than transport services. Use of own cars by households falls by 26 per cent, while use of fuels by households decreases by 29 percent.

The relative increase in social costs of allowing for technological measures is clearly larger than the rise in marginal abatement costs, as seen from the change in the uniform carbon price. As there are numerous distortions present in the calibrated model, the explanation can partly lie in interaction effects with existing price wedges. There are, for instance, several indirect taxes imposed on car purchases and fuel use besides the CO2 tax. If these are optimised by the government (or set too high) in the reference these may have distortive effects when transport activities are drastically cut. Other interaction effects may however work in the opposite direction. In scenario A we proposed that contractions of the manufacturing industries could have positive welfare effects. However, the cuts seen in this scenario B are drastic, and we cannot, based on the model simulations, establish whether these are welfare improving or deteriorating.

3.4 Conclusions from the simulations

The main conclusion from our analysis is that the traditional CGE approach tends to seriously overestimate abatement costs. Since climate technologies become available as political awareness and policy instruments develop, historical data cannot be expected to reflect technological trends and substitution possibilities that are relevant for futures with ambitious climate policies. The MSG6 model for Norway, which is calibrated to today’s technologies and parameterised with historical substitution elasticities, is found to overestimate abatement costs by a factor exceeding 4. The intuition is that a model that fails to account for a large part of the abatement alternatives that will become available in the future, reflects an unrealistically inflexible and inefficient economy.

Subsequently, bottom-up models that fail to account for reduced economic activity and new industrial patterns will also overestimate abatement costs. Reallocations among factors and industries are found to represent more than 40 per cent of the realised abatement opportunities. The hybrid approach enabled by MSG-TECH includes both technological abatement, down-scaling, and reallocations and is, thus, a more complete analytical tool.

The large cost difference we find between MSG-TECH and MSG6 is naturally sensitive to the marginal abatement cost estimates of technology projects. The uncertainty of such estimates is significant. There are reasons to believe that abatement costs differ considerably between firms, industries, countries, contexts, and through time. Our data are based on sector-specific, current knowledge and primarily on Norwegian studies, which should give a fairly good representation of relevant costs. However, future technological potentials are difficult to predict.

There are also some other sources of uncertainty applying to the technology assumptions. The available information usually depicts *social* costs of climate investments calculated without regard to market imperfections and behavioural irrationalities. If there are significant market failures in technology diffusion, the data may poorly represent the decision bases of firms and households. Stakeholders frequently claim that market failures tend to hamper climate technology diffusion and call for public facilitation. However, empirical evidence on such failures is still scarce, and there is reason to expect that if they exist, they tend to be largely case and market specific.

The outcome of simulating the original MSG6 model can represent situations where up-front investments are hampered. This can be the result of market failures or other inefficiencies that cause second-best situations. Up-front investments in climate technologies can for instance be hampered by the inability of policy makers to signal a trustworthy future climate policy. Investment surroundings for climate technologies are particularly sensitive to policies, as the profitability critically hinges on the costs of emitting GHGs in the future. In face of a *perceived* short-lived emission price, up-front investments in climate technologies will not appear profitable; firms will rather reduce their variable costs and scale down output, and consumers will respond by substituting other consumer goods for energy and leisure for consumption. Even though the usual recommendation for optimal abatement is uniform emission pricing, such situations can call for complementary policy responses, which optimal designs will depend on the kind of obstacles present.

The estimated cost levels of all the scenarios, including the reference scenario, are uncertain. Apart from a large variety of unsystematic sources of uncertainty, two main shortcomings of our method should be emphasised. Firstly, the CGE approach leaves out transition costs, tending to underestimate the abatement cost levels, particularly when the perspective is as short as in the illustrative analysis. The second reservation we wish to make is that, as shown, costs are highly sensitive to the range of potential abatement measures covered by the model. Some adjustments are by assumption excluded from the simulations. We have mentioned that possible contractions within the petroleum industry are omitted. Similar assumptions apply to agriculture and fisheries. There are also reports covering technological opportunities beyond those modelled in our approach (e.g. within heating; see NWREA, 2010), which would add to the abatement potential. Generally, including more abatement potential would decrease the cost levels (though not necessarily the ranking of the policy strategies).

4 Remaining challenges and plans

Hybrid models like MSG-TECH are useful tools in studies of current and future policies that simultaneously affect production and consumption scales, factor allocation and technological choices. In the simulations that test the model in the previous chapter, we have considered effects of greenhouse gas emission targets met by carbon pricing. Other climate policies worth studying in a similar framework are, e.g., investment support, abatement subsidies and introduction of technological standards. Hybrid approaches are also crucial for analysing the interplay between various policy instruments and policy targets. For instance, the EU 20-20-20 policies for 2020 will be adopted by Norway. The forthcoming changes in the energy-climate nexus of the Norwegian economy will inevitably involve technological adjustments and developments, along with energy efficiency efforts, factor substitution and contraction of the most energy-intensive economic activities. The new developments in MSG-TECH and further developments along similar strands can be suitable devices for addressing these transitions.

The MSG-TECH model has a large potential for further enlargement and improvement. First, no efforts are made to model existing technological opportunities within a number of economic sectors where we know there are alternatives, e.g. within agriculture, forestry, other transportation than by road, heating of buildings, other manufacturing, and public infrastructure. Similar methodology can be used for these sectors, provided there are available engineering data.

The technologies and the costs included in MSG-TECH are those assumed to be relevant for 2020. As time goes by, there are reasons to expect costs to come down due to new R&D results and learning. Existing evidence on the road transportation sector indicates that learning is essential and increases the abatement potential substantially over time. A large part of the forthcoming technological change can be regarded as external to the Norwegian economy. This could be modelled by an exogenous technological trend in the abatement cost equations. The endogenous part of technological change through learning by doing in Norwegian firms and households and through R&D efforts in Norwegian private and governmental research institutions would also be worth modelling. Bye et al. (2009) have developed a model where technological development of CCS takes place in Norway and affect emissions efficiency endogenously. An ideal model for capturing abatement costs and effects of climate policies should include both technological development and adaptation.

The included technological abatement costs in MSG-TECH are estimated based on uncertain data. There can be more to gain by further refining and updating as new information is gathered. A major caveat is that available cost estimates are assumed to equal private costs. In practice, it is uncertain what costs will fall on private firms and households and what are public costs of infrastructures etc. In cases where social and private costs depart it is also important to model the reasons for that. This could be due to some market failures, in which case proper modelling of the respective failure must be facilitated. Knowledge on the nature of the market failure is crucial for choosing the correct modelling and how policy instruments affect social costs.

A serious shortcoming of the chosen approach is its rough representation of the input-output effects of the climate technology investments. As each project would require quite different resources, an accurate representation would call for detailed modelling of each project, which is too comprehensive in a large macro model. Notwithstanding, better approximations could be a task for future modelling. The basic data underlying the model efforts in MSG-TECH have richer details on exactly what technologies are used at each level of abatement. These data could be exploited to let factor shares depend on the scale of technological abatement. For example, the cheapest abatement technologies within manufacturing are investments in new equipment and substitution of bio anodes for coal anodes. For larger abatement scales at higher marginal costs, the abatement will also include use of CCS equipment, which will have a different composition of costs. Scale-dependent cost compositions can be modelled that more accurately account for these changes.

As the analysis above points out, climate policies will transform the economy. Investments will change, old capital will become obsolete, and jobs will disappear in some sectors of the economy and emerge in others. Along with these transformations, regional imbalances will appear and people will need to move geographically as well as between sectors. A CGE model like MSG-TECH largely disregards such transaction costs.

CGE models are more appropriate for analysing long run impacts than to shed light on the transitional path towards a new steady state. The illustrative analysis above can legitimately be criticised for being too short-sighted and with too much emphasis on the transition pre 2020. In this respect, the calculations underestimate social costs. Another, and related, implication is that there is no lag between the investments and the emission abatement that follows. Investments are assumed to take place incrementally (as is de-investments) and each incremental NOK invested increases the abatement incrementally and instantly. The investments costs are counted as (annual) user costs, translated to annuities. This feature applies to all investments in the model, not only investments in climate technologies. In real life we know that investments typically takes place several years before productivity (in this case emission efficiency) improves.

This has left us with a trade-off between whether representing the cost profile or the emissions profile in a realistic manner. In the illustrative simulations in this analysis we chose a realistic facing in of emissions abatement at the expense of a realistic cost profile (in which case we should have implemented the 2020 target in the first simulation year (2008). Thus, social abatement costs, which are discounted utility costs, put relatively much weight on the transitional path, which reflects too low investment costs. The full costs are reached only from 2020 and onwards. The annuity calculations for each technological measure that form the basis for the abatement cost curves are, however, based on realistic cost profiles, so in a very indirect way the true profiles are partly reflected.

References

Aasness, J. and B. Holtsmark (1995): Effects on consumer demand patterns of falling prices in telecommunication, Working Paper 1995:8, Centre for International Climate and Environmental Research - Oslo (CICERO).

Bataille, C, M. Jaccard, J. Nyboer , and N. Rivers (2006): Towards general equilibrium in a technology-rich model with empirically estimated behavioural parameters, *The Energy Journal*, Special issue on Hybrid Modeling of Energy-Environment policies: Reconciling bottom-up and top-down, 13-38.

Böhringer, C., A. Müller, and M. Wickart (2003): Economic impacts of a premature nuclear phase-out in Switzerland – An applied General Equilibrium Analysis, *Swiss Journal of Economics and Statistics*, 139 (4): 461-505.

Bosetti V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006): WITCH: A World Induced Technical Change Hybrid Model; *The Energy Journal*, Special issue on Hybrid Modeling of Energy-Environment policies: Reconciling bottom-up and top-down, 13-38.

Bye, B. (2008): Macroeconomic modelling for energy and environmental analyses: Integrated economy-energy-environmental models as efficient tools, Documents 2008/14, Statistisk sentralbyrå.

Brita Bye, Taran Fæhn, Tom-Reiel Heggedal, Karl Jacobsen, and Birger Strøm (2008): *An innovation and climate policy model with factor-biased technological change: A small, open economy approach*, Reports 22/2008, Statistics Norway.

Chenery, Hollis B. (1949). Engineering production functions. Quarterly Journal of Economics, 63, 507-31

ETSAP (2004): Documentation for the MARKAL Family of Models, Energy Technology Systems Analysis Program, http://www.etsap.org/documentation.asp.

Fæhn, T., K. Jacobsen og B. Strøm (2010): Samfunnsøkonomiske kostnader ved klimamål for 2020 - en generell modelltilnærming, Rapporter 2010/22, Statistisk sentralbyrå.

Hamilton, L. D., G. Goldstein, J.C. Lee, A.S. Manne, W. Marcuse, S. C. Morris, and C.O. Wene (1992): MARKAL-MACRO: An Overview, Brookhaven National Laboratories #48377, November.

Heide, K. M., E. holmøy, L. Lerskau og I.F. Solli (2004): Macroeconomic Properties of the Norwegian Applied General Equilibrium Model MSG6, Reports 2004/18, Statistisk sentralbyrå.

Kanenergi/INSA (2009): Vurdering av biodrivstoff i transportsektoren, tiltak, virkemidler, effekter og kostnader i 2020 og 2030 (An assessment of biofuels in transportation), Report.

Climate Cure 2020 (2009): *Vurdering av framtidige kvotepriser (An assessment of future emission allowance prices)*, TA 2545/2009, Statens forurensningstilsyn (now Klima- og forurensningsdirektoratet), Norges vassdrags- og energidirektorat, Oljedirektoratet, Statistisk sentralbyrå, Statens vegvesen.

Climate Cure 2020 (2010): Tiltak og virkemidler for å nå norske klimamål mot 2020 (Measures and public instruments for meeting Norwegian climate targets towards 2020), TA 2590/2010, Klima- og forurensningsdirektoratet, Norges vassdrags- og energidirektorat, Oljedirektoratet, Statistisk sentralbyrå, Statens vegvesen; English summary available at www.klimakur2020.no.

Laitner, J.A and D. A. Hanson (2006): Modeling Detailed Energy-Efficiency Technologies and Technology Policies within a CGE Framework, *The Energy Journal*, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling bottom-up and top-down, 151-170.

Loulou, R. and D. Lavigne (1996): MARKAL model with elastic demands: Application to GHG emission control, in C. Carraro and A. Hairie (eds): *Operation Research and Environmental Engineering*, 201-220, Boston: Kluwer Academic Publishers.

NPD (2010): Prospects for abatements in the Norweigan oil and gas industry; a sub-report of Climate Cure 2020, Norwegian Petroleum Institute (NPI)

NWREA (2010): Energy supply and demand, an analysis for the CLIMATE CURE 2020, Norwegian Water Resources and Energy Administration

Sav, G. Thomas (1984): The engineering approach to economic production functions revisited: an application to solar processes. The Journal of Industrial Economics, 33, 21-35

SFT (2007): Tiltak for reduksjon av klimagassutslipp i Norge, delnotat om virkning av mulige tiltak for reduserte utslipp fra kjøretøy, Statens forurensningstilsyn (nå Klima- og forurensningsdirektoratet)

SINTEF (2009): Tiltak og virkemidler for reduksjon av klimagasser i norsk prosessindustri (Measures and public instruments for abating climate emissions from Norwegian processsing industries, Report A11606 SINTEF.

TELTEK (2009): CO2-fangst av utslipp fra industrianlegg (Carbon capture of emissions from manufacturing) Report 2109020

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Appendix A

Industries, factors and consumption goods in MSG-TECH

Table A.1: Industries in MSG-TECH

MSG-TECH code	**Description**
11	Agriculture
12	Forestry
13	Fishing
14	Fish farming
15	Manufacture of other consumption goods
18	Manufacture of textiles and apparel
21	Preserving and processing of fish
22	Manufacture of meat and dairy
26	Manufacture of wood and wood products, except furniture
27	Manufacture of chemical and mineral products
28	Printing and publishing
34	Manufacture of pulp and paper products
37	Manufacture of industrial chemicals
40	Petroleum refining
43	Manufacture of metals
45	Manufacture of metal products, machinery and equipment
48	Building of ships
49	Manufacture of oil production platforms
55	Construction, excl. oil well drilling
63	Finance and insurance
65	Ocean transport
66	Extraction of crude oil and natural gas, including pipeline transport
68	Oil and gas exploration and drilling
70	Production of electricity
74	Transmission and distribution of electricity
75	Road transport etc.
76	Air transport etc.
77	Transport by railways and tramways
78	Coastal and inland water transport
79	Postal and telecommunication services
81	Wholesale and retail trade
83	Dwelling services
85	Other private services
89	Imputed service charges from financial institutions
	Central government
92S	Defence
93S	Central government education
94S	Central government health-care and veterinary services etc.
95S	Other central government services

	Local government
93K	Local government education
94K	Local government health-care and veterinary services etc.
95K	Other local government services
96K	Water supply and sanitary services

Figure A.1: Input factors in the production

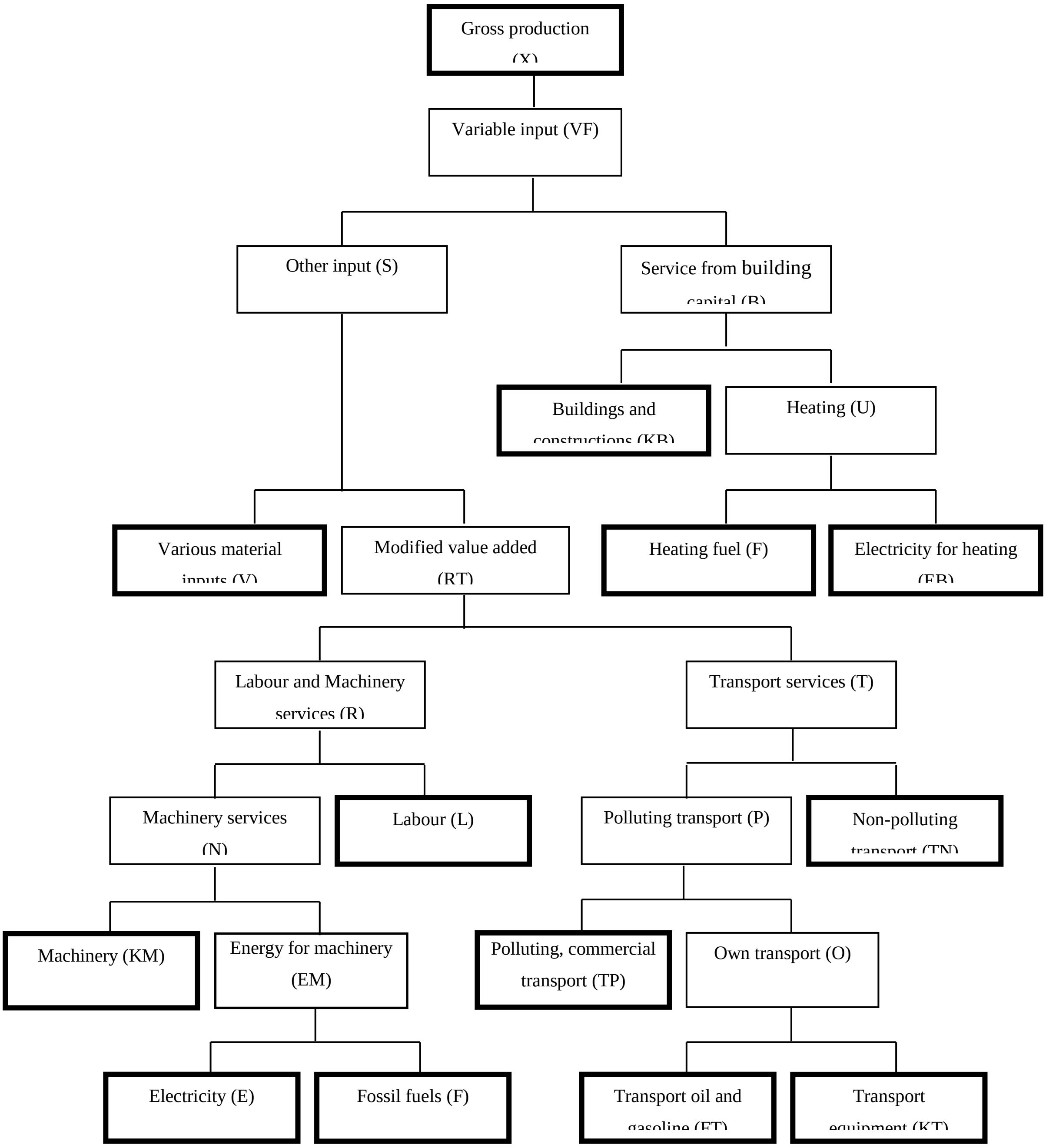
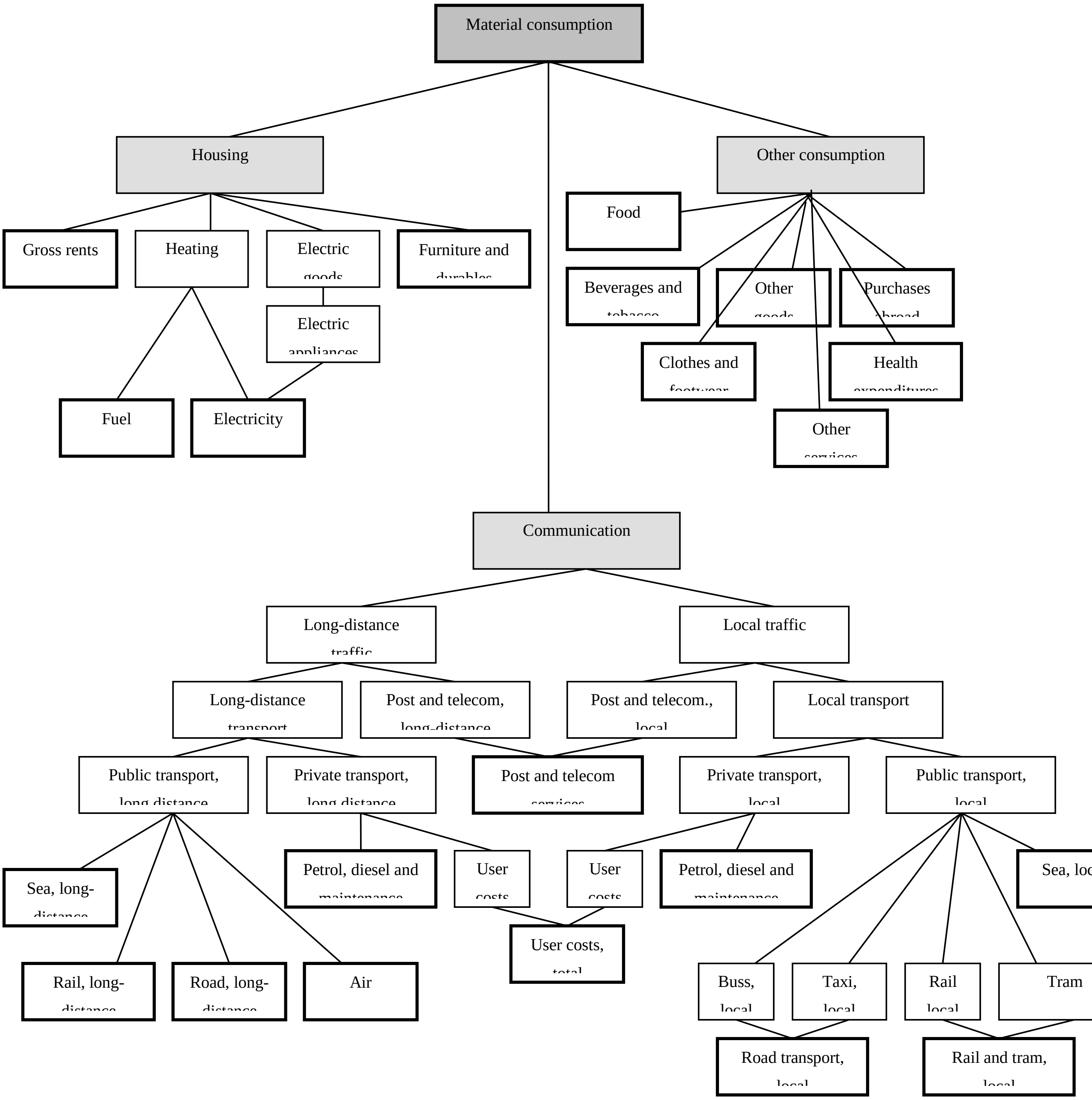


Figure A.2 Material consumption



Appendix B

Equations in the technology module in MSG-TECH

B.1 Industry/consumption sector

A list of all the industries/consumption sectors, *j*, can be found in Table A.1 in Appendix A. In addition to the industries listed in Appendix A, *TRANS* represents an aggregation of all road transport, both in industries and in households.

B.2 Emission generating activity

Emission of CO_2 is projected based on volume development in the following emission generating activities (*k*): Production processes (*X*), production process, including non-production related activity (*TX*), factor input (*V*), heating oils (*F*), transport oils (*FT*) and household consumption (*CA*). Emissions are measured in tonnes of CO_2 equivalents (*Q*).

Table B.1: Emission generating activity

MSG Code	Name
CA	Household consumption
F	Heating fuel
FT	Transport oils
V	Various material inputs
X	Production-related activity
EX	Non-production related acidity
M	Intermediate consumption: sum of various material inputs (V), production-related activity (X) and heating fuel (F).
TX	Sum of production and non-production related activity (X + EX)

Table B.2: Variables in the technology module in MSG-TECH

Variable	**Description**
$CO2_{k,}Q_j$	Emissions in tonnes CO_2 equivalents from activity k and industry j, where k $\in$ (CA, FT, TX, V) and j$\in$ {11,12,14,14B,15,18,21,22,26,27,28,34,37,40,43,45,55,63,70,75,79,81,85,92C,94S,94K,95S,95K,96K, TR
$CO2_{k}QR_{,j}$	CO_2-emissions in tonnes before technological abatement from activity k and industry j, where k$\in$ (CA, FT, and j$\in$ {11,12,14,14B,15,18,21,22,26,27,28,34,37,40,43,45,55,63,70,75,79,81,85,92C,94S,94K,95S,95K, TRANS}
COSTTRANS	Technological abatement cost in road transport
$COSTK_{kj}$	Technological abatement cost from activity *k* and industry *j*, where *k* $\in$ *(F, V, X , M)* and *j* $\in$ *{27,34,37,43,*
$DCO2_{kj}$	Dummy variable indicating if the industry and activity is compromised by the EU ETS sector, where *k* $\in$ *[* and *j* $\in$ *{27,34,37,43,66}.* A dummy variable equal to 1 indicates that the industry is comprised by the EU E whereas a value of 0 indicates that the industry and activity is not part of the EU ETS.
$DELCO2_{k}Q_{,j}$	Technological abatement in tonnes CO_2 equivalents from activity k and industry j, where k $\in$ (CA, FT, TX j$\in$ {11,12,14,14B,15,18,21,22,26,27,28,34,37,40,43,45,55,63,70,75,79,81,85,92C,94S,94K,95S,95K,96K, TRANS}
$EKSTRA_j$	Extra CO_2-price levied on the petroleum sector, where *j* $\in$ *(66)*
EPS	General productivity index
EPS_{kj}	Factor specific productivity index, where *k* $\in$ *(V)* and *j* $\in$ Table A.1\{65,66,68,70,92S}
EPS_kR_j	Factor specific productivity index before technological abatement , where *k* $\in$ *(V)* and *j* $\in$ *{27,34,37,43}*
EUTHETACO2	Uniform emission price (nominal) in EU ETS sector
I02	Import of vehicles in NOK, fixed prices
INFLTCO2	Expected inflation in emission prices (value=0.02)
MR_j	Intermediate consumption, excluding technological abatement cost, where *j* $\in$ *(66)*
PI02	Price index for imported vehicles
PIR02	Price index for imported vehicles, excluding technological abatement costs
$PRISCO2_kQ_{,j}$	Uniform emission price in NOK/tonne CO_2 equivalents, where k $\in$ *(F, V, X)* and *j* $\in$ *(27, 34, 37, 43, 66, T*
SCO2GEN	Technological parameter that works proportional on all emissions of CO_2

$SCO2_kR_j$	Technological parameter connected to activity k and industry j. Based on emissions of CO_2 before technolo abatement. k ∈ (CA, F, FT, V, X) and j∈ {11,12,14,14B,15,18,21,22,26,27,28,34,37,40,43,45,55,63,70,75,79,81,85,92C,94S,94K,95S,95K,96K, TR
VR_j	Factor input in industry *j* before technological abatement, where *j ∈ (27, 34, 37, 43, 66)*
WMTHETACO2	Uniform emission price (nominal) in non EU ETS sector
XEUTHETACO2	Uniform emission price (real) in EU ETS sector
XR_j	Gross production in industry *j* before technological abatement, where *j ∈ (27, 34, 37, 43, 66)*
XWMTHETACO2	Uniform emission price (real) in non EU ETS sector
$ZCSV_j$	Coefficient assigned to various material inputs (*V*) in the CES-aggregate consisting of other input (*S*), wher j∈Table A.1\{65,66,68,70,92S,93S,94S,95S,93K,94K,95K}
$ZCVFS_j$	Coefficient assigned to other input (*S*) in the CES-aggregate consisting of variable input (*VF*), where j∈Tab A.1\{65,66,68,70,92S,93S,94S,95S,93K,94K,95K}

B.3 New Equations in the technology module in MSG-TECH

```
1017:   WMTHETACO2 = XWMTHETACO2*INFLTCO2

1018:   EUTHETACO2 = WMTHETACO2

1019:    CO2TXQR66 = SCO2GEN*SCO2XR66*30.0107734666051*X66

1020:   PRISCO2XQ66 = DCO2TX66*(EKSTRA66+XEUTHETACO2)+(1-DCO2TX66)*

        XWMTHETACO2

1021:   PRISCO2XQ66 = 120.61*10**(-18)*(1/(CO2TXQR66/CO2Q66.0))**3*

        DELCO2TXQ66**3-796.01*10**(-12)*(1/(CO2TXQR66/CO2Q66.0))**2*

        DELCO2TXQ66**2+1873*10**(-6)*1/(CO2TXQR66/CO2Q66.0)*DELCO2TXQ66

1022:   CO2TXQ66 = CO2TXQR66-DELCO2TXQ66

1023:   COSTKX66 = (120.61*10**(-18)*(1/(CO2TXQR66/CO2Q66.0))**3*1/4*

        DELCO2TXQ66**4-796.01*10**(-12)*(1/(CO2TXQR66/CO2Q66.0))**2*1/3*

        DELCO2TXQ66**3+1873*10**(-6)*1/(CO2TXQR66/CO2Q66.0)*1/2*

        DELCO2TXQ66**2)/1000000

1024:   CO2VQR66 = SCO2GEN*SCO2VR66*12.242156512621*V66

1025:   PRISCO2VQ66 = DCO2V66*(EKSTRA66+XEUTHETACO2)+(1-DCO2V66)*

        XWMTHETACO2

1026:   PRISCO2VQ66 = 120.61*10**(-18)*(1/(CO2VQR66/CO2Q66.0))**3*

        DELCO2VQ66**3-796.01*10**(-12)*(1/(CO2VQR66/CO2Q66.0))**2*

        DELCO2VQ66**2+1873*10**(-6)*1/(CO2VQR66/CO2Q66.0)*DELCO2VQ66
```

```
1027:   CO2VQ66 = CO2VQR66-DELCO2VQ66

1028:   COSTKV66 = (120.61*10**(-18)*(1/(CO2VQR66/CO2Q66.0))**3*1/4*
        DELCO2VQ66**4-796.01*10**(-12)*(1/(CO2VQR66/CO2Q66.0))**2*1/3*
        DELCO2VQ66**3+1873*10**(-6)*1/(CO2VQR66/CO2Q66.0)*1/2*DELCO2VQ66
        **2)/1000000

1029:   COSTKM66 = COSTKX66+COSTKV66

1030:   M66 = MR66+COSTKM66

1031:   PRISCO2QTRANS = XWMTHETACO2

1032:   PRISCO2QTRANS = 106.48*10**(-18)*(1/(CO2QRTRANS/CO2QTRANS.0))**3*
        DELCO2QTRANS**3-284.38*10**(-12)*(1/(CO2QRTRANS/CO2QTRANS.0))**2
        *DELCO2QTRANS**2+656.17*10**(-6)*1/(CO2QRTRANS/CO2QTRANS.0)*
        DELCO2QTRANS

1033:   COSTTRANS = (106.48*10**(-18)*(1/(CO2QRTRANS/CO2QTRANS.0))**3*1/4
        *DELCO2QTRANS**4-284.38*10**(-12)*(1/(CO2QRTRANS/CO2QTRANS.0))**
        2*1/3*DELCO2QTRANS**3+656.17*10**(-6)*1/(CO2QRTRANS/CO2QTRANS.0)
        *1/2*DELCO2QTRANS**2)/1000000

1034:   PI02 = PIR02+COSTTRANS/(I02-COSTTRANS)

1035:   DELCO2FTQ11 = DELCO2QTRANS*CO2FTQR11/CO2QRTRANS

1036:   DELCO2FTQ12 = DELCO2QTRANS*CO2FTQR12/CO2QRTRANS

1037:   DELCO2FTQ14 = DELCO2QTRANS*CO2FTQR14/CO2QRTRANS
```

```
1038:   DELCO2FTQ15 = DELCO2QTRANS*CO2FTQR15/CO2QRTRANS

1039:   DELCO2FTQ18 = DELCO2QTRANS*CO2FTQR18/CO2QRTRANS

1040:   DELCO2FTQ21 = DELCO2QTRANS*CO2FTQR21/CO2QRTRANS

1041:   DELCO2FTQ22 = DELCO2QTRANS*CO2FTQR22/CO2QRTRANS

1042:   DELCO2FTQ26 = DELCO2QTRANS*CO2FTQR26/CO2QRTRANS

1043:   DELCO2FTQ27 = DELCO2QTRANS*CO2FTQR27/CO2QRTRANS

1044:       DELCO2FTQ28 = DELCO2QTRANS*CO2FTQR28/CO2QRTRANS

1045:       DELCO2FTQ34 = DELCO2QTRANS*CO2FTQR34/CO2QRTRANS

1046:       DELCO2FTQ37 = DELCO2QTRANS*CO2FTQR37/CO2QRTRANS

1047:       DELCO2FTQ40 = DELCO2QTRANS*CO2FTQR40/CO2QRTRANS

1048:       DELCO2FTQ43 = DELCO2QTRANS*CO2FTQR43/CO2QRTRANS

1049:       DELCO2FTQ45 = DELCO2QTRANS*CO2FTQR45/CO2QRTRANS

1050:       DELCO2FTQ55 = DELCO2QTRANS*CO2FTQR55/CO2QRTRANS

1051:       DELCO2FTQ63 = DELCO2QTRANS*CO2FTQR63/CO2QRTRANS

1052:       DELCO2FTQ70 = DELCO2QTRANS*CO2FTQR70/CO2QRTRANS

1053:       DELCO2FTQ75 = DELCO2QTRANS*CO2FTQR75/CO2QRTRANS

1054:       DELCO2FTQ79 = DELCO2QTRANS*CO2FTQR79/CO2QRTRANS

1055:       DELCO2FTQ81 = DELCO2QTRANS*CO2FTQR81/CO2QRTRANS

1056:       DELCO2FTQ85 = DELCO2QTRANS*CO2FTQR85/CO2QRTRANS

1057:       DELCO2FTQ92C = DELCO2QTRANS*CO2FTQR92C/CO2QRTRANS
```

1058: DELCO2FTQ94S = DELCO2QTRANS*CO2FTQR94S/CO2QRTRANS

1059: DELCO2FTQ95S = DELCO2QTRANS*CO2FTQR95S/CO2QRTRANS

1060: DELCO2FTQ94K = DELCO2QTRANS*CO2FTQR94K/CO2QRTRANS

1061: DELCO2FTQ95K = DELCO2QTRANS*CO2FTQR95K/CO2QRTRANS

1062: DELCO2FTQ96K = DELCO2QTRANS*CO2FTQR96K/CO2QRTRANS

1063: DELCO2CAQ14B = DELCO2QTRANS*CO2CAQR14B/CO2QRTRANS

1064: CO2FTQ11 = CO2FTQR11-DELCO2FTQ11

1065: CO2FTQ12 = CO2FTQR12-DELCO2FTQ12

1066: CO2FTQ14 = CO2FTQR14-DELCO2FTQ14

1067: CO2FTQ15 = CO2FTQR15-DELCO2FTQ15

1068: CO2FTQ18 = CO2FTQR18-DELCO2FTQ18

1069: CO2FTQ21 = CO2FTQR21-DELCO2FTQ21

1070: CO2FTQ22 = CO2FTQR22-DELCO2FTQ22

1071: CO2FTQ26 = CO2FTQR26-DELCO2FTQ26

1072: CO2FTQ27 = CO2FTQR27-DELCO2FTQ27

1073: CO2FTQ28 = CO2FTQR28-DELCO2FTQ28

1074: CO2FTQ34 = CO2FTQR34-DELCO2FTQ34

1075: CO2FTQ37 = CO2FTQR37-DELCO2FTQ37

1076: CO2FTQ40 = CO2FTQR40-DELCO2FTQ40

1077: CO2FTQ43 = CO2FTQR43-DELCO2FTQ43

1078: CO2FTQ45 = CO2FTQR45-DELCO2FTQ45

1079: CO2FTQ55 = CO2FTQR55-DELCO2FTQ55

1080: CO2FTQ63 = CO2FTQR63-DELCO2FTQ63

1081: CO2FTQ70 = CO2FTQR70-DELCO2FTQ70

1082: CO2FTQ75 = CO2FTQR75-DELCO2FTQ75

1083: CO2FTQ79 = CO2FTQR79-DELCO2FTQ79

1084: CO2FTQ81 = CO2FTQR81-DELCO2FTQ81

1085: CO2FTQ85 = CO2FTQR85-DELCO2FTQ85

1086: CO2FTQ92C = CO2FTQR92C-DELCO2FTQ92C

1087: CO2FTQ94S = CO2FTQR94S-DELCO2FTQ94S

1088: CO2FTQ95S = CO2FTQR95S-DELCO2FTQ95S

1089: CO2FTQ94K = CO2FTQR94K-DELCO2FTQ94K

1090: CO2FTQ95K = CO2FTQR95K-DELCO2FTQ95K

1091: CO2FTQ96K = CO2FTQR96K-DELCO2FTQ96K

1092: CO2CAQ14B = CO2CAQR14B-DELCO2CAQ14B

1093: CO2FTQR11 = SCO2GEN*SCO2FTR11*707.00486646128*FT11

1094: CO2FTQR12 = SCO2GEN*SCO2FTR12*473.978835227273*FT12

1095: CO2FTQR14 = SCO2GEN*SCO2FTR14*222.87555609809*FT14

1096: CO2FTQR15 = SCO2GEN*SCO2FTR15*418.847551366458*FT15

1097: CO2FTQR18 = SCO2GEN*SCO2FTR18*430.3815574646*FT18

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1098:	CO2FTQR21 = SCO2GEN*SCO2FTR21*474.433996347281*FT21
1099:	CO2FTQR22 = SCO2GEN*SCO2FTR22*416.330611357818*FT22
1100:	CO2FTQR26 = SCO2GEN*SCO2FTR26*569.512929220612*FT26
1101:	CO2FTQR27 = SCO2GEN*SCO2FTR27*662.663963875624*FT27
1102:	CO2FTQR28 = SCO2GEN*SCO2FTR28*262.874937012082*FT28
1103:	CO2FTQR34 = SCO2GEN*SCO2FTR34*832.423518604702*FT34
1104:	CO2FTQR37 = SCO2GEN*SCO2FTR37*432.719322344836*FT37
1105:	CO2FTQR40 = SCO2GEN*SCO2FTR40*1435.22447299957*FT40
1106:	CO2FTQR43 = SCO2GEN*SCO2FTR43*703.768368695233*FT43
1107:	CO2FTQR45 = SCO2GEN*SCO2FTR45*413.791802475188*FT45
1108:	CO2FTQR55 = SCO2GEN*SCO2FTR55*291.540378230803*FT55
1109:	CO2FTQR63 = SCO2GEN*SCO2FTR63*5034.3203125*FT63
1110:	CO2FTQR70 = SCO2GEN*SCO2FTR70*104.682322432355*FT70
1111:	CO2FTQR75 = SCO2GEN*SCO2FTR75*433.780192162688*FT75
1112:	CO2FTQR79 = SCO2GEN*SCO2FTR79*749.929214697406*FT79
1113:	CO2FTQR81 = SCO2GEN*SCO2FTR81*80.4377224632007*FT81
1114:	CO2FTQR85 = SCO2GEN*SCO2FTR85*89.2815116444569*FT85
1115:	CO2FTQR92C = SCO2GEN*SCO2FTR92S*860.165771484375*FT92C
1116:	CO2FTQR94S = SCO2GEN*SCO2FTR94S*16.1315385867388*FT94S
1117:	CO2FTQR95S = SCO2GEN*SCO2FTR95S*486.142159598214*FT95S
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1118: CO2FTQR94K = SCO2GEN*SCO2FTR94K*2.77582682370663*FT94K

1119: CO2FTQR95K = SCO2GEN*SCO2FTR95K*2.32739501753989*FT95K

1120: CO2FTQR96K = SCO2GEN*SCO2FTR96K*90.8593041731074*FT96K

1121: CO2CAQR14B = SCO2GEN*SCO2CAR14B*202.039997475114*C14B

1122: CO2QRTRANS =
CO2FTQR11+CO2FTQR12+CO2FTQR14+CO2FTQR15+CO2FTQR18+

CO2FTQR21+CO2FTQR22+CO2FTQR26+CO2FTQR27+CO2FTQR28+CO2FTQR34+

CO2FTQR37+CO2FTQR40+CO2FTQR43+CO2FTQR45+CO2FTQR55+CO2FTQR63+

CO2FTQR70+CO2FTQR75+CO2FTQR79+CO2FTQR81+CO2FTQR85+CO2FTQR92C+

CO2FTQR94S+CO2FTQR95S+CO2FTQR94K+CO2FTQR95K+CO2FTQR96K+

CO2CAQR14B

1123: VR43 = ZCSV43/(EPS*EPSVR43)*ZCVFS43*VF43

1124: CO2VQR43 = SCO2GEN*SCO2VR43*135.440251832427*V43

1125: PRISCO2VQ43 = DCO2V43*XEUTHETACO2+(1-DCO2V43)*XWMTHETACO2

1126: PRISCO2VQ43 = 62.744*10**(-12)*(DELCO2VQ43/(CO2VQR43/CO2QGR1.0))

2+134.81*10(-6)*DELCO2VQ43/(CO2VQR43/CO2QGR1.0)

1127: CO2VQ43 = CO2VQR43-DELCO2VQ43

1128: COSTKV43 = (62.744*10**(-12)/(3*(CO2VQR43/CO2QGR1.0)**2)*

DELCO2VQ43**3+134.81*10**(-6)/(2*CO2VQR43/CO2QGR1.0)*DELCO2VQ43

**2)/1000000

1129: CO2TXQR43 = SCO2GEN*SCO2XR43*1.70428511814132*X43

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1130:     PRISCO2XQ43 = DCO2TX43*XEUTHETACO2+(1-DCO2TX43)*XWMTHETACO2

1131:     PRISCO2XQ43 = 62.744*10**(-12)*(DELCO2TXQ43/(CO2TXQR43/CO2QGR1.0)

          )**2+134.81*10**(-6)*DELCO2TXQ43/(CO2TXQR43/CO2QGR1.0)

1132:     CO2TXQ43 = CO2TXQR43-DELCO2TXQ43

1133:     COSTKX43 = (62.744*10**(-12)/(3*(CO2TXQR43/CO2QGR1.0)**2)*

          DELCO2TXQ43**3+134.81*10**(-6)/(2*CO2TXQR43/CO2QGR1.0)*

          DELCO2TXQ43**2)/1000000

1134:     COSTKM43 = COSTKV43+COSTKX43

1135:     V43 = VR43+COSTKM43

1136:     VR37 = ZCSV37/(EPS*EPSVR37)*ZCVFS37*VF37

1137:     CO2VQR37 = SCO2GEN*SCO2VR37*32.3127508581742*V37

1138:     PRISCO2VQ37 = DCO2V37*XEUTHETACO2+(1-DCO2V37)*XWMTHETACO2

1139:     PRISCO2VQ37 = 62.744*10**(-12)*(DELCO2VQ37/(CO2VQR37/CO2QGR1.0))

          **2+134.81*10**(-6)*DELCO2VQ37/(CO2VQR37/CO2QGR1.0)

1140:     CO2VQ37 = CO2VQR37-DELCO2VQ37

1141:     COSTKV37 = (62.744*10**(-12)/(3*(CO2VQR37/CO2QGR1.0)**2)*

          DELCO2VQ37**3+134.81*10**(-6)/(2*CO2VQR37/CO2QGR1.0)*DELCO2VQ37

          **2)/1000000

1142:     CO2TXQR37 = SCO2GEN*SCO2XR37*79.4879275460098*X37

1143:     PRISCO2XQ37 = DCO2TX37*XEUTHETACO2+(1-DCO2TX37)*XWMTHETACO2
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1144:     PRISCO2XQ37 = 62.744*10**(-12)*(DELCO2TXQ37/(CO2TXQR37/CO2QGR1.0)
          )**2+134.81*10**(-6)*DELCO2TXQ37/(CO2TXQR37/CO2QGR1.0)
1145:     CO2TXQ37 = CO2TXQR37-DELCO2TXQ37
1146:     COSTKX37 = (62.744*10**(-12)/(3*(CO2TXQR37/CO2QGR1.0)**2)*
          DELCO2TXQ37**3+134.81*10**(-6)/(2*CO2TXQR37/CO2QGR1.0)*
          DELCO2TXQ37**2)/1000000
1147:     COSTKM37 = COSTKV37+COSTKX37
1148:     V37 = VR37+COSTKM37
1149:     VR34 = ZCSV34/(EPS*EPSVR34)*ZCVFS34*VF34
1150:     CO2VQR34 = SCO2GEN*SCO2VR34*4.2584531315067*V34
1151:     PRISCO2VQ34 = DCO2V34*XEUTHETACO2+(1-DCO2V34)*XWMTHETACO2
1152:     PRISCO2VQ34 = 62.744*10**(-12)*(DELCO2VQ34/(CO2VQR34/CO2QGR1.0))
          **2+134.81*10**(-6)*DELCO2VQ34/(CO2VQR34/CO2QGR1.0)
1153:     CO2VQ34 = CO2VQR34-DELCO2VQ34
1154:     COSTKV34 = (62.744*10**(-12)/(3*(CO2VQR34/CO2QGR1.0)**2)*
          DELCO2VQ34**3+134.81*10**(-6)/(2*CO2VQR34/CO2QGR1.0)*DELCO2VQ34
          **2)/1000000
1155:     CO2TXQR34 = SCO2GEN*SCO2XR34*2.90106389927722*X34
1156:     PRISCO2XQ34 = DCO2TX34*XEUTHETACO2+(1-DCO2TX34)*XWMTHETACO2
1157:     PRISCO2XQ34 = 62.744*10**(-12)*(DELCO2TXQ34/(CO2TXQR34/CO2QGR1.0)
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          )**2+134.81*10**(-6)*DELCO2TXQ34/(CO2TXQR34/CO2QGR1.0)
1158:       CO2TXQ34 = CO2TXQR34-DELCO2TXQ34
1159:       COSTKX34 = (62.744*10**(-12)/(3*(CO2TXQR34/CO2QGR1.0)**2)*
          DELCO2TXQ34**3+134.81*10**(-6)/(2*CO2TXQR34/CO2QGR1.0)*
          DELCO2TXQ34**2)/1000000
1160:       CO2FQR34 = SCO2GEN*SCO2FR34*1492.16285390546*F34
1161:       PRISCO2FQ34 = DCO2F34*XEUTHETACO2+(1-DCO2F34)*XWMTHETACO2
1162:       PRISCO2FQ34 = 62.744*10**(-12)*(DELCO2FQ34/(CO2FQR34/CO2QGR1.0))
          **2+134.81*10**(-6)*DELCO2FQ34/(CO2FQR34/CO2QGR1.0)
1163:       CO2FQ34 = CO2FQR34-DELCO2FQ34
1164:       COSTKF34 = (62.744*10**(-12)/(3*(CO2FQR34/CO2QGR1.0)**2)*
          DELCO2FQ34**3+134.81*10**(-6)/(2*CO2FQR34/CO2QGR1.0)*DELCO2FQ34
          **2)/1000000
1165:       COSTKM34 = COSTKV34+COSTKX34+COSTKF34
1166:       V34 = VR34+COSTKM34
1167:       VR27 = ZCSV27/(EPS*EPSVR27)*ZCVFS27*VF27
1168:       CO2VQR27 = SCO2GEN*SCO2VR27*45.4484820732471*V27
1169:       PRISCO2VQ27 = DCO2V27*XEUTHETACO2+(1-DCO2V27)*XWMTHETACO2
1170:       PRISCO2VQ27 = 62.744*10**(-12)*(DELCO2VQ27/(CO2VQR27/CO2QGR1.0))
          **2+134.81*10**(-6)*DELCO2VQ27/(CO2VQR27/CO2QGR1.0)
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1171:      CO2VQ27 = CO2VQR27-DELCO2VQ27

1172:      COSTKV27 = (62.744*10**(-12)/(3*(CO2VQR27/CO2QGR1.0)**2)*

         DELCO2VQ27**3+134.81*10**(-6)/(2*CO2VQR27/CO2QGR1.0)*DELCO2VQ27

         **2)/1000000

1173:      CO2TXQR27 = SCO2GEN*SCO2XR27*2.49844298774148*X27

1174:   PRISCO2XQ27 = DCO2TX27*XEUTHETACO2+(1-DCO2TX27)*XWMTHETACO2

1175:   PRISCO2XQ27 = 62.744*10**(-12)*(DELCO2TXQ27/(CO2TXQR27/CO2QGR1.0) )**2+

        134.81*10**(-6)*DELCO2TXQ27/(CO2TXQR27/CO2QGR1.0)

1176:      CO2TXQ27 = CO2TXQR27-DELCO2TXQ27

1177:      COSTKX27 = (62.744*10**(-12)/(3*(CO2TXQR27/CO2QGR1.0)**2)*

         DELCO2TXQ27**3+134.81*10**(-6)/(2*CO2TXQR27/CO2QGR1.0)*

         DELCO2TXQ27**2)/1000000

1178:      COSTKM27 = COSTKV27+COSTKX27

1179:      V27 = VR27+COSTKM27
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