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Abstract:
Publicly announced GHG mitigation targets and emissions pricing strategies by individual governments may suffer from inherent commitment problems. When emission prices are perceived as short-lived, socially cost-effective upfront investment in climate technologies may be hampered. This paper compares the social abatement cost of a uniform GHG pricing system with two policy options for overcoming such regulatory uncertainty: one with a state guarantee scheme whereby the regulatory risk is borne by the government and one which combines emissions pricing with subsidies for upfront climate technology investments. A technology-rich CGE model is applied that accounts for abatement both within and beyond existing technologies. Our findings suggest a tripling of abatement costs if domestic climate policies fail to stimulate investment in new technological solutions. Since the cost of funding investment subsidies is found to be small, the subsidy scheme performs almost as well as the guarantee scheme.

Keywords: abatement costs, climate technologies, credible commitment, computable general equilibrium model, technological change, technological diffusion, hybrid modelling

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Sammendrag

Det er flere grunner til at et lands ambisjoner om utslippskutt gjennom utslippsprising fremover kan ha manglende troverdighet i befolkningen. Dersom avgiftssystemer eller kvotehandelssystemer ikke forventes å bli opprettholdt særlig lenge vil de ikke utløse investeringer i klimateknologier, selv om disse fra et samfunnsøkonomisk ståsted er kostnadseffektive tiltak. I dette arbeidet sammenligner vi velferdskostnadene ved norske klimapolitiske ambisjoner i tre virkemiddelscenarioer; ett med bare utslippsprising i et kvotehandelssystem, ett der kvotehandelen kombineres med en garantiordning som legger risikoen for svakere regulering i fremtiden på myndighetenes skuldre, og ett der et subsidieringsprogram for teknologiinvesteringer supplerer kvotesystemet. Vi bruker en teknologi-rik numerisk likevektsmodell som modellerer både velkjente og hittil ikke implementerte teknologier.

Resultatene våre tyder på at en garantiordning som sikrer langsiktig troverdighet vil kunne redusere kostnadene til 1/3 sammenlignet med å innføre bare et kvotehandelssystem, fordi sistnevnte ikke er i stand til å utløse samfunnsøkonomisk lønnsomme teknologiinvesteringer. Subsidiering er et mer kjent virkemiddel for å stimulere til klimavennlige investeringer. Vi finner at de samfunnsøkonomiske finansieringskostnadene for et slikt system er små, slik at kostnadene ikke blir vesentlig høyere enn for en garantiordning. Det er imidlertid en utfordring for myndighetene å plukke ut de mest lønnsomme investeringsprosjektene. Beregningene vi har gjort kan også belyse hvor viktig det er å bruke en teknologi-rik likevektsmodell. I tradisjonelle numeriske likevektsmodeller vil kostnadene ved å gjennomføre en best mulig politikk bli sterkt overvurdert – i vårt studerte tilfelle med en faktor 3.

1 Introduction

Several jurisdictions have announced unilateral climate policy ambitions for the coming decades. The cost of imposing a domestic cap will heavily depend on whether the domestic policy design generates the most cost-effective projects within the respective jurisdictions. Even though the usual recommendation for optimal abatement is uniform emissions pricing, market failures or other inefficiencies may render emissions pricing insufficient. This study addresses one such case that may arise if policymakers prove unable to credibly commit to future policy. Several socially cost-effective abatement options involve upfront investment, and these may be hampered if politicians fail to determine future policies and instead leave it up to future politicians to do so. Indeed, even if the same politicians remain in office, there is an inherent time inconsistency problem in their behaviour that tends to discourage investments. If agents take on immediate investment costs in response to announced future ambitions and emission prices, future prices need only to encourage operational costs in the future and can be set lower than earlier announced. On the other hand, if agents do not invest today, future abatement costs will be substantially larger than assumed by current policymakers, and optimal ambitions will fall; see Blackmon and Zeckhauser (1992). Whether the source of commitment failures in climate policy is time inconsistency or the inability of politicians to commit their successors, the phenomenon may impede the diffusion of available climate technologies (Ulph and Ulph, 2013: Brunner et al., 2012).

Quantification of the potential inefficiencies of such regulatory uncertainty is scarce in the literature. The main purpose of this study is to compare the costs of mitigating national greenhouse gas (GHG) emissions under different policy designs, given that upfront investment in climate technologies is hampered by the inability of policymakers to signal trustworthy ambitions. When emissions pricing is perceived as short-lived, upfront investment in climate technologies will not appear profitable; firms will instead reduce their variable costs and scale down output, while consumers will respond by substituting other consumer goods for energy, and leisure for consumption (Spiller, 1996). We numerically analyse the consequences in terms of abatement costs and lack of technological change and evaluate alternative policy responses to such regulatory uncertainty, including a guarantee scheme and an upfront investment subsidy scheme.

Bosetti and Victor (2011) numerically study commitment problems of a global emissions pricing system and assume the view of economic agents in powerful states, which differs from our perspective of a small, ambitious country. They argue that, due to the lack of supranational legal institutions, problems with confidence in international agreements may be even more serious than problems with confidence in actions/decisions that are actually taken by large states. For small states, however, unilateral ambitions imply taking on extra costs without reaping obvious climate gains. This could easily become more politically controversial, less reliable and, thus, more costly than taking part in a binding international agreement. Furthermore, it is often the case that the smaller the coalition, the smaller the variety of emission sources and, consequently, the more expensive the abatement. Countries showing a willingness to act are also likely to have tried out the cheaper options already.

Numerically assessing mitigation strategies and abatement costs under various policy regimes requires a computational model that allows for abatement both within and beyond existing technologies. For this purpose, we developed a CGE model which, besides including options of downscaling emission-intensive activities and substituting factors within existing technologies, accounts for potential endogenous changes in climate technologies (Fæhn et al., 2013). This is in contrast to conventional CGE models which lack technological responsiveness beyond historically observed practice and thus tend to overestimate abatement costs. On the other hand, like traditional energy system models, technology-rich models exclude realistic flexibility of economies that stems from existing, profitable downscaling options both in supply and demand and from cost-shifting opportunities among market agents. Our modelling solution differs from the bulk of recent years' development of large-scale hybrid approaches, as in Bataille et al. (2009), Bosetti et al. (2006), and Laitner and Hanson (2006) by being simple and easily applicable while at the same time being capable of representing, with good approximation, a variety of potential technological options. We expand the scope compared to other contributions in the field by not limiting the technological adaptation possibilities to the energy supply side alone and instead allowing for investment in climate technologies within energy-intensive sectors. Energy-intensive manufacturing industries have several technological options, as have many households, firms, and public service sectors when it comes to, for example, transportation technologies.

Our analysis considers Norway's ambitious domestic target, representing an approximate 20-per-cent cut in GHG emissions in 2020 from a business-as-usual (BAU) Reference Scenario (Climate Cure 2020, 2010a). We find that the most cost-effective commitment device – a guarantee scheme that ensures long-lasting commitment to a uniform emissions pricing scheme – implies an economy-wide welfare loss of ¼ per cent, or about EUR 25 per capita as a yearly average. In this cost-effective regime, more than half of the necessary reduction is achieved by choosing more climate-friendly technological solutions. The rest is obtained by scaling down relatively emission-intensive industries and consumption activities. In other words, abatement at this ambitious level is not overwhelmingly costly. However, failure to implement a reliable, enduring climate policy more than triples the abatement costs compared to the scenario with the guarantee scheme. When technology options are ruled out, the main extra costs fall on traditional manufacturing firms that shut down production, typically in areas with few alternative job opportunities. Subsidising upfront investment in climate technologies is a feasible policy option. The marginal cost of raising funds is found to be minor. Finally, note that the case where technological options are ruled out also serves to illustrate the outcome of a traditional CGE analysis. Our findings indicate that traditional CGE models significantly overestimate the costs of the first-best policy – in our case by a factor of 3.

The hybrid model is presented in section 2, while the design of the analysis and the main assumptions in the simulated scenarios are presented in section 3. Section 4 reports from the analysis, while section 5 concludes and discusses some contributions and caveats.

2 The model

2.1 General

MSG-TECH, a CGE-based hybrid model of the Norwegian economy, is a recursively dynamic, integrated economy-energy-emission model with endogenous climate technology options.[1] It specifies 60 commodities and 40 industries. Real capital and labour are perfectly mobile within the economy, while financial capital is perfectly mobile across borders. As the economy is small, all agents face exogenous world market prices and interest rates (the exchange rate is numeraire). The model gives a detailed description of the empirical tax, production, and final consumption structures. Several second-best features due to market imperfections or policy interventions are modelled, including taxation of labour and existing industrial policies. In addition, barriers to climate technology investment can be represented.

2.2 Behaviour

Consumers are represented by a single average consumer whose utility in every period depends on the consumption of leisure and of 26 different consumer goods organised in a CES structure; see Figure A.1 in the appendix. Environmental benefits are not accounted for. Consumer goods are specified at a

[1] The model is a recursively dynamic version of MSG-6; see Heide et al. (2004) and Bye (2008), enriched with technology options.

detailed level with a view to capturing important substitution possibilities. Energy goods such as transport fuel, heating oil, and electricity are specified, and different forms of commercial transport, either polluting or environmentally benign, can replace own car use in households and industries. Own car use can also avoid GHG emissions by investing in new vehicle types with alternative technologies. The modelling of these choices is explained in section 2.3. Consumer welfare is defined as the present value of utility received from consumption and leisure.

Firms in each industry maximise the current value of their cash flow by setting production levels and the composition of factor inputs subject to exogenous expected capital prices. Factors include labour, different types of capital, a variety of goods, services, and energy goods, among them fossil fuels – see Figure A.1. As for households, firms may also choose to invest in vehicle types with different emission intensities. Firms may also invest in other types of climate technologies; see section 2.3. Each firm within an industry produces its own unique product variety; this implies a certain degree of market power in separate domestic market niches. A wider range of varieties increases utility and productivity of the goods (love of variety); see Dixit and Stiglitz (1977). External effects on productivity from environmental change are not modelled.

The model provides a detailed description of electricity supply that distinguishes between hydropower production, natural gas power production, transmission, and distribution. Gas power producers can invest in carbon capture and storage (CCS) technology. Norway's international power trade in the Nordic market is modelled. Due to policy and resource restrictions, the following activities are exogenously determined in our simulations: production of public goods and services, extraction of oil and gas, power generation, and output from agriculture, forestry, and fishery.

Norwegian firms compete with foreign suppliers in domestic markets and abroad. According to the Armington hypothesis, import shares depend negatively on the ratio of the import price to the price of domestic deliveries. The markets for domestic and exported deliveries are segregated by means of a constant elasticity-of-transformation function, allowing prices of domestic deliveries to develop differently from the exogenous export prices.

2.3 Technology adaptations

The distinct feature of the MSG-TECH model is that households, firms, and public institutions can choose to invest in completely new technologies with lower emission intensities. This applies to *Process industries* and *Petroleum extraction* as well as to the own land transport activities of firms, households, and the public sector. Along with households, the service industries *Commercial road transportation* and *Other private servicing* are the largest users of own land transport.[2] By adding realistic emission reduction possibilities to the model through technology investments and their associated economic costs, agents will have a wider range of possibilities than traditional CGE models allow for.

The method resembles the classical engineering approach to economic production functions (Chenery, 1949 and Sav, 1984): i.e., in the absence of statistical data on the abatement functions, we use engineering information directly. There are reasons to believe that abatement costs differ considerably between firms, industries, countries, and contexts, and over time. Our data are based on sector-specific current knowledge and primarily on Norwegian studies, which should give a good representation of costs. However, we acknowledge that learning potential and technological development are difficult to predict, even within the relatively short time span assumed by our sources and simulations. As the Norwegian market is small, we model learning and technological development as unaffected by investments by domestic firms and households. The modelling, data, and estimations are accounted for below. See Fæhn et al. (2013) for more details.

A stylised representation of technology adaptations[3]

Before introducing technology adaptations in the model, representative profit-maximising firms have the following stylised production functions:

(1) $$X = \left(\frac{V}{\varepsilon_0} \right)^{\rho},$$

where X is output, V factor input, ε_0 is exogenous factor productivity and ρ the scale elasticity parameter ($0 < \rho < 1$). The profit, π for the representative firm in the presence of an emission tax τ is:

(2) $$\pi = B \cdot X - P^V \cdot \varepsilon_0 \cdot X^{1/\rho} - \tau \cdot \mu_0 \cdot X ,$$

where B is the output price, P^V the input price, and μ_0 the exogenous emission intensity of the firm. The first order condition renders:

[2] See Table A.1 in the appendix for a list of model industries.

[3] The most important simplifications made here is to aggregate inputs and assume that emissions are linked to the output level. See section 2.4 for more details. This simplified presentation is less representative for our modelling of land transport, where we link emissions to the use of fuels and add abatement costs to the price of (imported) vehicles.

(3) $$B = \frac{P^V}{\rho} \cdot \varepsilon_0 \cdot X^{\left(\frac{1}{\rho}-1\right)} + \tau \cdot \mu_0 .$$

In our modelling of the effects of endogenous abatement technology adaptations, we insert an additional module that accounts for additional *costs* in terms of investment, operation, and maintenance and for *benefits* in terms of reduced unit emissions. We do this by introducing two endogenous parameters ε and μ that allow for changes in factor productivity and emission efficiency, respectively:

(4) $$\varepsilon = \varepsilon_0 + \frac{E}{X^{1/\rho}}$$

(5) $$\mu = \mu_0 - \frac{D}{X}$$

The endogenous ε parameter accounts for the abatement cost of the firm, *E*, by adding its effect to the initial factor productivity level, ε_0. The interpretation is that the input use needed for a given output increases when technological adaptation takes place; i.e., factor productivity decreases and $\varepsilon > \varepsilon_0$. Quite similarly, μ accounts for endogenous unit abatement through technological adaptations, D/X. As long as technological abatement takes place, $\mu < \mu_0$.

The rest of the inserted technology module determines *E* and *D*. First, technological opportunities are represented by marginal abatement costs, *c*, as a function of abatement through technological adaptations, *D*:

(6) $$c = f(D)$$

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

(7) $$c = \tau$$

Next, we define the total technological abatement costs, *E*, as the integral of marginal abatement costs in equation (6):

(8) $$E = \int f(D) dD .$$

Note that as long as $\tau = 0$, *c*, *D*, and *E* are all zero, and the solution for ε and μ will be $\varepsilon = \varepsilon_0$ and $\mu = \mu_0$ as in the original model without abatement technologies. If $\mu_0 = 0$, then $\varepsilon = \varepsilon_0$ and $\mu = 0$.

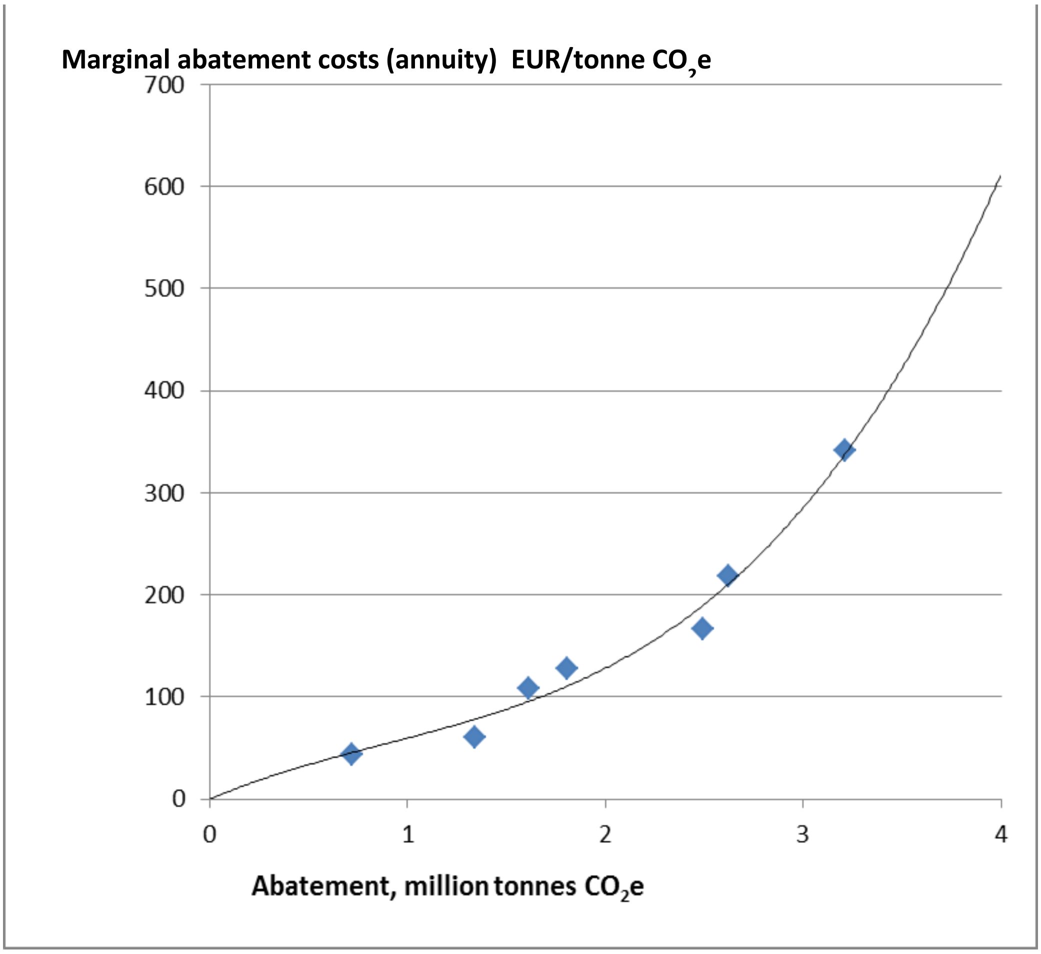
The three next sections describe the data and estimations as well as further modelling details that apply to specific industries.

Process industries

We estimate the costs for the following industrial processes: cement production (in *Manufacture of chemical and mineral products;* see Table A.1); production of chemical commodities (in *Manufacture of industrial chemicals*); production of aluminium, iron, steel, and ferroalloys (in *Manufacture of metals*); and oil refining (in *Petroleum refining*). The technological adaptations investigated include case-specific ways of converting to bioenergy, of process optimisation, and of sequestration of GHG emissions, including CCS.[4] We arrange the measures by cost annuities and estimate a marginal abatement cost curve that links marginal costs to accumulated abatement potentials. We choose estimates based on their combined performance on fit as well as on reasonable extrapolations in both ends. In other words, we want to ensure that abatement costs for small potentials never fall below zero and that marginal abatement costs always increase with accumulated abatement. Figure 1 depicts the outcome of the estimation procedure for *Process industries* as a whole. The curve shows an R^2 of 0.85. The curve is fairly linear in the relevant area, also for large, extrapolated abatement levels. The most expensive measures are CCS-based, and it is reasonable to expect potentials for this technology in plants smaller than those included in the data set, though at rising marginal costs due to significant economies of scale.

[4] The following sources of costs and potentials are used: SFT (2007), SINTEF (2009), TELTEK (2009) and Climate Cure 2020 (2010a).

Figure 1: Marginal abatement cost curve, *Process industries*. EUR/tonne CO_2e

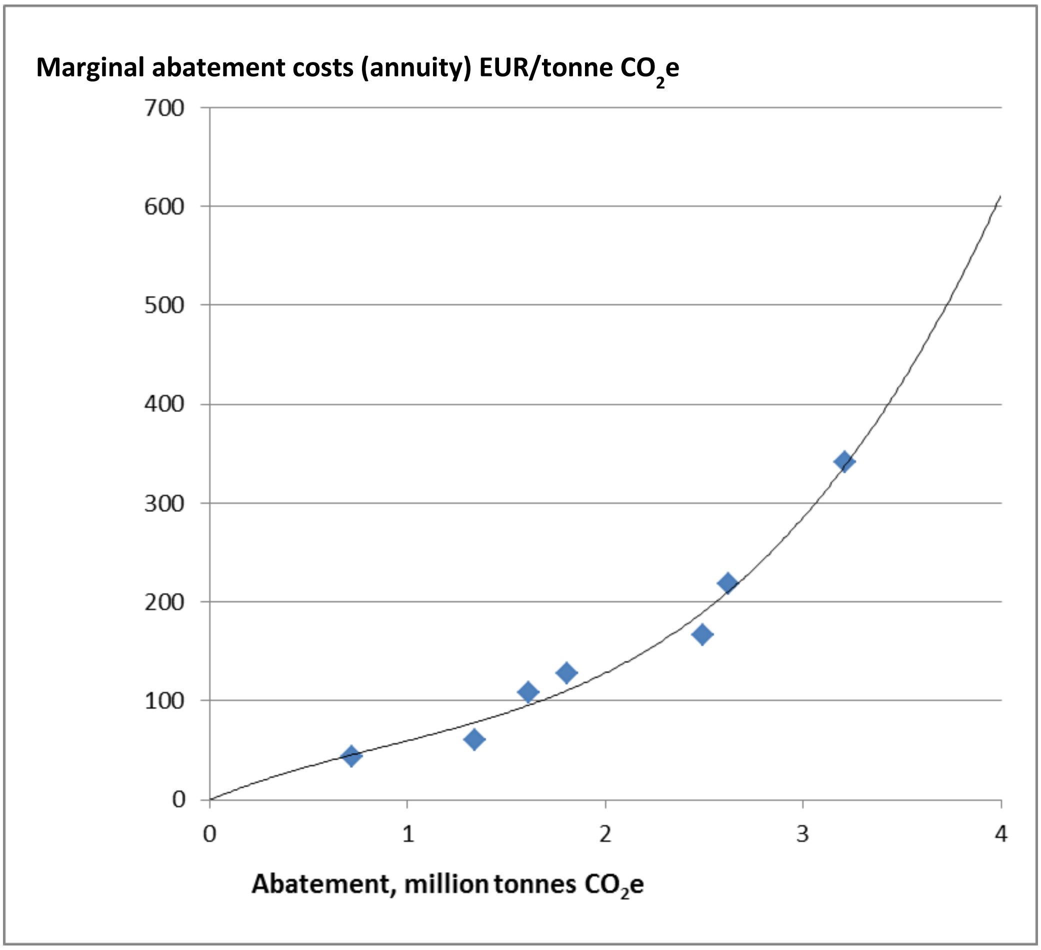


Land transport

The variety of quantified measures for reducing emissions from Norwegian land transport includes efficiency improvement of passenger cars and commercial vehicles, private and public zero-emission vehicles, and fuel intermixture of ethanol and biodiesel, as well as measures to coordinate land planning. Our sources assess uncertainty as well as sensitivity to costs and potentials for the sequence in which the measures are phased in.[5] We pick the medium estimates, and the cheapest measures are assumed to be introduced first. As shown in Figure 2, the estimated marginal cost curve for land transport fits very well to the data, with an R^2 of 0.98. When extrapolating upwards, the marginal costs increase sharply. Because there are limits to efficiency improvements and bio-blending potentials, this slope can be reasonable unless a breakthrough in battery and hydrogen technology is imminent.

[5] See SFT (2007) and Kanenergi/INSA (2009).

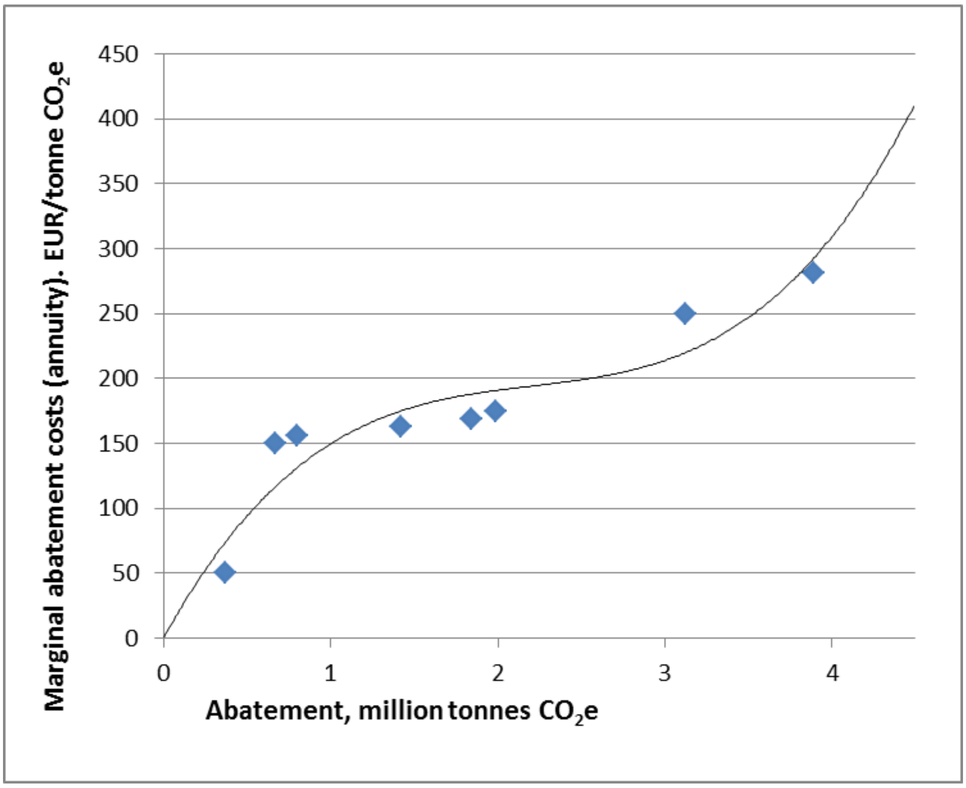
Figure 2: Marginal abatement cost curve, *Land transport*. EUR/tonne CO_2e



Petroleum extraction

Measures for the petroleum extraction sector were quantified by the Norwegian Petroleum Directorate (NPD, 2010). They include various forms of alternative power supply to the offshore sector (electrification from land, offshore wind power), power efficiency improvements, and CCS. Figure 3 presents the outcome of the estimation. The curve is fairly steep for large abatement volumes, reflecting the fact that measures within petroleum extraction rely to a large extent on individual solutions coming from each area, which proves costly. R^2 of 0.93 indicates a very good fit to data.

Figure 3: Marginal abatement cost curve, *Petroleum extraction*. EUR/tonne CO_2e



2.4 Emissions and climate policy instruments

The production and consumption activities in the model are linked to coefficients for emissions to air in accordance with the emissions inventory developed by Statistics Norway. Emission-generating activities include intermediate goods, energy goods, consumption activities, production processes, and waste disposal sites. Emission compounds include the six GHGs in the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the fluorine compounds SF6, CFC, and HFC. The emissions are all measured in CO_2 equivalents (CO_2e) according to their global warming potential. In addition, emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), ammonia (NH_3), and particulate matter (PM_x) are modelled.

This is a relatively detailed modelling of climate policy instruments, allowing for differentiated and uniform GHG taxes, national and international allowance trading systems, free allowances, and investment subsidies for climate technologies. It is assumed that the authorities' budget balances are always maintained. In the version of the model used here, this is accomplished by adjusting employers' payroll taxes.

3 Design of the analysis and main assumptions

Section 4 analyses and compares three different policy strategies, all aimed at fulfilling the same ambitions for 2020, exemplified by the agreed climate ambitions of the Norwegian parliament. These include continued participation in the European emissions trading system (EU ETS), contributions to global abatement, and a cap on emissions from the domestic territory, representing a 20-per-cent cut in GHG emissions from BAU.

The three scenarios differ with respect to how the domestic cap is met. In all scenarios a uniform emission price is imposed on all Norwegian GHG sources. The difference between Scenarios I and II is that the government succeeds in committing to the future policy in Scenario I, while the policy lacks confidence in Scenario II. In Scenario III, commitment to a long-lasting emission price is not ensured, but the emissions pricing scheme is supplemented by subsidies for upfront investments as a second-best approach to encouraging technological adaptations.

3.1 The Reference Scenario

Besides important drivers like demographic development, natural resource forecasts, and technological change, domestic emissions in the Reference Scenario follow from BAU policy assumptions.[6] For climate policy, BAU implies, inter alia, that the Norwegian differentiated system of CO_2 taxes in 2004 is included and prolonged at real levels.[7] The 2004 rates vary between EUR 0 and EUR 50 per tonne, with petrol and emissions from offshore extraction of oil and gas at the highest rates; see Table 1.

Norway's association with the EU ETS from 2008 is included in the Reference Scenario, and the previous tax system for the quota-regulated industries is simultaneously removed.[8] For the period 2008–2012 the EU ETS participation implies that *Petroleum extraction*, *Process industries* (except most of *Manufacture of metals*), *Petroleum refining*, and *Generation of electricity* are quota-regulated, embracing about 40 per cent of Norwegian climate gas emissions (in 2005). From 2013, *Manufacture of metals* is fully included, which increases the quota-regulated share to 50 per cent. The majority of the EU ETS allowances are allocated free of charge. Their value is modelled as a lump-sum subsidy, since they rely on historical emissions. Besides commitments under the EU ETS, Norway has commitments under the global Kyoto agreements. To meet those, we assume that the government

[6] See Fæhn et al. (2013) for details. The assumptions are based on Climate Cure 2020 (2010a), the report of an officially appointed commission tasked with preparing the ground for evaluating Norway's climate policy.

[7] Note that in the BAU scenario the existing CO_2 tax system, which has been in place since 1991, is assumed to maintain its confidence in the years to come.

[8] The exception is North Sea petroleum extraction, which is subject to both quota pricing and tax rates.

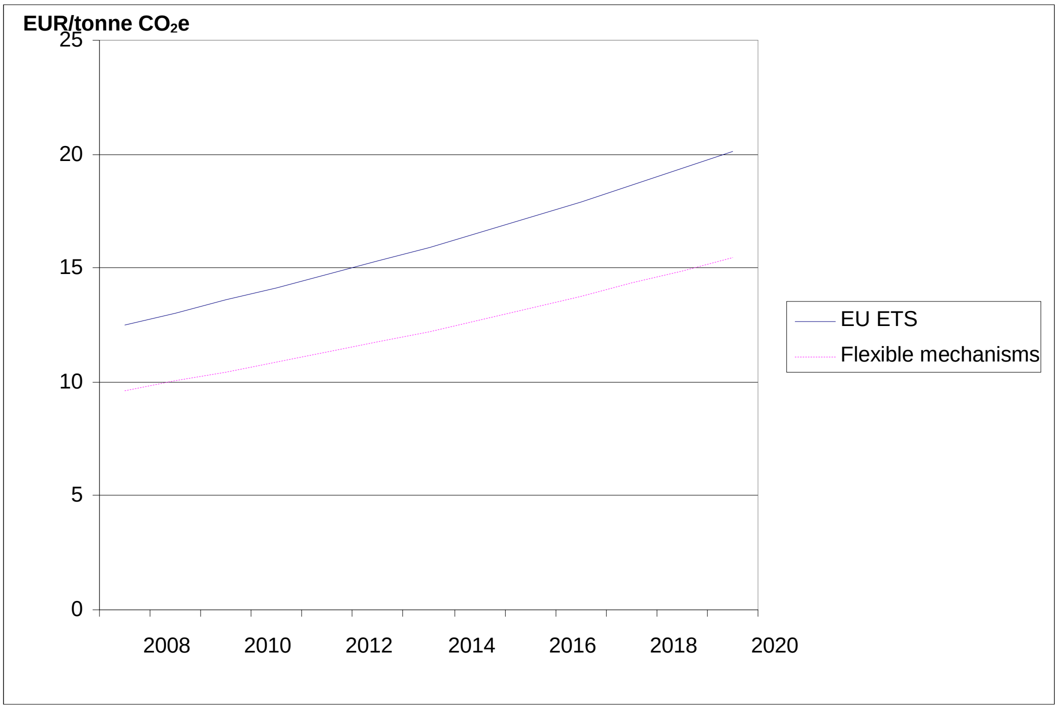
supplements the EU ETS instruments and its domestic policies with the use of flexible mechanisms until 2020. The projected development in the price of EU ETS allowances and flexible mechanisms is shown in Figure 4.[9] Both are assumedly determined abroad, independent of domestic actions.

Table 1: CO_2 tax rates in the Reference Scenario. EUR/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
Ferroalloys, carbide, and aluminium 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

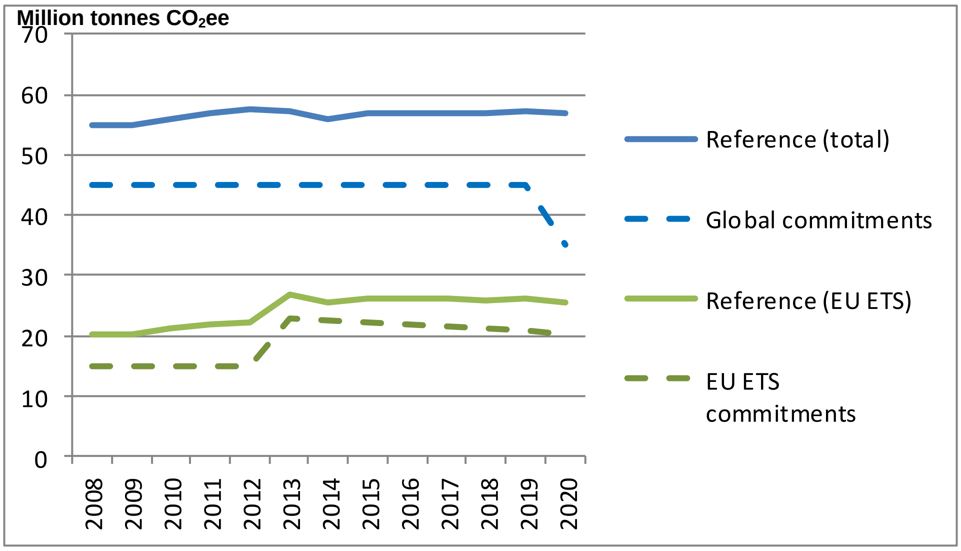
Figure 4: Allowance prices. EUR/tonne CO_2e (2004 prices). 2008–2020



[9] The projections are based on the low scenario in Climate Cure 2020 (2010b).

sThe computed Reference Scenario emissions for the economy as a whole and for the domestic EU ETS industries are depicted in Figure 5, along with the global target and the committed emissions cap for the EU ETS industries. Over the period as a whole, the domestic GHG emissions increase slightly. In 2020 the EU ETS sector emits 45 per cent of the national total, with the largest contributions from *Petroleum extraction*, *Manufacture of metals*, and *Manufacture of industrial chemicals*. Among non-EU ETS sources, *Agriculture* and households dominate, with own land transport constituting the main source of household emissions.

Figure 5: Reference Scenario emissions (total and in EU ETS sector) and European and global caps. Million tonnes CO_2e. 2008–2020



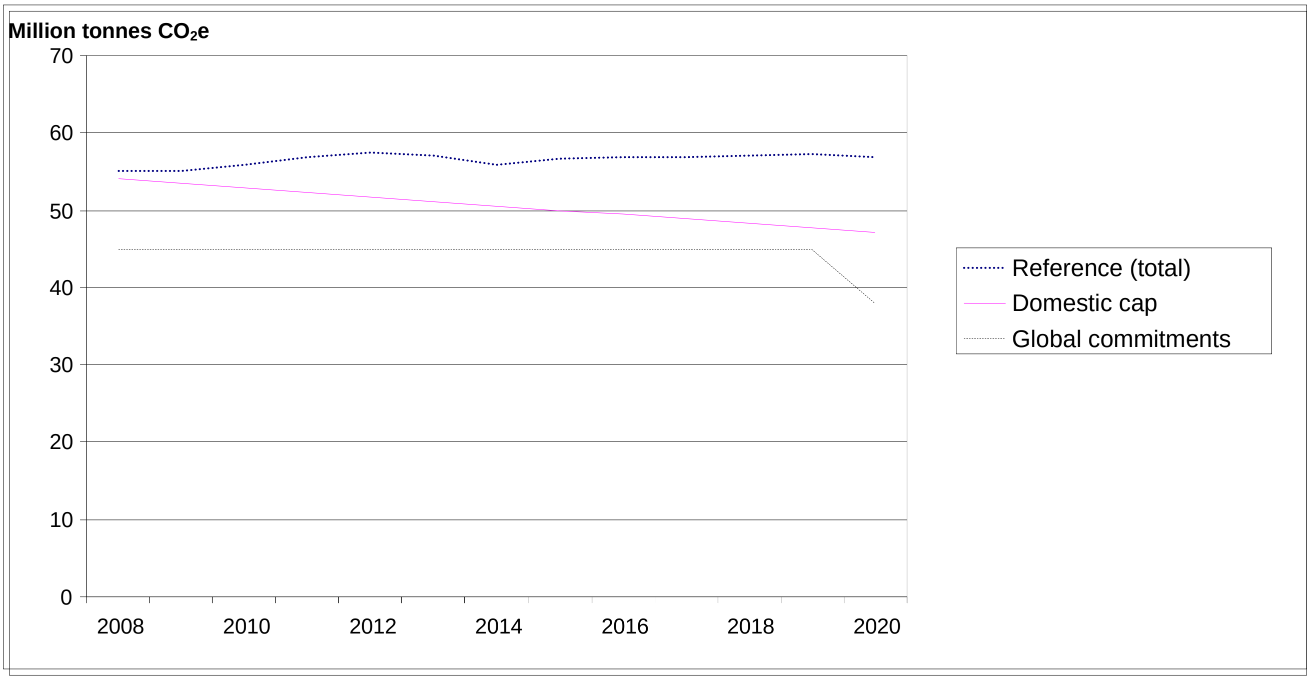
As is evident from Figure 5, both the EU ETS and the Kyoto commitments will have to be fulfilled by firm's purchasing of allowances in the EU ETS markets and by the state through flexible mechanisms. In 2020, a purchase of 22 million tonnes of CO_2e will have to be realised, to which EU ETS firms will contribute about a fourth, according to estimates. The overall cost of quota purchases in 2020 is estimated at EUR 340 million.

3.2 Policy assumptions in Scenarios I, II, and III

In Scenarios I, II, and III a domestic cap on emissions is imposed. It corresponds to the Norwegian government's domestic emission target announced for 2020 and comes on top of the international commitments and aspirations described in the Reference Scenario. We assume that the domestic goal for 2020 is approached gradually from the 2008 level; see Figure 6. In 2020, the abatement from the

Reference Scenario within domestic borders corresponds to almost half of the ambition in terms of global contributions.

Figure 6: Reference Scenario emissions, global cap, and domestic cap. Million tonnes CO_2e. 2008–2020.



In order to keep emissions below the cap, an endogenous, uniform price on all GHG emission sources is imposed on all GHG emission sources. This substitutes the differentiated CO_2 tax system in the Reference Scenario. For the EU ETS sources, which still pay the allowance price, the total emission price must equal the price in rest of the economy, implying an additional price (tax) on top of the allowance price.

In Scenario I, the private risk related to future costs of emissions is neutralised by a legal assurance scheme between the private agents undertaking emission reductions and the government. Ismer and Neuhoff (2009) sketch an alternative with allowance sales options. An agent undertaking investments based on the future price forecast by the government receives sales options for each forthcoming year corresponding to the emission reductions he realises. The sales options guarantee that the government purchases the allowances at the forecasted price. If the price in a given year falls short of the forecast, the agent can buy relatively cheap allowances in the market and use his sales options to earn the difference between the market price and the forecasted price. The allowance trading will exactly compensate for the costs in excess of the expenditure savings on allowances caused by his abatement efforts. If the price reaches the forecasted level, the undertaken abatement efforts are profitable without allowance sales. There will be nothing to earn on the sales options, and they will not be used. The idea behind Scenario I is that an assurance scheme similar or equivalent to sales options is introduced which compensates perfectly for the political risk component of the domestic emission price. The implication is that the agents relate to the announced emission price path and undertake the optimal investments.

At the other extreme, Scenario II depicts a situation whereby emissions pricing is not perceived to last for more than the current period (year). All upfront investments in climate technologies will, thus, be perceived as unprofitable. This regime is implemented by increasing firms' technological investment costs to prohibitive levels. When merely abatement efforts with rather instantaneous emissions effects appear worthwhile, firms will choose to reduce variable costs and scale down output, while households will substitute consumer goods for energy, and leisure for consumption.

In Scenario III, both downscaling and technological adaptation take place in spite of lack of confidence, though the latter is triggered not by emissions pricing, but by upfront subsidies. Contrary to announced future carbon prices, investment subsidies paid out immediately are likely to overcome the commitment problem, as it will be hard to reclaim investment subsidies paid out in the past (see Abrego and Perroni, 2002).

We assume that the upfront subsidies fully compensate for the firms' technology adaptation costs, as suggested in, inter alia, Ulph and Ulph (2013), Conconi and Perroni (2011), and Montero (2011). This has two implications. First, it implicitly defines all costs of converting to new technologies as investment costs. In practice, the cost structure of climate-friendly technology adaptations varies, as does the durability of the capital. Nevertheless, technological adaptations are typically highly capital-intensive. Second, it ensures that the socially optimal investments will be triggered. Consequently, the social costs of the subsidy scheme relate to the marginal costs of public funds only.

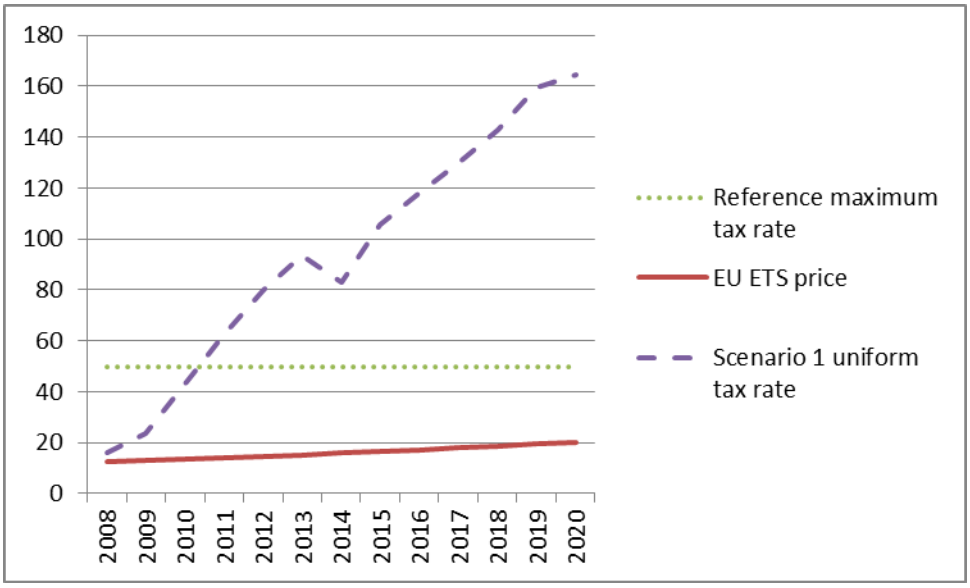
4 Analysis and comparison of the three policy scenarios

4.1 Scenario I: Guaranteed future emission prices

Impact on domestic emissions and allowance trading

To comply with the domestic target, the uniform emission price rises to EUR 164 per tonne $CO_2e$by 2020. This price is well above all emission prices in the Reference Scenario; see Figure 7.

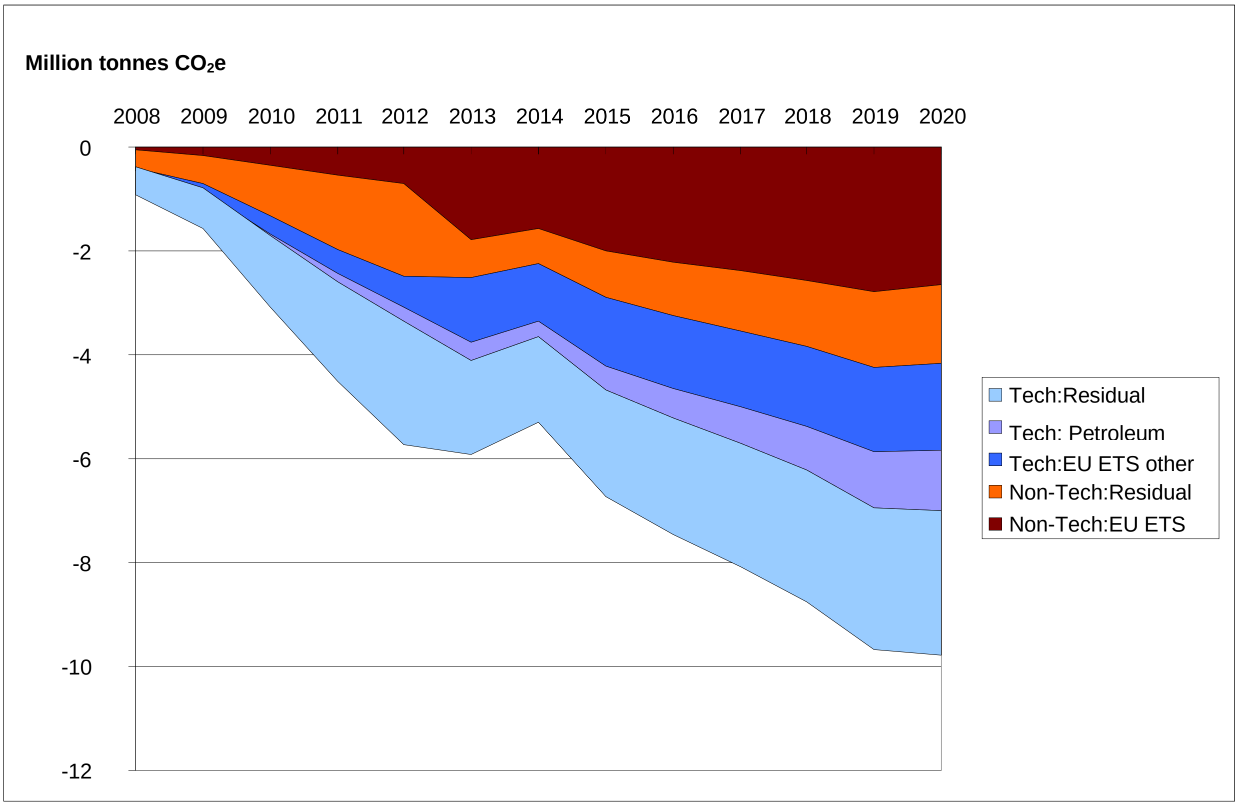
Figure 7: Scenario I and Reference Scenario: Emission prices. EUR/tonne CO_2e (2004 prices). 2008–2020



Petroleum extraction, the remaining EU ETS sector, and land transport are subject to the strictest emissions pricing in the Reference Scenario. Thus, compared to the reference, relatively little mitigation takes place from these emission sources during the first few years. However, as the domestic cap tightens and the associated price increases, gradually more takes place, particularly in EU ETS industries. Of the total emission cuts of 9.8 million tonnes CO_2e by 2020, 6.2 million tonnes are undertaken in the EU ETS sector; see Figure 8.

Reductions are achieved both within already adopted technologies (labelled 'Non-Tech' in Figure 8) and through investments in new technologies (labelled 'Tech' in the same figure). Throughout the period, the technological measures account for around 50 per cent of total reductions. While the reductions in *Process industries* are largely obtained by scaling down operations, the lion's share of cuts in other industries and in households are achieved through technological adaptations, primarily in the form of novel modes of land transport.

Figure 8: Scenario I: Changes in emission from the Reference Scenario, by category. Million tonnes CO_2e. 2008 –2020



Macroeconomic effects

The social costs, measured as consumer welfare costs, of fulfilling the national target equal a cut in welfare of ¼ per cent from the Reference Scenario.[10] This is equivalent to EUR 25 annually per capita. The dominating cost component is the costs associated with the efforts of firms and households to cut domestic emissions. The marginal abatement cost of these measures is represented for each year by the estimated domestic emission price depicted in Figure 7. On the other hand, several reallocations take place that contribute to dampen costs. First, the decline in the need for allowance purchases, particularly for the relatively expensive EU ETS allowances, reduces costs corresponding to about 1/5 of the abatement costs. Further, the revenue earnings from the uniform emission price are recycled through reduced payroll taxes and thereby yield so-called double dividends (Goulder, 1995). By 2020 the decrease in payroll tax rates amounts to 20 per cent. 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. Since initial tax distortions are considerable in the labour/leisure choice, these adjustments contribute to reduce the losses in social efficiency and welfare. Another positive contribution to welfare arises from the climate

[10] In the discounting, the yearly consumer utility of the policies is assumed to remain unchanged after 2020 (to infinity).

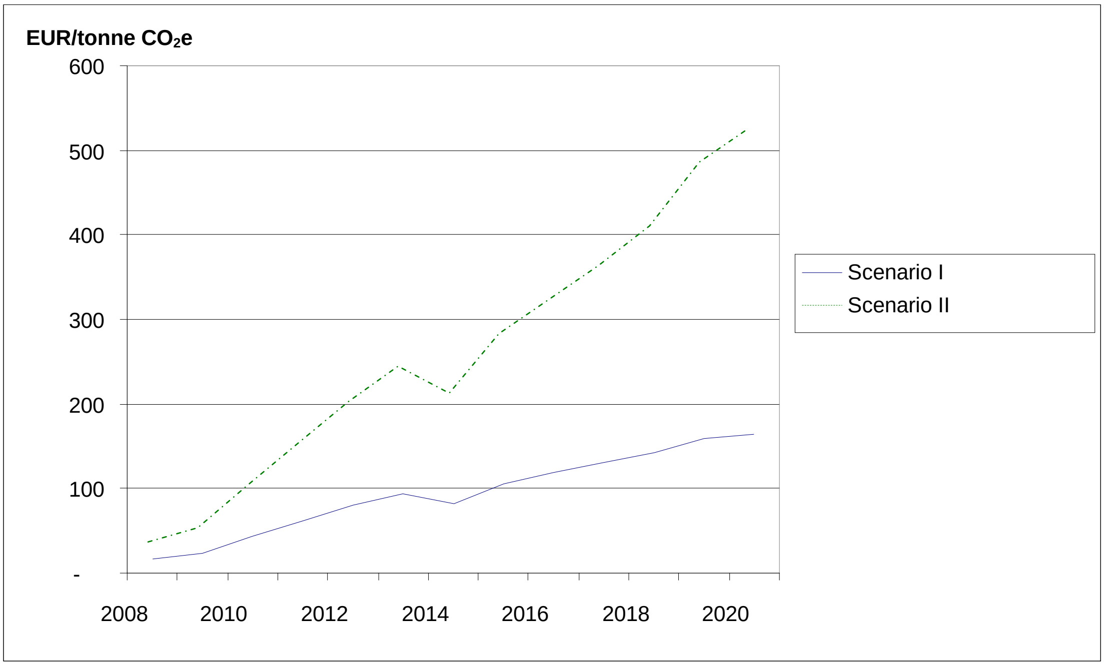
policy's interaction with existing favourable industrial policy schemes within energy-intensive manufacturing. The *Process industries* contract, and this, in isolation, benefits the economy as a whole, because their marginal productivity at the outset is lower than average. Outputs within *Manufacture of metals* and *Manufacture of industrial chemicals* drop by 22 and 32 per cent, respectively. This releases resources for activities with relatively higher macroeconomic marginal returns.

4.2 Scenario II: Unreliable future emission prices

Impact on domestic emissions and allowance trading

In this scenario, absence of reliable emissions pricing signals renders costs of potentially profitable upfront investments prohibitive. Given that no action is taken by the government to tackle the commitment problem, the uniform emissions price necessary to meet the domestic cap reaches far higher levels than under the guarantee scheme in Scenario I. The estimated developments in the national emission price in Scenarios I and II are depicted in Figure 4.3. In 2020 the level exceeds 500 EUR/tonne of CO_2e, which is more than three times higher than in the more cost-effective case of Scenario I.

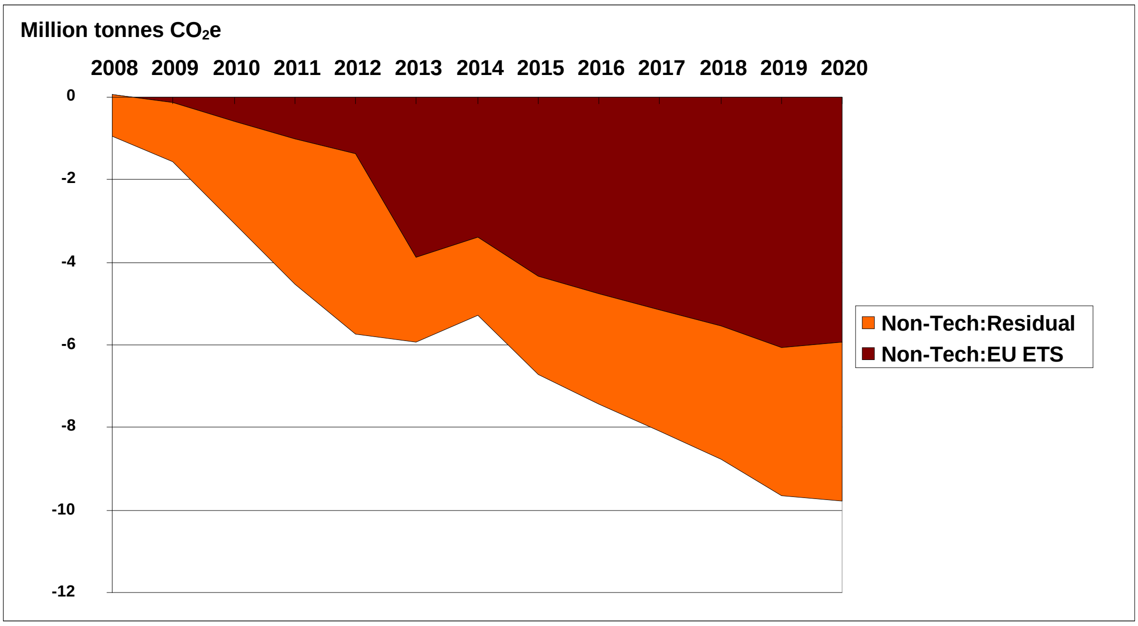
Figure 9: Scenarios I and II: Emission prices. EUR/tonne CO_2e (2004 prices). 2008–2020



While technological adaptation accounted for over half of the emission reductions in Scenario I, almost the entire emission reduction in Scenario II is realised by downscaling emission-intensive activities. The simulations reveal that these cuts are far more costly than the technological measures they replace.

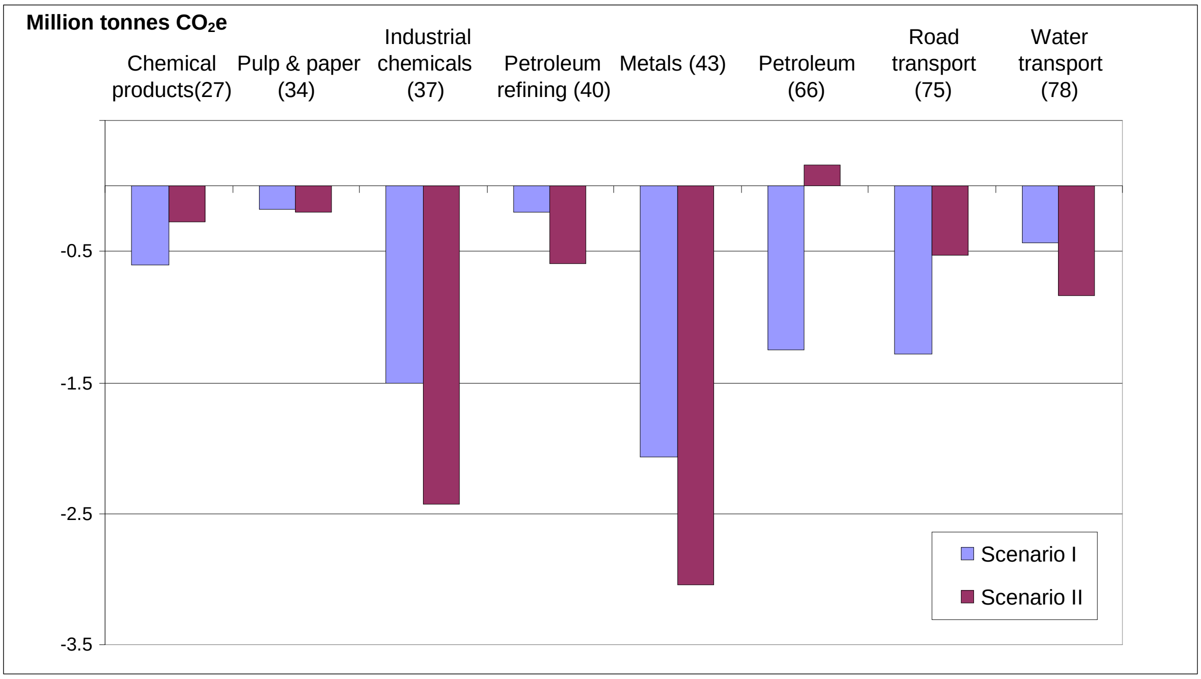
Figure 10 illustrates the change in emissions from the Reference Scenario. As the domestic cap is given, total emission reductions are the same as those illustrated under Scenario I in Figure 8. The allocation of cuts between the EU ETS and the residual sector also follows broadly the same pattern: the residual sector accounts for most of the cuts during the first years, while the share of the EU ETS sector increases after 2013 in the wake of the inclusion of more metallurgical industries.

Figure 10: Scenario II: Changes in emission from the Reference Scenario, by sector. Million tonnes CO_2e. 2008–2020.



On a more detailed level, however, we can see interesting shifts in the abatement composition. As the *Petroleum extraction* activity level is exogenously given, emission reductions in this sector can only be achieved by investing in emission-reducing technologies. Within the EU ETS sector, the exclusion of technological opportunities in Scenario II leads to a shift in abatement from *Petroleum extraction* to *Manufacture of metals* and *Manufacture of industrial chemicals*; see Figure 11. These process industries take more of the burden in Scenario II than in Scenario I, since their production is highly cost-elastic due to high export shares and negligible opportunities for cost-shifting within the world markets. The activities within the non-EU ETS sector are less elastic. This translates into a lower abatement share for the residual sector compared to Scenario I. Service production is more oriented towards the home markets, where costs can be passed on to the consumers to a higher degree. Typically, *Commercial road transportation* has little price elasticity. When upfront technology investments prove unprofitable because of a high level of perceived uncertainty, less car driving hardly compensates in terms of abatement. Coastal and inland water transport does, however, adjust more elastically and takes a significantly larger share of the burden.

Figure 11: Scenarios I and II: Changes in emission from the Reference Scenario in selected industries. Million tonnes CO_2e. 2020



The scope of international allowance trading will be the same as in Scenario I and is determined by domestic and global caps. There will be a slight shift towards less, relatively expensive, EU ETS purchases in Scenario II, mirroring the increased abatement efforts within the EU ETS sector.

Macroeconomic effects

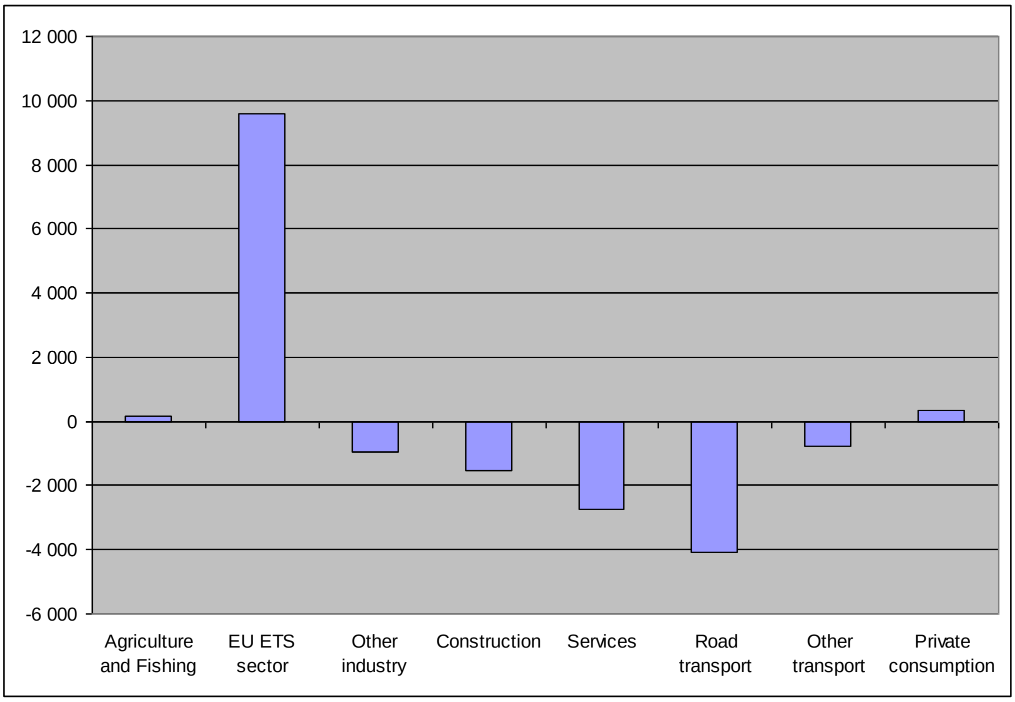
Failure to signal that the climate policy is reliable and enduring renders a welfare loss of about 1 per cent compared to the Reference Scenario. This loss is more than four times higher than that faced in the case of a guarantee scheme as in Scenario I. Domestic abatement costs explain most of this. Replacing socially profitable technological measures with costly contractions of consumption and production activities will more than triple the marginal abatement costs, defined by the emission price. The increase in total social costs from Scenario I to Scenario II is even larger. As there are numerous distortions present in the calibrated model, explanations lay in interaction effects with existing price wedges. We see a drastic contraction of *Process industries*; a fall that brings about social costs to the extent that the emissions pricing more than offsets the existing favourable industrial policy schemes. Outputs from *Manufacture of metals* and *Manufacture of industrial chemicals* drop by 62 and 79 per cent, respectively. *Commercial road transportation* and *Coastal and inland water transportation* also cut services substantially, by 8 and 32 per cent, respectively. Also, use of own cars by households falls by 26 per cent, while use of fuels by households decreases by 29 per cent. As there are several indirect taxes besides the CO_2 tax imposed on car purchases and fuel use already, their distortive effects will increase when transport activities are drastically cut. It must be kept in mind that local beneficial effects of reduced transportation, such as reduced emissions and less congestion, are not accounted for. However, welfare is also affected by interaction effects working in the opposite direction. The abovementioned savings on allowances contribute somewhat. Furthermore, revenue recycling has a greater impact in Scenario II than in Scenario I. Payroll tax rates fall by as much as 70 per cent in 2020 compared to the Reference Scenario, and received wages increase by 1.8 per cent, resulting in a 2-per-cent rise in labour supply, which is beneficial for the economy.

4.3 Scenario III: Subsidising technological adaptations

Impact on domestic emissions and allowance trading

The domestic and international targets are unchanged from the former two scenarios. The subsidy scheme is designed so as to trigger exactly the same climate technology adaptations as in Scenario I, i.e. the most cost-effective measures. The composition of non-technological abatement does, however, change somewhat compared to Scenario I, as the funding of the subsidy scheme increases the payroll tax rates. The result is that abatement shifts away from relatively capital-intensive industries as well as from households. These relatively small shifts are evident from Figure 12. The corresponding shift of allowance purchases to the EU ETS market is equally small.

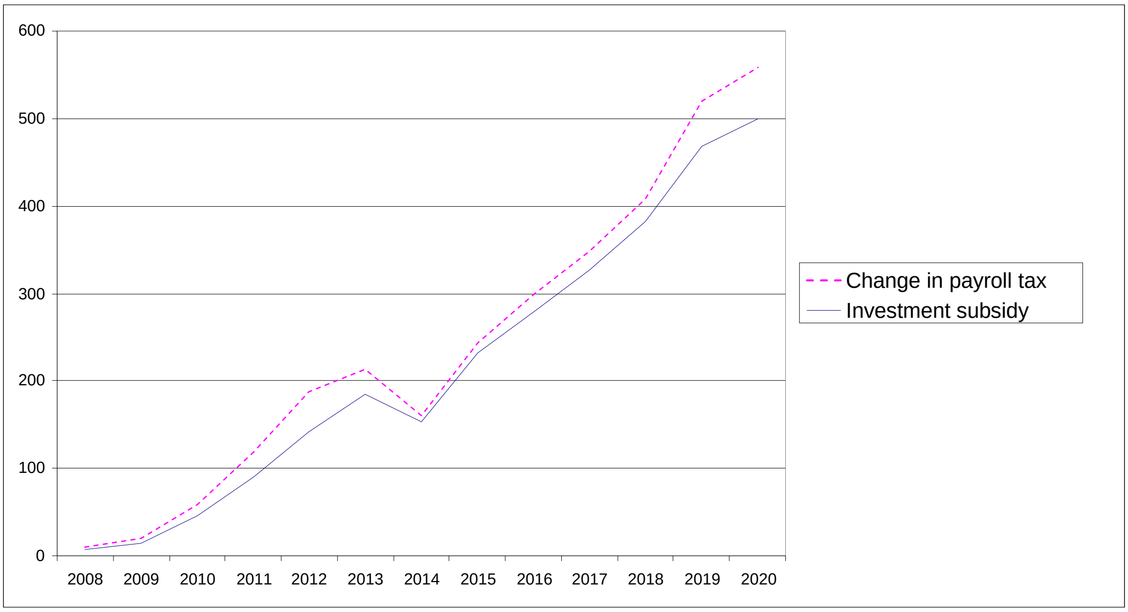
Figure 12: Changes in emission from Scenario I to Scenario III, by industry. Tonnes CO_2e. 2020.



Macroeconomic effects

Figure 4.13 shows that the change in payroll tax revenue from Scenario I to Scenario II exceeds the subsidy expense. The main reason is that the payroll tax revenue also needs to compensate for a lower emission price, which falls by an average of ½ per cent along the path.

Figure 4.13: The investment subsidy and change in payroll tax expense from Scenario I to Scenario III. EUR million



As the subsidy scheme is, by assumption, well targeted at the most cost-effective technology measures, the welfare cost compared to Scenario I is caused by the cost of public funds. This is a strong assumption, as it requires a rational, fully informed social planner. In practice, subsidy schemes can have considerable administration and information costs that are not accounted for in the simulations. We discuss such costs in the next section. Besides the abovementioned restructuring of the economy towards less labour-intensive activities, reallocation effects of the cost of funding through higher payroll tax materialise as lower labour supply. Both these reallocations contribute negatively to productivity, GDP, and welfare compared to Scenario I. However, the changes are minor. In 2020 we find an increase in aggregate labour costs of 0.1 per cent, a fall in wage rates of 0.2 per cent, a negative response in labour supply of 0.07 per cent, and reductions in GDP and consumption of 0.05 per cent compared to Scenario I. In previous periods the changes are even smaller. Another reallocation that implies minor social costs is the shift in allowance purchases from the flexible mechanisms to the relatively more expensive EU ETS market.

Nevertheless, the simulations reveal an insignificant overall welfare cost from Scenario I to Scenario III. The main modifying reallocation taking place results from the lowered GHG emission price. In household transportation, where several existing tax interventions interplay, reduced taxation contributes positively to welfare and explains the small overall cost of the subsidy scheme.

5 Final discussion and conclusions

Two main conclusions can be drawn from our computations. First, our estimates suggest a tripling of costs if the government fails to give reliable policy signals that match its announced domestic target. The reason is that upfront investment in climate technologies will be hampered. Some lines of policy response are suggested, provided the barriers can be attributed to commitment failures. Comparing the scenarios with and without technology adaptations also illustrate the shortcomings of a traditional CGE analysis compared to our hybrid approach. It reveals that the danger of overestimating abatement costs in top-down analyses is sizable and that hybrid approaches are pivotal; note that analogous shortcomings apply to bottom-up models, too.

Second, even if technological adaptations fail to be triggered by emissions pricing, a second-best subsidy policy could ensure their implementation. Subsidising technological diffusion can be politically and practically easier than designing an insurance scheme. A subsidy scheme will increase costs, as budgetary transfers will be needed. However, our study finds that the costs of funding these transfers are minor. We have not considered administrative costs in our computations, let alone market failures and strategic behaviour in the presence of subsidy policies. Additionality problems are well-known from the literature. Subsidies will not just be claimed by firms that need the subsidy for the investment to be profitable, but also by agents who would have invested in the abatement technology anyway, without the subsidy. The regulator will therefore require substantial information on production costs in order to separate firms that really need the subsidy from those that do not and to pick the most cost-effective investment projects. With asymmetric information, improper design of subsidies can lead to ineffective incentives and rent-seeking that further increases the social costs. (Florax et al., 2011).

Our computations indicate that the implications of technological barriers and investment hold-up are most likely severe. Even with conservative estimates, costs seem to be significantly higher for small and ambitious countries than those found for the world in Bosetti and Victor (2011). They find an additional cost of 76 per cent when they compare a global agreement with no credibility to the first-best case.[11] Our corresponding result for the prosperous and well-organised Norwegian economy exceeds 300 per cent. It is reasonable to expect higher costs in our unilateral case, as climate consciousness and policies have already inspired climate-friendly economic behaviour, while technology is close to state of the art at the outset.

There is reason to emphasize the high uncertainty associated with our computed cost levels. In particular, future technological and political opportunities are difficult to predict. Apart from a large variety of unsystematic sources of uncertainty, we know that some potential abatement measures are ruled out. This applies both to technological options and to compositional changes which by assumption are prohibited in the model, such as fixing *Petroleum extraction*. These omissions contribute to increasing abatement costs. On the other hand, transitional costs are unrealistically small, particularly given the relatively short time horizon of the analysis. Despite the high uncertainty of the cost levels, more confidence can be attached to the welfare ranking of the policy strategies.

[11] The cost in Bosetti and Victor (2011) is measured as discounted reductions in gross world output, while in this study we use discounted welfare; see section 2.2.

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Appendix

Table A.1: Production activities in MSG-TECH

MSG-TECH code	Description
11	Agriculture
12	Forestry
13	Fishery
14	Fish farming
15	Manufacture of other consumer 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
28	Printing and publishing
34	Manufacture of pulp and paper products
40	Petroleum refining
45	Manufacture of metal products, machinery and equipment
48	Building of ships
49	Manufacture of oil production platforms
55	Construction, excluding oil well drilling
63	Finance and insurance
65	Ocean transport
66	Petroleum extraction (including oil and gas, plus pipeline transport)
68	Oil and gas exploration and drilling
70	Generation of electricity
74	Transmission and distribution of electricity
75	Commercial road transportation
76	Air transportation
77	Transportation by railway and tramway
78	Coastal and inland water transportation
79	Postal and telecommunication services
81	Wholesale and retail trading
83	Dwelling servicing
85	Other private servicing
89	Imputed service charges from financial institutions
	Central government
92S	Defence
93S	Central government, education
94S	Central government, health care and veterinary servicing
95S	Central government, other servicing
	Local government
93K	Local government education
94K	Local government health care and veterinary servicing
95K	Other local government servicing
96K	Water supply and sanitary servicing

Figure A.1: Input factors in the production process

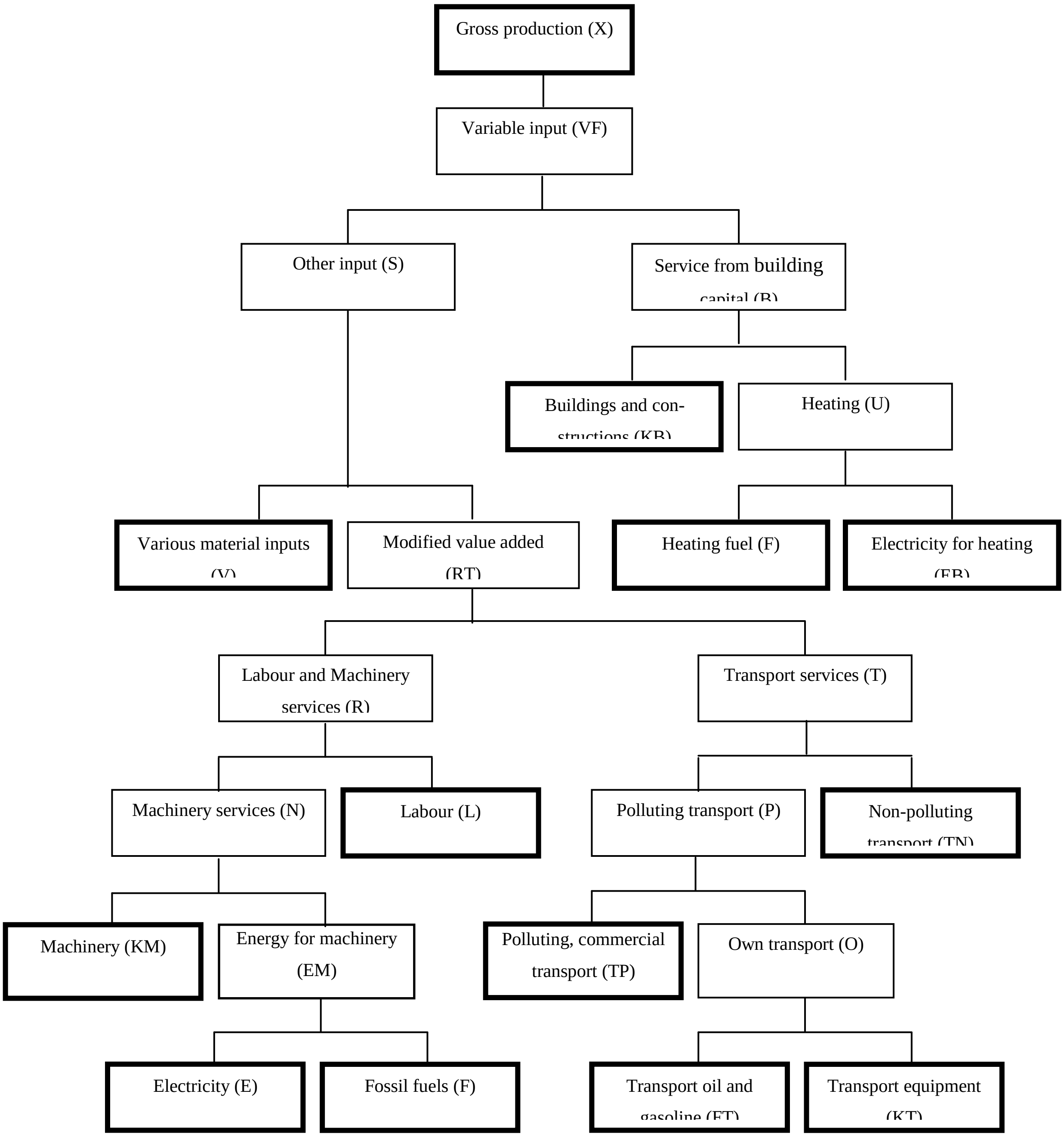
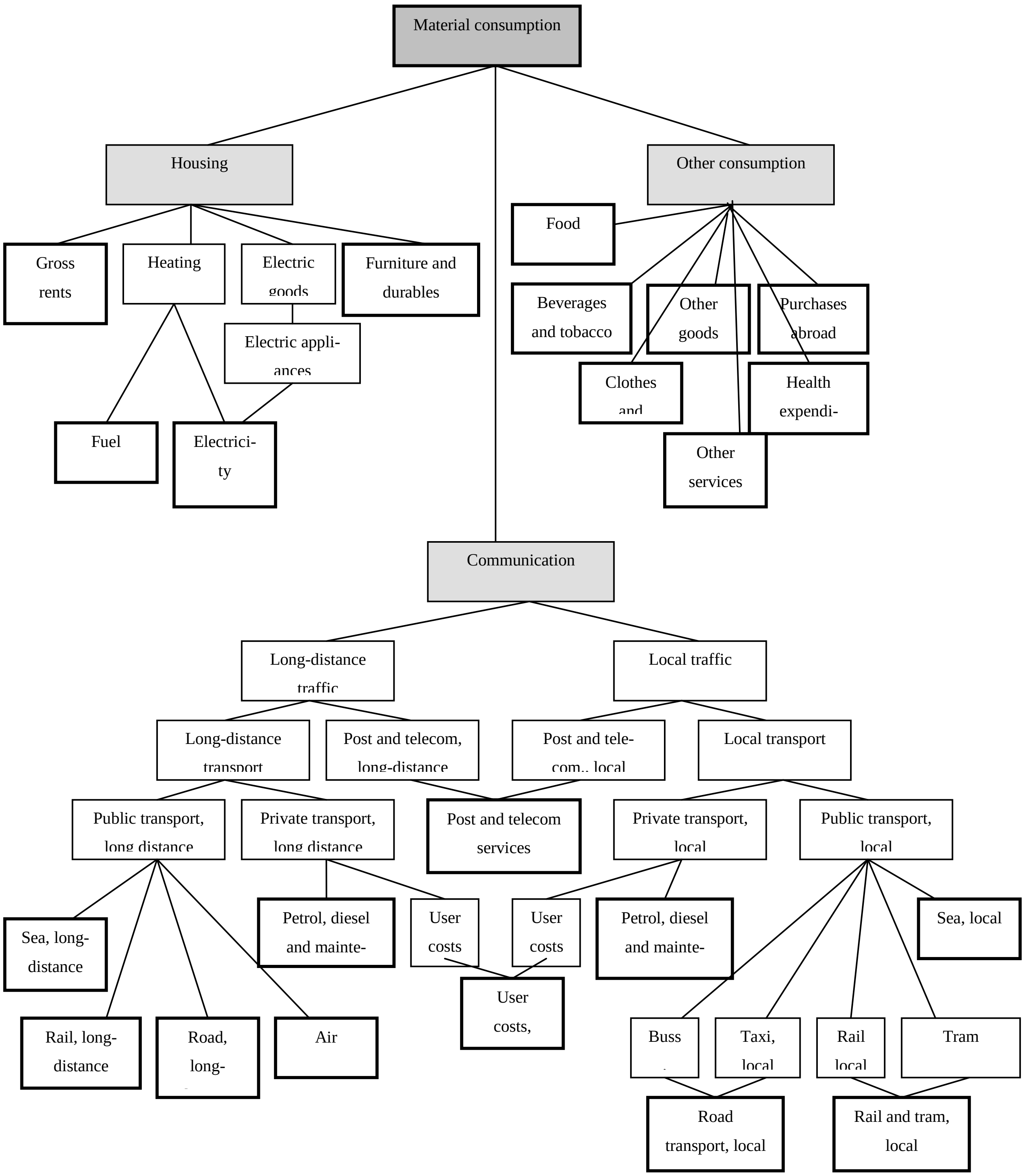


Figure A.2 Material consumption



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