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"Diffusion of climate technologies in the presence of commitment problems"

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Abstract:

Publicly announced greenhouse gas (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 combines the emissions pricing with a state guarantee scheme whereby the regulatory risk is borne by the government and one combines the system with subsidies for upfront climate technology investments. A technology-rich computable general equilibrium 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; Hybrid modelling; Technological change; Technological diffusion

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 prove unable to commit to 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 operations and service of the instalments 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 decisions that are 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 computable general equilibrium (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. 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, technology-rich models like traditional energy system 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. Ours combine the strengths of the two model traditions.

CGE modelling of induced climate technological progress has blossomed during the recent decades, with research and development (Goulder and Schneider, 1999) or learning by doing (Gerlagh and Lise, 2005) being the main endogenous mechanisms. A fairly recent survey of the literature is given in Gillingham et al. (2008). Several well-established, global CGE models have included such mechanisms, including the ENTICE (Popp, 2004), WIAGEM (Kemfert, 2005) and WITCH (Bosetti et al., 2006) models. Some models are also developed for national technology policy studies, early birds being Heggedal and Jacobsen (2011) for Norway and Bretschger et al. (2011) for Switzerland. However, our ambition is different and complementary to these; we endogenise the adoption of climate technologies rather than their abatement productivity. The main justification for keeping productivity given in our analysis is that we look at the small, open economy case where productivity change depends on the largely exogenous movement of the global technology frontier.

Our adoption module is more comparable to the recent years' large-scale hybrid approaches; see Bataille et al. (2009), Bosetti et al. (2006), and Laitner and Hanson (2006). In relation to these, it stands out 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. Instead, our model allows for investment in climate technologies within energy-intensive industries. Our approach has most in common with the modelling of industry-specific marginal costs of transport technologies in Kiuila and Rutherford (2013). Ours does, however, have the advantage of avoiding adjustments of the social accounts matrix when including abatement costs. This property makes updating of the adoption module to new base years, more industries, or novel technological information less challenging. Moreover, we include technological options in petroleum extraction and several energy-intensive process industries along with in transport, the latter involving investments in households, private firms and public services. The technological options with their costs and abatement potentials are easy traceable in the modelled representation.

Our analysis considers Norway's ambitious domestic target, representing an approximate 20-per-cent cut in GHG emissions in 2020 from an official reference scenario prolonging current and decided policies. 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 and some of these industries shut down most of their activity, typically in regions with few alternative job opportunities. Subsidising upfront investment in climate technologies is a feasible policy option. The 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 Section 3 reports from the analysis. Section 4 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. Financial capital is perfectly mobile across borders, while real capital and labour are perfectly malleable and can be smoothly reallocated within the economy.[2] 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.2 in the appendix. Environmental benefits are not accounted for. Consumer goods are specified at a 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 transportation services, 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. Due to policy and resource restrictions, some industrial activities are exogenously determined in our simulations: *Petroleum extraction, Agriculture, Forestry, Fishery, Governmental services (Central and Local)*, and *Generation of electricity*.[3] Production factors include labour, different types of capital, and 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

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[1] The model is a version of MSG6; see Heide et al. (2004) and Bye (2008), enriched with technology options. Fæhn et al. (2013) provides a documentation.

[2] Real capital refers to the categories *Buildings and constructions*, *Machinery* and *Transport equipment* in Figure A.1 in the appendix.

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

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.

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 Technological 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 input activities of private firms, households, and the public sector. Along with households, the service industries *Commercial road transportation*, and *Other private services* are the largest users of own land transport. 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 among firms, industries, countries, contexts, and over time. Our data are based on industry-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. Note that as the Norwegian market is small in the global context, we model learning and technological progress as exogenous processes irrespective of the domestic demand. The modelling, data, and estimations are accounted for below. See Fæhn et al. (2013) for more details.

A stylised representation of technology adaptations[4]

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

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

where X is output, V factor input, ε_0 is an exogenous factor productivity parameter and ρ the scale elasticity parameter ($0 < \rho < 1$). Note that a higher ε_0 implies lower factor productivity, i.e. less output per unit of input. The profit, π, for the representative firm in the presence of an emission tax, τ, is:

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

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:

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

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:

$$\mu = \mu_0 - \frac{D}{X} \tag{4}$$

$$\varepsilon = \varepsilon_0 + \frac{E}{X^{1/\rho}} \tag{5}$$

As seen from equation (4), μ accounts for endogenous technological abatement, D, per unit of output, X. As long as technological abatement takes place, $\mu < \mu_0$. Quite similarly, the endogenous ε-parameter accounts for the abatement cost of the firm, E, in equation (5). The interpretation of the ε-parameter is that the input use needed for a given output increases when technological adaptation takes place; i.e., factor productivity decreases and $\varepsilon > \varepsilon_0$. In other words, abatement spending increases factor use without increasing output, thereby lowering factor productivity. This modelling ensures that the actual resource costs of technological abatement are captured, while avoiding the need to insert a new

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[4] 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 model 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.

activity in the input-output system. The latter would require recalibration of the model, which complicates updating to new base years, more abatement industries, or novel technological information.

It is important to note that the productivity decrease only accounts for *direct* investment, installation, and operational costs related to the abatement projects. Several empirical studies have scrutinised the *net* effects on productivity of taking on abatement efforts. Most of these studies find productivity drops, and frequently they seem to exceed the direct effect of the abatement costs (Gray and Shadbegian, 2003). Some, particularly more recent, econometric analyses find smaller drops or even productivity gains (Ambec et al., 2013), indicating that more stringent environmental regulations trigger productive innovation as suggested by Porter and van der Linde (1995). Our ambition is to model the direct costs, only, not to quantify and model other indirect effects on productivity.

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*:

$$c = f(D) \tag{6}$$

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

$$c = \tau \tag{7}$$

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

$$E = \int f(D)dD \tag{8}$$

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.[5]

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 production of pulp and paper (in *Manufacture of pulp and paper products).* The technological adaptations investigated include case-specific ways of

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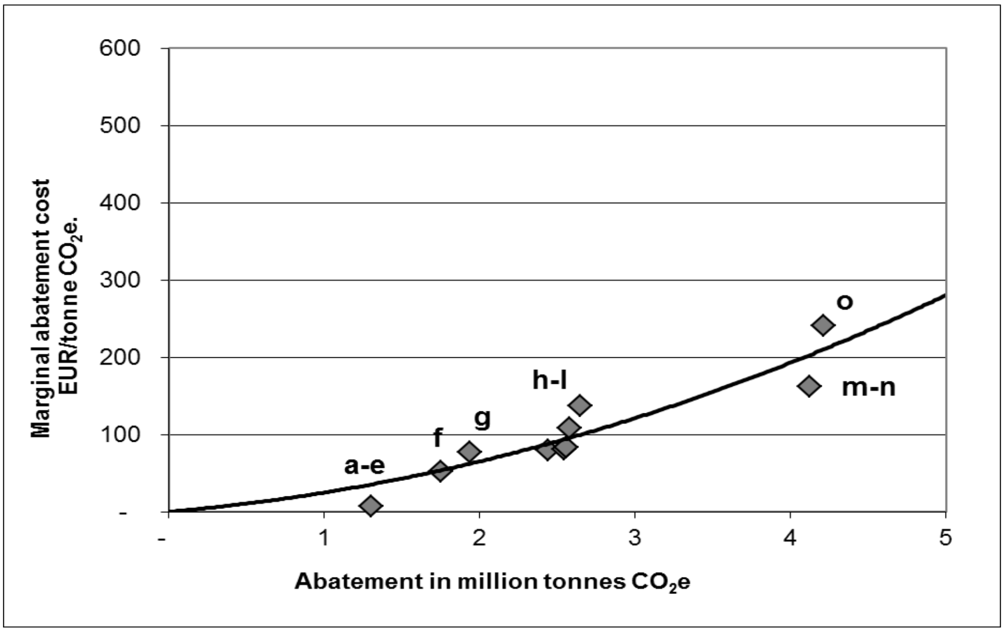
[5] A more detailed description of the abatement costs and abatement potentials by measure is provided in Fæhn et al. (2013).

converting to bioenergy, of process optimisation, and of sequestration of GHG emissions, including CCS; see Table 1. We arrange the measures by cost annuities and estimate a marginal abatement cost curve that links marginal costs to accumulated abatement potentials. The method involves giving a smooth representation of abatement options that in the data are stepwise measures, each with its pre-defined individual potential and cost. We choose abatement cost functional forms and 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.[6] 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. Among the most expensive measures we find CCS, and it is reasonable to expect potentials for this technology in plants that are smaller than those included in the data set, though at higher marginal costs due to significant economies of scale for this technology.

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



Notes: CO_2e = CO_2 equivalents measured by global warming potential (GWP). See Table 1 for information on the abatement measures a-o.

Table 1: Abatement costs and potentials in *Process industries*, by measure.

	Abatement measure	**Annuity (EUR/ tonne CO_2e)**	**Abatement (million tonnes CO_2e)**	**Accumulated abatement (million tonnes CO_2e)**
a	Process optimisation (metals)	6	0.50	0.50
b	Energy efficiency and substitution (metals)	6	0.30	0.80
c	Energy efficiency and substitution (pulp and paper)	6	0.29	1.09

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[6] Our data only include measures with positive costs. The fact that bottom-up calculations sometimes give negative abatement costs at variance with standard economic theory, and how to interpret and treat this in CGE modelling, is discussed in , e.g., Dellink (2005, p 113).

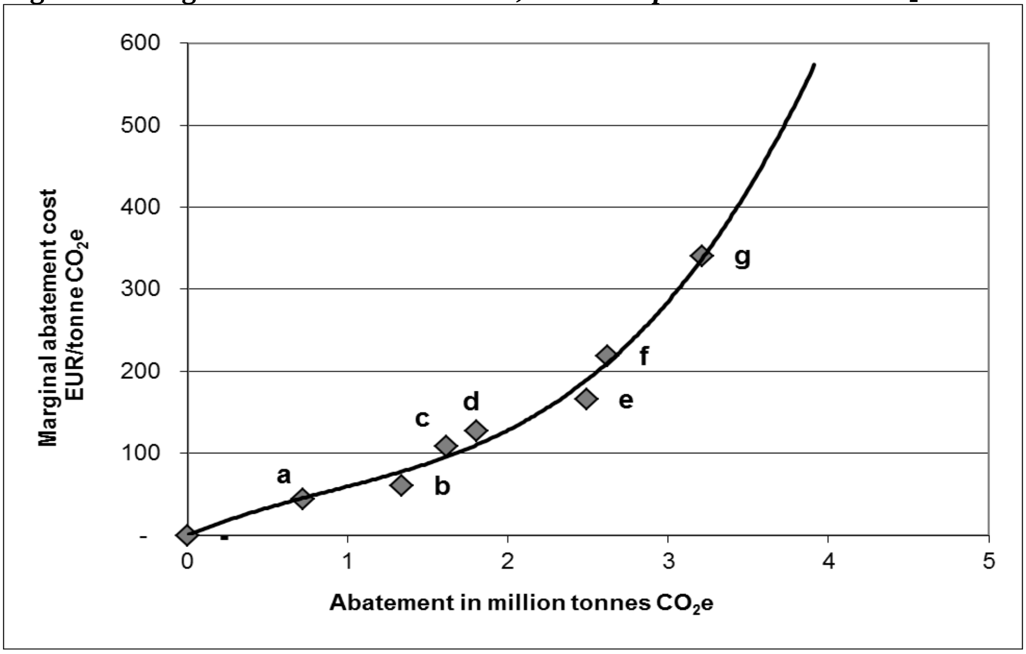
d	Substitution of bio (cement and other minerals)	6	0.16	1.25
e	Energy efficiency and substitution (chemicals)	6	0.04	1.30
f	<40% charcoal for coke (ferrosilicon)	52	0.45	1.75
g	<20% charcoal for coke (ferromanganese)	76	0.19	1.94
h	<80% charcoal for coke (ferrosilicon)	79	0.50	2.44
i	Substitution of bio (cement)	81	0.10	2.54
j	Process optimisation (petrochemicals)	83	0.02	2.56
k	Charcoal substitute for coke (silicon carbide)	109	0.02	2.58
l	Substitution of bio (anodes)	137	0.07	2.65
m	CCS (fertilisers)	163	0.69	3.34
n	CCS (cement)	163	0.79	4.13
o	Substitution of bio (pulp and paper)	241	0.09	4.21

Sources: SFT (2007), SINTEF (2009), TELTEK (2009) and Climate Cure 2020 (2010).

Land transport

Measures for reducing emissions from Norwegian land transport are summed up in Table 2. 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.

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



Notes: See Table 2 for information on the abatement measures a-g.

Table 2: Abatement costs and potentials in *land transport*, by measure.

	Abatement measure	Annuity (EUR/ tonne CO_2e)	Abatement (million tonnes CO_2e)	Accumulated abatement (million tonnes CO_2e)
a	Efficiency improvements private cars– level 1	44	0.72	0.72
b	Efficiency improvements private cars– level 2	60	0.62	1.34

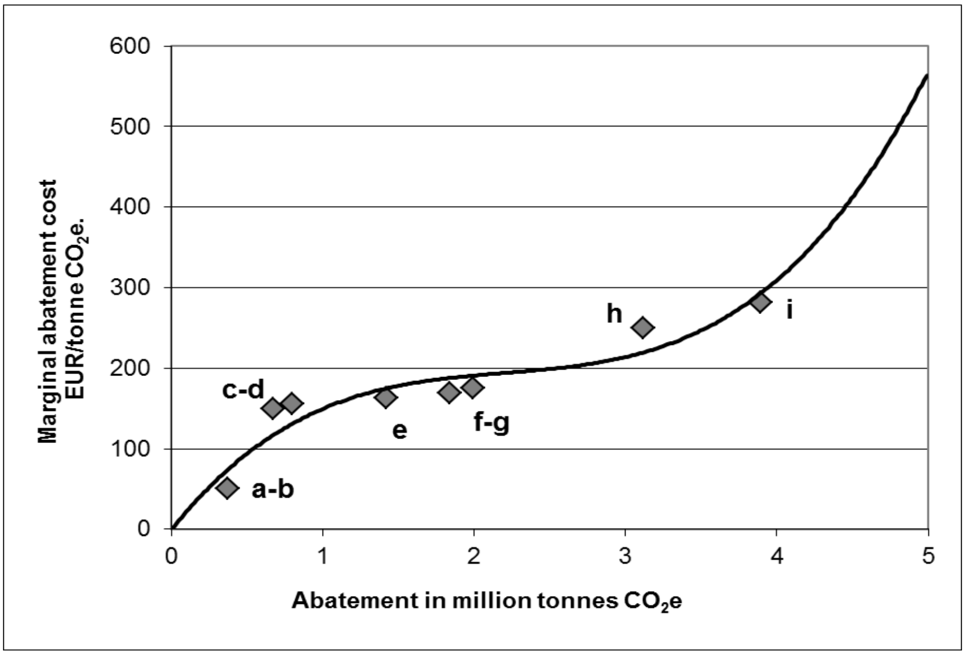
c	Zero emissions vehicles– private and public	109	0.27	1.61
d	Intermixture of ethanol E85	128	0.19	1.80
e	Intermixture of 1.generation biodiesel	166	0.69	2.49
f	Intermixture of ethanol E5, E10, E20	219	0.13	2.62
g	Intermixture of 2. generation biodiesel	341	0.59	3.21

Sources: SFT (2007), SINTEF (2009), TELTEK (2009) and Climate Cure 2020 (2010).

Petroleum extraction

Potential measures within *Petroleum extraction* include various forms of alternative power supply to the offshore industry (electrification from land, offshore wind power), power efficiency improvements, and CCS; see Table 3. 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.



Notes: See Table 3 for information on the abatement measures a-i.

Table 3: Abatement costs and potentials in *Petroleum extraction*, by measure.

	Abatement measure	**Annuity (EUR/tonne CO_2e)**	**Abatement (million tonnes CO_2e)**	**Accumulated abatement (million tonnes CO_2e)**
a	Energy efficiency offshore	50	0.20	0.20
b	Electrification Melkøya -1	50	0.17	0.37
c	Electrification Melkøya 2	150	0.30	0.67
d	Electrification Melkøya 3	156	0.13	0.80

e	Mongstad processing CCS	163	0.62	1.42
f	Electrification North Sea south	169	0.42	1.84
g	Electrification new site	175	0.15	1.99
h	Electrification North Sea north	250	1.13	3.12
i	Kårstø processing CCS	281	0.77	3.89

Source: NPD (2010).

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_2e according to their GWP. In addition, emissions of sulphur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), ammonia (NH3), and particulate matter (PM_x) are modelled.

There 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 Analysis

3.1 Design of the analysis and main assumptions

We analyse three different policy strategies for fulfilling the agreed climate ambitions of the Norwegian Parliament (see Climate Cure 2020, 2010) compared to a reference scenario that builds on officially available projections.[7] The reference scenario stretches from 2008 to 2020 and includes a prolonging of existing policies as well as implementation of decided climate policies for the period. This includes Norway's participation in the emissions trading system of the EU (EU ETS). The EU ETS comprises *Petroleum extraction*, *Petroleum refining* and *Process industries.*[8] Together

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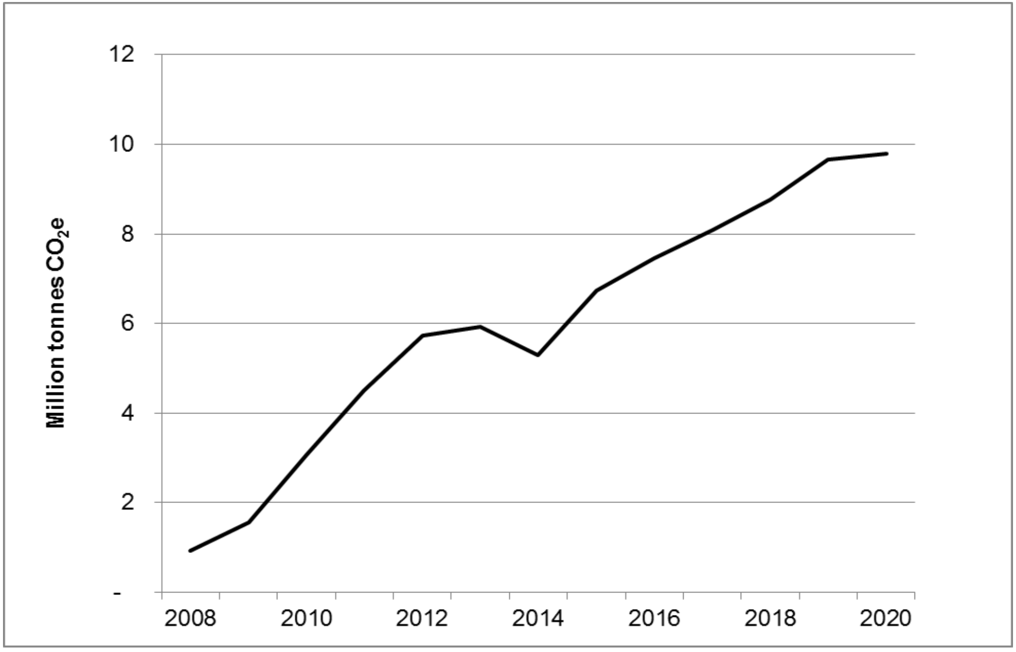
[7] The basis for the reference scenario are the National Budget 2011 (Norwegian Ministry of Finance, 2010) and the governmental climate policy report Climate Cure 2020 (2010) - see also Fæhn et al. (2013) for more details.

[8] *Generation of electricity* is also included in the EU ETS, but Norwegian power generation is almost exclusively based on hydropower. *Manufacture of metals* is included in the EU ETS from 2013. Combined with the assumption of a smooth phasing-in of the national cap, this industry's change in conditions from a tax-exempted Non-EU ETS industry to an EU ETS-restricted industry causes a kink in the curves in 2013 in Figures 4-7 and Figure 10.

these three industries constitute approximately 45 per cent of the reference scenario's GHG emissions by 2020. The EU ETS quota price is assumedly determined abroad and anticipated to rise steadily from 12 to 20 EUR/tonne CO_2e by 2020. The reference scenario also includes a prolonging at real rates of an existing differentiated system of CO_2 taxes imposed on non-EU ETS sources. Real tax rates vary between EUR 0 and EUR 50 per tonne, the highest imposed on petrol for land transport.

Figure 4: Abatement in Scenario I, II and III, compared to the reference scenario. Million tonnes CO_2e. 2008 –2020.



Notes: The drop in abatement in 2013 arises, first of all, from the inclusion of *Manufacture of metals* in the EU ETS, which renders the commitments in the EU ETS in the reference scenario more stringent. Combined with the gradual reduction of the cap, the necessary abatement temporarily drops.

The Parliament's climate agreement can be translated into a domestic GHG emissions reduction in 2020 of 9.8 million tonnes CO_2e, corresponding to a 20-per-cent cut from the reference scenario. The emission cap is the same in all three policy scenarios and is assumed to be equally and smoothly phased in in all the scenarios. The resulting total abatement required is depicted in Figure 4. Also, all the scenarios assume the use of a domestic cap-and-trade system that ensures a uniform emission price faced by all Norwegian GHG sources. However, the necessary emission price level is endogenous and will depend on the simultaneous use of additional climate policy measures. In Scenario I the government supplements the cap-and-trade system with a guarantee scheme that ensures its reliable commitment to the caps for future periods. Scenario II assumes the cap-and-trade introduction is not supported by this commitment device. Consequently, the emissions pricing is perceived by agents as short-lived, which reduces their profitability prospects of upfront investments in climate technologies. In Scenario III, commitment to a long-lasting emission price is still not ensured, but the emissions pricing scheme is supplemented by subsidies to upfront investments as a second-best approach to encouraging technological adaptations.

In all the three policy scenarios, the domestic emission price necessary to meet the national abatement ambitions replaces the emission prices in the reference scenario.[9] 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 investment based on the future price forecast by the government receives sales options for each forthcoming year corresponding to the emission reduction 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 macro, the abatement target must be met.

In Scenario III, technological adaptations take place along with other adaptations in spite of lack of confidence in the pricing system. They are 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

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[9] A national cap-and-trade system is compatible with the EU ETS. For the EU ETS sectors this implies that they pay an emission price on top of the EU ETS price that exactly renders the total emission price equal to the uniform emission price in the cap-and-trade system. For sources charged with CO_2 tax in the reference, the tax is substituted by the uniform emission price.

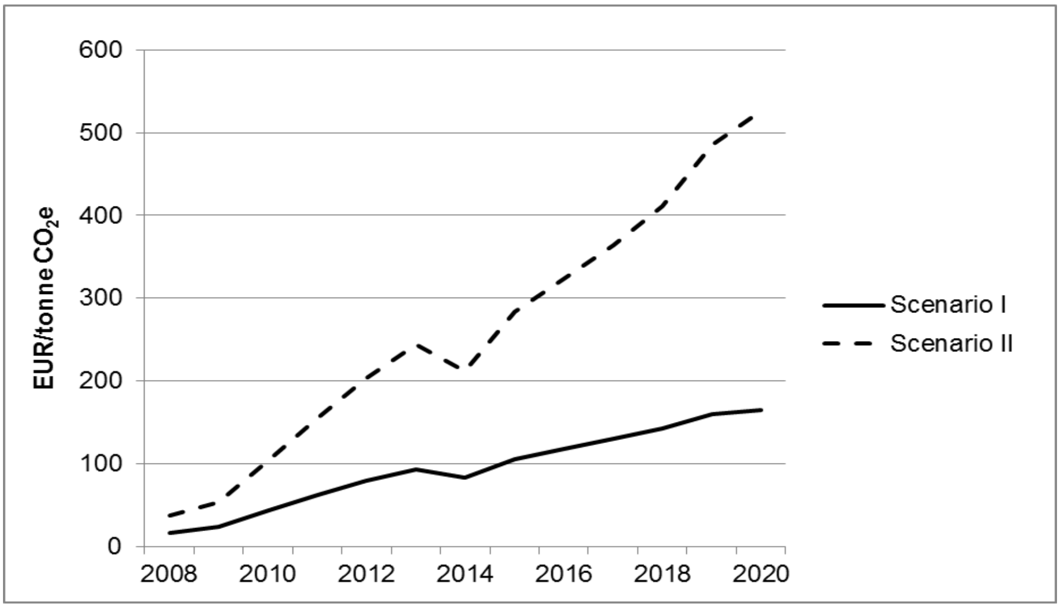
subsidies fully compensate for the firms' technology adaptation costs, as suggested in, inter alia, Ulph and Ulph (2013), Conconi and Perroni (2009), and Montero (2011). This has two implications. First, it implicitly defines all costs of converting to new technologies as investment costs. In practice, 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 cost of public funds, only.

3.2 Scenario I: Guaranteed future emission prices

Impact on emission price and abatement composition

When confidence in the cap-and-trade system is assured, simulations reveal a rise in the emissions price necessary to comply with the domestic target up to 164 EUR/tonne CO_2e by 2020; see Figure 5.

Figure 5: Scenarios I and II: Emission prices. EUR/tonne CO_2e (2004 prices). 2008–2020.

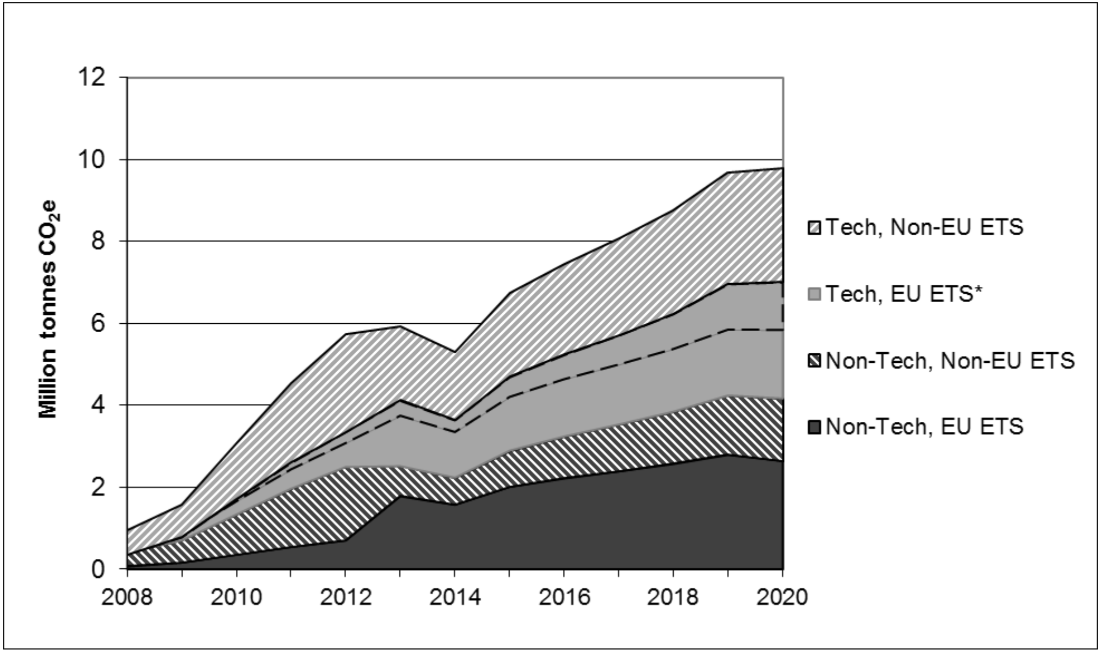


Notes: The drop in the emission price from 2013-2014 is primarily due to the inclusion of *Manufacture of metals* in the EU ETS, as explained in the note to Figure 4.

Figur 6 shows both the sectoral and the technological composition of abatement measures.[10] During the first years, most of the abatement takes place at emission sources *not* comprised by the EU ETS regulations (labelled `Non-EU ETS´ in Figure 6 and represented by hatched fillings), first of all in industries with low CO_2 taxes in the reference scenario, like *Manufacture of metals*. However, as this industry enters the EU ETS and the domestic cap tightens, the share abated within EU ETS industries increases (labelled `EU ETS´ in Figure 6 and represented by solid fillings). 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.

Emission reductions from the reference scenario are achieved both within already adopted technologies (labelled `Non-Tech´ in Figure 6 and represented by black fillings) and through investments in new technologies (labelled `Tech´ in the same figure and represented by green fillings). The technological measures account for around half of the total reductions. The reductions in *Petroleum extraction* are almost exclusively achieved through technological abatement, as downscaling is ruled out by assumption (see Section 2.2). The abatement in the rest of the EU ETS sector, i.e., in *Process industries* and *Petroleum refining*, is also largely obtained by scaling down operations. For Non- EU ETS industries the lion's share of cuts are achieved through technological adaptations, primarily in the form of novel modes of land transport.

Figure 6: Scenario I: Abatement compared to the reference scenario, by category. Million tonnes CO_2e. 2008 –2020.



Notes: `Tech´=Technological abatement, `Non-Tech´=Abatement through downscaling and substitution, `EU ETS´= sources covered by EU ETS `Non-EU ETS´=sources not covered by EU ETS. *The green, solid area `Tech, EU ETS´ is split in two; upper part is *Petroleum extraction*, lower is other EU ETS sources.

Macroeconomic and sectoral 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.[11] This is equivalent to EUR 25 annually per capita. The dominating cost component is the cost 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 5. Of far less importance, but still at work, are several reallocations that, in sum, yield double dividends able to dampen efficiency

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[10] Mitigation in all sectors comes smoothly along time as a consequence of the general equilibrium model assumptions of malleability and mobility of resources – see Section 2.

costs (Goulder, 1995). By recycling of the revenue earnings from the emissions pricing through reduced payroll taxes, the payroll tax rate can be cut by 20 per cent by 2020. 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, it is a well-known result from the double dividend literature that such adjustments contribute to reduce the losses in social efficiency and welfare.[12] Another positive contribution to welfare arises from the climate 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. Among these industries, outputs within *Manufacture of metals* and *Manufacture of industrial chemicals* drop by 22 and 32 per cent, respectively, while employment cuts amount to similar relative magnitudes. Even if these industries have relatively low labour intensity, the employment cuts are significant for some enterprises and communities. However, our results indicate a gain to the economy as a whole, because it releases resources for activities with relatively higher macroeconomic marginal returns: We see an increase in the low-emitting service industries, most prominently in *Other private services* and *Wholesale and retail trading*. These results should be seen as long-term outcomes. As the CGE model treats reallocations as smooth processes, transition costs in terms of increased unemployment and scrapped equipment are disregarded.

3.3 Scenario II: Unreliable future emission prices

Impact on emission price and abatement composition

As the domestic cap is given, total abatement is the same as in Scenario I (see Figure 4). However, 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 endogenous uniform emissions price necessary to meet the domestic cap reaches far higher levels than under the guarantee scheme in Scenario I; see Figure 5. 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.

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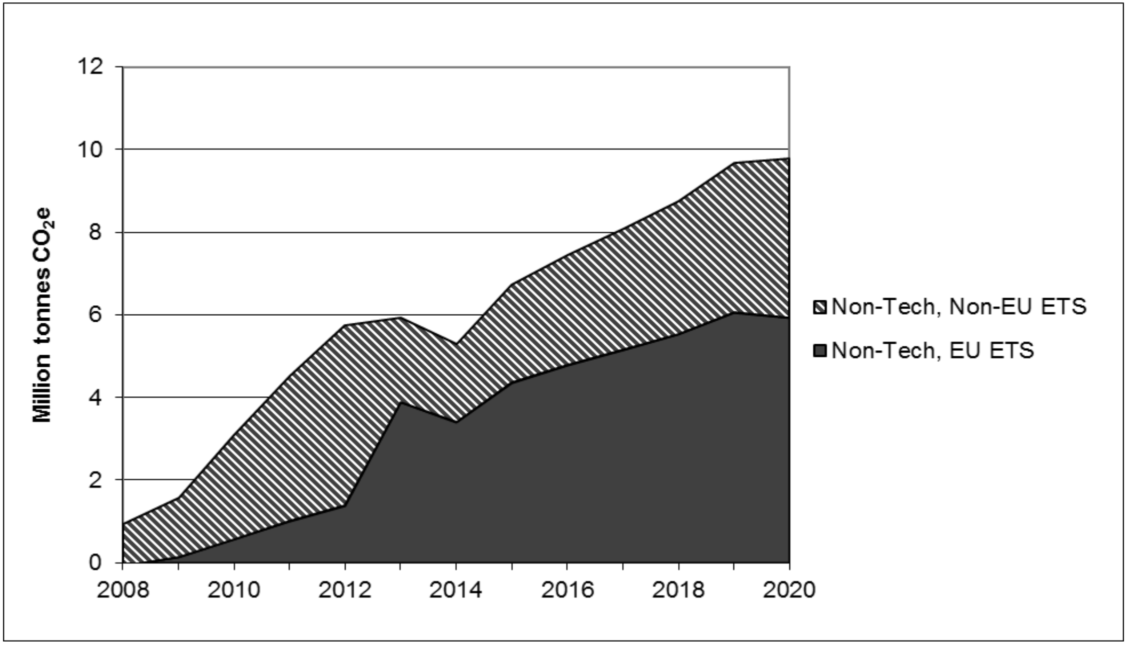
[11] In the discounting, the yearly consumer utility of the policies is assumed to remain unchanged after 2020 (to infinity).

[12] The ordinary Norwegian payroll tax rate is 14.1 per cent. The tax is differentiated across regions. This implies some degree of industrial differentiation, first of all benefitting the industries related to fishing (*Fish farming*, *Fishery*, and *Preserving and processing of fish*), which have rates 2.5-5 percentage points below the ordinary rate. For all industries, the payroll tax constitutes only a small part of the price wedge between labour and leisure, which also includes income tax, VAT and excise taxes. A study of Norwegian marginal cost of funds, Holmøy and Strøm (2004), uses a similar model and shows that the marginal cost of funds would be more or less identical if other components of the price wedge are adjusted, like the VAT, the income tax or a combination of VAT, payroll tax and income tax. These results are equally relevant for recycling effects. Our results of payroll tax changes are, thus, representative for a variety of alternative tax recycling options.

Figure 7 illustrates the composition of the cuts from the reference scenario. 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. The allocation of cuts between the EU ETS and Non-EU ETS sectors follows broadly the same pattern as in Scenario I. The Non-EU ETS 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 *Manufacture of metals*.

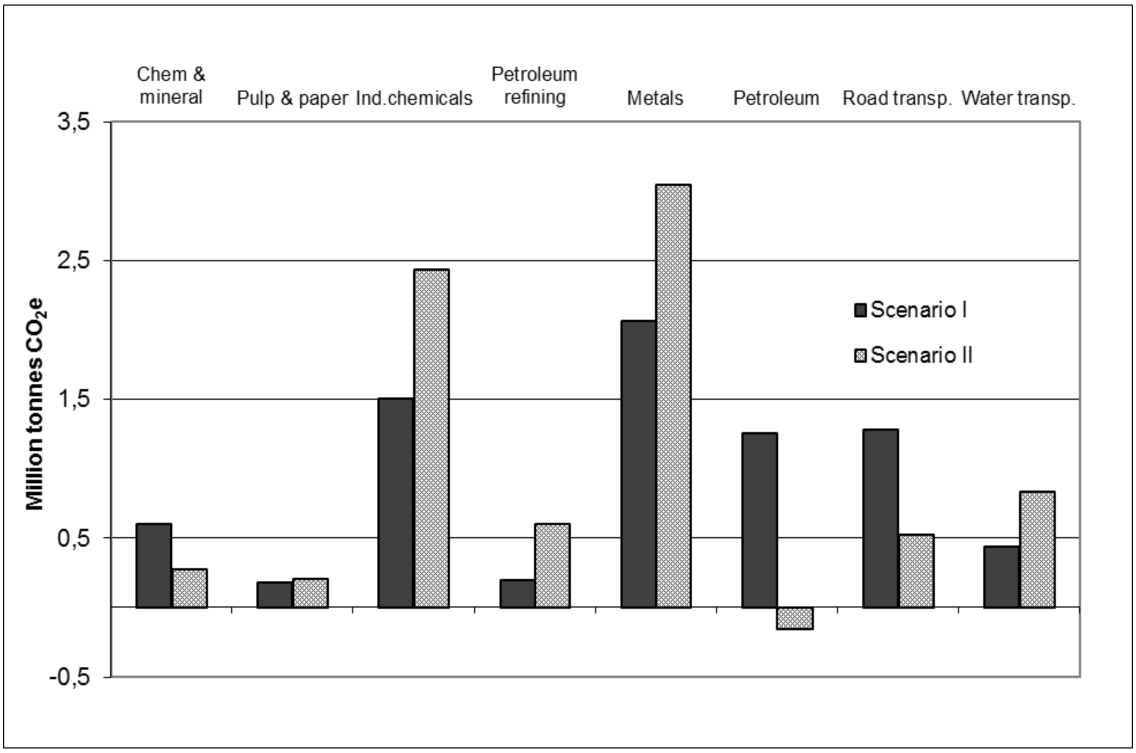
Figure 7: Scenario II: Abatement compared to the reference scenario, by category. Million tonnes CO_2e. 2008 –2020.



Notes: `Non-Tech'=Abatement through downscaling and substitution, `EU ETS´= sources covered by EU ETS `Non-EU ETS´=sources not covered by EU ETS.

As depicted in Figure 8, we see interesting shifts in the abatement composition on the more detailed level. Within the *EU ETS sector*, the exclusion of technological opportunities in Scenario II leads to a shift in the 2020 abatement away from *Petroleum extraction*. Recall that the activity level in *Petroleum extraction* is exogenously given, so emission reductions in this sector can only be achieved by investing in emission-reducing technologies. *Manufacture of industrial chemicals* and *Manufacture of metals* 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.

Figure 8: Scenarios I and II: Abatement in 2020 compared to the reference scenario, selected industries. Million tonnes CO2e.



Notes: Chem & mineral = *Manufacture of chemical and mineral products*, Pulp & Paper = *Manufacture of pulp and paper products,* Ind. chemicals = *Manufacture of industrial chemicals*, Metals = Manufacture of metals, Petroleum = Petroleum extraction, Road transp.= *Commercial road transportation,* Water transp.= *Coastal and inland water transportation.* See Table A.1. All the selected industries, except Road transp. and Water transp. are EU ETS industries.

The activities within the Non-EU ETS sector are less elastic, which translates into a lower abatement share compared to Scenario I. Typically, *Commercial road transportation* has low price elasticity, and when upfront technology investments prove unprofitable because of the unreliable policy signals, less car driving hardly compensates in terms of abatement. *Coastal and inland water transportation* does, however, adjust more elastically as costs can be passed on to domestic consumers.

Macroeconomic and sectoral effects

Failure to signal that the climate policy is reliable and enduring implies a welfare loss of about one per cent compared to the reference scenario. This loss is almost four times higher than that faced in the case of a guarantee scheme in Scenario I. The rise in marginal abatement costs explains far the most of this – see Figure 5. As there are numerous distortions present in the calibrated model, the explanations of the increase also lay in interaction effects with existing price wedges. General doubt about the durability of the cap-and-trade policy will in the long run lead to a stronger reallocation of resources. The flow of labour towards non-emitting industries like *Other private services* and *Wholesale and retail trading* triples compared to Scenario I. We see a drastic contraction of the *Process industries*; a fall that brings about efficiency costs to the extent that the emissions pricing more than offsets the existing favourable industrial policy schemes. For instance, outputs from two of the *Process industries*, *Manufacture of metals* and *Manufacture of industrial chemicals,* drop by 62 and 79 per cent, respectively. The employment effects are of the same magnitude, with a drop in hours worked by 62 and 82 per cent.

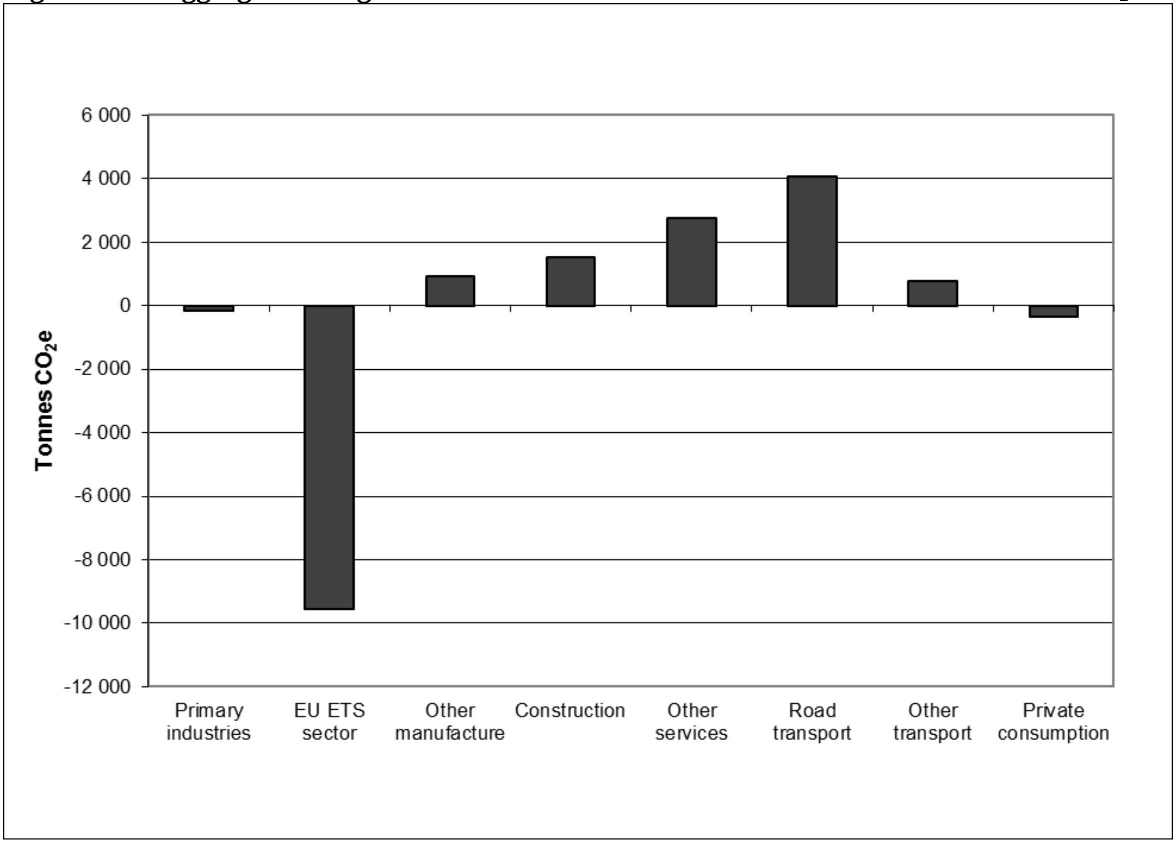
The *Non-EU ETS* industries *Commercial road transportation* and *Coastal and inland water transportation* also cut services substantially, by eight and 32 per cent, respectively, with employment effects of similar relative magnitude. Further, the use of own cars by households falls by 26 per cent, while their use of fuels for heating 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 land transport activities are drastically cut. It must be kept in mind that local beneficial effects of reduced land transport, such as reduced pollution and less congestion, are not accounted for. However, welfare is also affected by interaction effects working in the opposite direction. The revenue from the considerable emission tax allows payroll tax rates to fall by as much as 70 per cent in 2020 without reducing the public budget compared to the reference scenario. Received wages increase by 1.8 per cent, which result in a 2-per-cent rise in labour supply. In isolation, this yields dividends for the economy, as the present price wedge caused by labour taxation is relatively high in Norway.

3.4 Scenario III: Subsidising technological adaptations

Impact on emission price and abatement composition

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. Total non-technological abatement is, thus, also unchanged from Scenario I, as the same yearly emissions targets apply. Compared to Scenario I the emission price fall by an average of ½ per cent along the path. The fall in the emission price reflects that the compositional shifts in the public budget contribute to decrease emissions as an auxiliary effect. This reduces the required stringency of the emission price.

Figure 9: Disaggregate changes in abatement from Scenario I to Scenario III. Tonnes CO_2e in 2020.



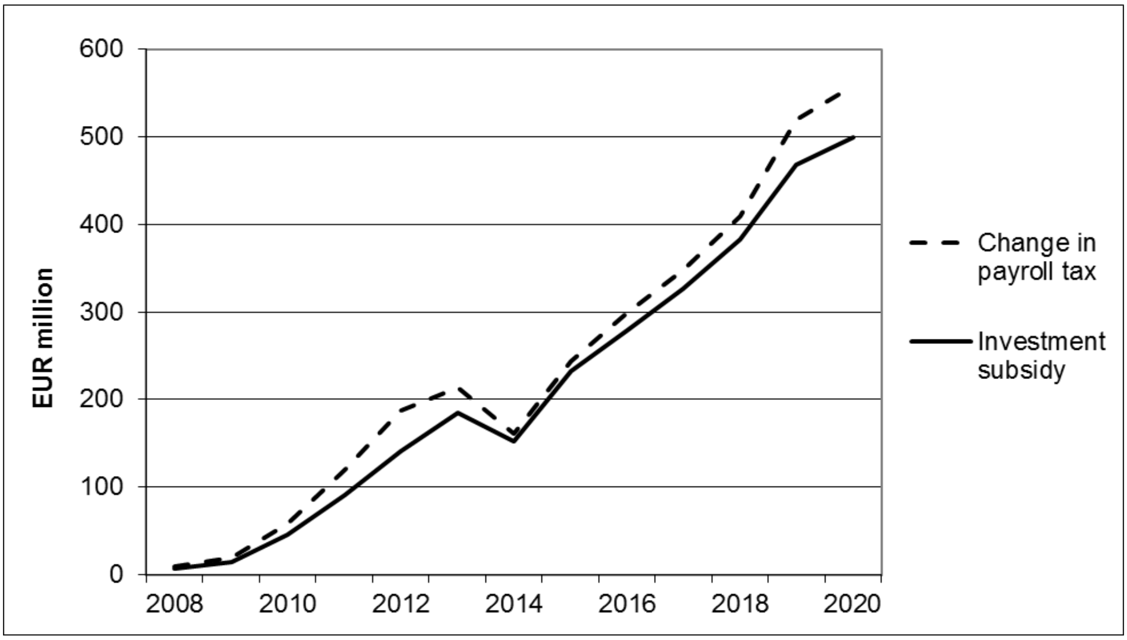
Notes: The figure includes abatement in all industries, grouped as in Table A.1 with the following exceptions: Other manufacture = *Manufacturing Non-EU ETS industries*, Other services = *Service industries* except *Construction*, Other transport = *Transportations industries* except *Commercial road transportation* (Road transport)

Even though the total non-technological abatement is the same in in Scenario I and III, the composition change somewhat, since the funding of the subsidy scheme increases the payroll tax rates. The increased payroll tax rates imply that labour-intensive sectors will scale down more relative to capital-intensive sectors. This small response compared to Scenario I is illustrated in Figure 9, where abatement shifts away from relatively capital-intensive industries in the EU ETS sector to more labour-intensive industries like *Construction*, *Commercial road transportation* and other services.

Macroeconomic and sectoral effects

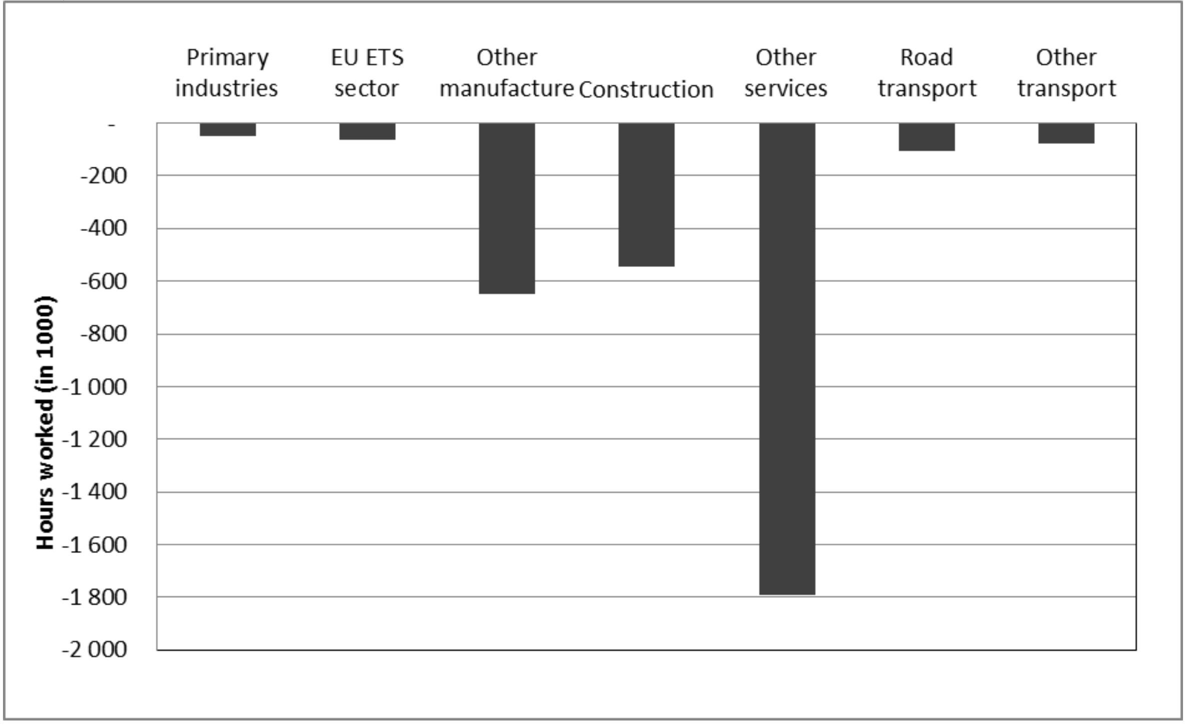
Figure 10 shows that the change in payroll tax revenue from Scenario I to Scenario III exceeds the subsidy expense. The main reason is that the payroll tax revenue also needs to compensate for a lower emission price; see above.

Figure 10: The investment subsidy and change in payroll tax expense from Scenario I to Scenario III. EUR million.



The simulations reveal an insignificant overall welfare reduction from Scenario I to Scenario III. As the subsidy scheme is, by assumption, well targeted at the most cost-effective technology measures, the main cost component compared to Scenario I is the cost of public funds. Well-targeted subsidisation 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. The cost of funds is reductions in efficiency caused by the payroll tax funding. They are primarily related to two reallocations: first, a lower labour supply in the wake of higher payroll tax rates than in Scenario I, and second, a restructuring of the economy towards less labour-intensive activities, as mentioned above. 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.

Figure 11: Disaggregate changes in employment from Scenario I to Scenario III. Hours worked (in 1000). 2020.



Notes: The figure includes employment effects in all industries; see notes below Figure 9 for industry notations.

The sectoral reallocations are reflected in the employment effects depicted in Figure 11. *Service industries* and *Construction*, along with *Manufacturing Non-EU ETS industries*, experience stronger reductions in hours worked compared to Scenario I, reflecting their relative labour intensity. Interestingly, the most abating sector, the EU ETS industries, faces only as small part of the employment reductions, both in absolute and relative terms.

Though both the labour supply response and the industrial reallocations contribute negatively to productivity, GDP, and welfare compared to Scenario I, the changes are minor. In other words: The marginal cost of funds in the Norwegian economy is relatively low.[13] Furthermore, there are reallocations taking place that modify the costs and contribute to explain the very small welfare difference between Scenario III and I. One modification arises from the fact that households' use of own land transport is subject to several existing tax interventions. Thus, a reduced emission price has a partial positive welfare effect by reducing this price wedge. We should emphasise that local externalities of households' transport activities are not accounted for in the model and, also, recall that the general equilibrium model disregard transitional costs.

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[13] This result is also confirmed in Holmøy and Strøm (2004).

4 Final discussion and conclusions

Two main conclusions can be drawn from our computations. First, our estimates suggest more than 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 illustrates 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 social costs, as budgetary transfers will be needed. However, our study finds that the cost of funding these transfers is 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 need substantial insight into production processes, markets and abatement 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). Nevertheless, competitiveness and employment considerations can leave subsidy schemes as the most, perhaps the sole, feasible instrument for reducing GHG emissions in trade-exposed industries.

Our computations indicate that the consequences of technological barriers and investment hold-up are most likely severe. Even with conservative estimates, costs for small and ambitious countries seem to be significantly higher 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.[14] 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

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[14] 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.

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 emphasise 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 contracting the *Petroleum extraction* industry. These omissions contribute to increasing abatement costs. On the other hand, transitional costs including adjustment costs for workers and real capital owners 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.

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Appendix

Table A.1: Production activities in MSG-TECH.

Description
EU ETS sector
Process industries *
Manufacture of chemical and mineral products *
Manufacture of pulp and paper products *
Manufacture of industrial chemicals *
Manufacture of metals *[1]
Petroleum extraction (incl. oil and gas, plus pipeline transport) *
Petroleum refining
Generation of electricity
Non-EU ETS sector
Primary industries
Agriculture
Forestry
Fishery
Fish farming
Manufacturing Non-EU ETS industries
Manufacture of other consumer goods
Manufacture of textiles and apparel
Preserving and processing of fish
Manufacture of meat and dairy
Manufacture of wood and wood products, except furniture
Printing and publishing
Manufacture of metal products, machinery and equipment
Building of ships
Manufacture of oil production platforms
Transportation industries
Commercial road transportation
Transportation by railway and tramway
Air transportation
Coastal and inland water transportation
Ocean transportation
Service industries

Wholesale and retail trading
Finance and insurance
Postal and telecommunication services
Oil and gas exploration and drilling
Construction, excluding oil well drilling
Transmission and distribution of electricity
Dwelling services
Imputed service charges from financial institutions
Other private services
Central governmental services
Defence
Central public, education
Central public health care and veterinary services
Other central public services
Local governmental services
Local public education
Local public health care and veterinary services
Other local public services
Water supply and sanitary services

Notes: Industries marked with * have technological abatement options in the model. In addition, all industries have the option to invest in transport technologies to the extent that they use own land transport as input; see Figures A.1 and A.2. Along with households, *Commercial road transportation* and *Other private services* are the largest users of own land transport.

[1] Included in the EU ETS from 2013.

Figure A.1: Input factors in the production process.

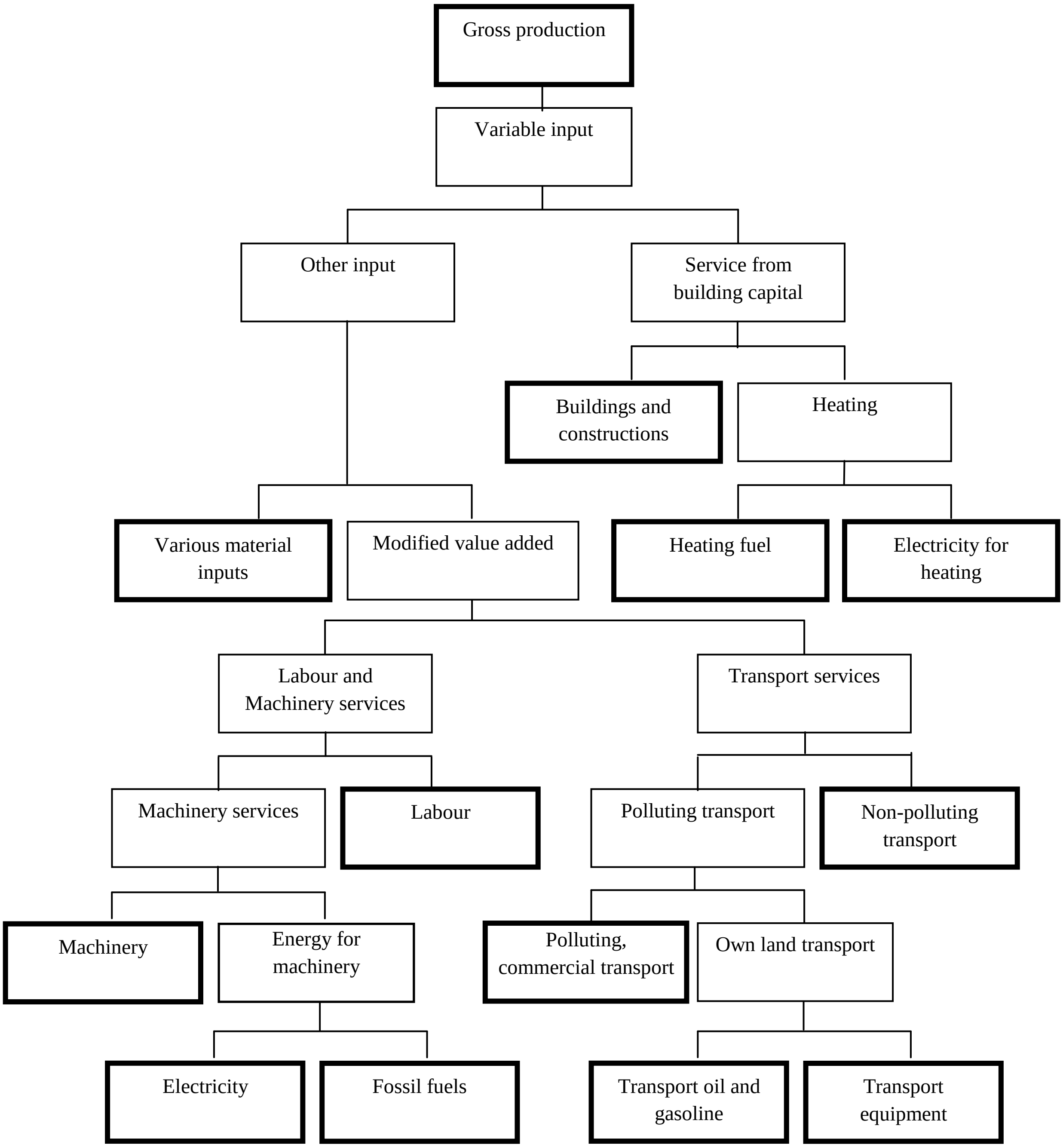

Figure A.2 Material consumption of households.