Working Paper 18/2015

Residential energy efficiency and European carbon policies

A CGE-analysis with bottom-up information on energy efficiency technologies

Brita Bye, Taran Fæhn and Orvika Rosnes

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-214-5
ISSN: 1892-9680
http://www.cree.uio.no

Abstract in Norwegian:

CREE - Working Paper 18/2015

Residential energy efficiency and European carbon policies

A CGE-analysis with bottom-up information on energy efficiency technologies

Brita Bye, Taran Fæhn and Orvika Rosnes

Sammendrag

Energieffektivisering i husholdningene ikke er god klimapolitikk, viser denne studien. Faktisk øker de samlede norske CO_2-utslippene om det settes et tak på husholdningenes energibruk eller energiintensitet.

Ambisiøse mål

Energieffektivisering står sentralt i EUs og Norges vei mot lavutslippssamfunnet. Norge har nylig knyttet sine klimaambisjoner til EUs 2030-målsettinger. Innen 2030 er EUs mål å:

- Redusere utslippene av klimagasser med 40 prosent i forhold til 1990-nivået
- Øke fornybarandelen i energibruk til 27 prosent
- Øke energieffektiviseringen med 27 prosent

Denne studien ser på virkninger av å gjennomføre energieffektiviseringsmål i norske husholdninger og hvordan dette samspiller med andre klimapolitiske mål og virkemidler. Foreløpig er ikke EUs målsetting om 27 prosents energieffektivisering blitt helt konkretisert. Derfor ser vi på to ulike mål for effektivisering av energibruken i boliger: et tak på energibruken og et tak på energiintensiteten, det vil si forholdet mellom bruken av energi i boligen og bruken av selve boligen. Husholdningene kan redusere *energiintensiteten* ved å investere i for eksempel bedre isolering eller nye vinduer. *Energibruken* kan også kuttes ved å redusere boligkonsumet, for eksempel flytte til nye boliger med mindre areal.

Ulike mål og virkemidler motvirker hverandre

For å nå de ambisiøse målene introduseres stadig nye virkemidler. Nyere studier finner at slike mål og virkemidler til dels overlapper og motvirker hverandre. Kunnskapen om samspillseffektene er fortsatt mangelfull, spesielt når det gjelder hvordan energieffektiviseringstiltak virker sammen med andre deler av energi- og klimapolitikken, slik som prising av CO_2-utslipp.

Studien viser at energieffektiviseringstiltak som skal gi energisparing er lite effektive som klimapolitikk i Norge: Faktisk øker de samlede CO_2-utslippene når det settes et tak på energibruken eller energiintensiteten i husholdningene. Dette skjer fordi husholdningenes energibruk i all hovedsak er elektrisitet. Når husholdningene bruker mindre elektrisitet, faller elektrisitetsprisene, og kraftkrevende industri med store prosessutslipp øker dermed sitt elektrisitetsforbruk. Også priser på andre innsatsfaktorer faller som følge av lavere etterspørsel etter flere varer og tjenester, og det kommer disse utslippsintensive bedriftene til gode. Jo strengere karbonpolitikken er, jo mer øker CO_2-utslippene som følge av energieffektiviseringspålegg.

Energibruket i resten av økonomien går opp

Studien tallfester også energisparingen i økonomien som helhet av å innføre tiltakene i husholdningene. Begrepet «rebound» brukes om effekter som motvirker den opprinnelige effekten av energieffektiviseringen. Beregningene våre anslår at økningen i industriens elektrisitetsforbruk bidrar til at rebound-effektene motvirker opp til 40 prosent av den opprinnelige energisparingen i husholdningene.

Kostbare tiltak

Et tak på energibruken er kostbart. Skulle de samme energibesparelsene i husholdningene bli oppnådd ved en avgift, ville den måttet ligge på rundt 200 prosent av elektrisitetsprisen. Det er vesentlig høyere enn dagens elavgift. Settes taket på energiintensiteten i husholdningene, blir velferdskostnadene, rebound-effektene og utslippene enda høyere, fordi ensidig reduksjon i boligkonsumet ikke vil bidra til å nå målet.

Metode

Studien bruker en numerisk generell likevektsmodell som gir en detaljert beskrivelse av samspillet mellom produsenter og forbrukere i norsk økonomi. Analyser av rebound-effekter ser gjerne på effekter av at utstyr og bygninger blir mer energieffektive uten at det gjør dem dyrere. Vår studie tar innover seg tilgjengelige anslag av hva slike energieffektiviseringstiltak koster i form av investeringer og driftsutgifter. Anslagene er basert på detaljert informasjon fra Institutt for Energiteknikk. Konklusjonene i studien avhenger av den valgte operasjonaliseringen av energieffektiviseringspolitikken som kan vise seg å få andre utfall enn vi har antatt. I tillegg er det stor usikkerhet knyttet til investeringskostnadene ved nye energieffektiviseringstiltak. Økt kunnskap om slike kostnader kan endre resultatene.

.

Brita Bye, Taran Fæhn and Orvika Rosnes

Residential energy efficiency and European carbon policies

A CGE-analysis with bottom-up information on energy efficiency technologies

Abstract:
While the introduction and reformation of climate policy instruments take place rapidly in Europe, the knowledge on how the instruments interact lags behind. In this paper we analyse different interpretations of the 2030 climate policy goals for residential energy efficiency and how they interact with targets for restricting CO_2 emissions. We focus on Norway, whose climate and energy policies are integrated with those of the EU. As we account for investment costs of improving energy efficiency we find substantial welfare costs of energy efficiency policies, particularly when interacting with carbon pricing. Rebound effects within households are small, but economy-wide indirect rebound is significant because energy-intensive, trade-exposed (EITE) industries expand. As residential energy use consists mainly of carbon-free electricity, this expansion of EITE-industries leads to increased total CO_2 emissions.

Keywords: Carbon policies, Energy efficiency policies, General Equilibrium analysis, Rebound effects

JEL classification: D58, Q43, Q48

Acknowledgements: Financial support from the European Community's Seventh Framework Programme, Project ENTRACTE (No 308481) is acknowledged. While carrying out this research, all the authors have been associated with CREE – Oslo Centre for Research on Environmentally Friendly Energy. CREE acknowledges financial support from the Research Council of Norway, University of Oslo and user partners.

Address: Brita Bye, Statistics Norway, Research Department. E-mail: Brita.Bye@ssb.no

Taran Fæhn, Statistics Norway, Research Department. E-mail: Taran.Faehn@ssb.no

Orvika Rosnes, Statistics Norway, Research Department. E-mail: Orvika.Rosnes@ssb.no

1 Introduction

Ambitious energy efficiency goals constitute an important part of the EU's road to a low carbon economy. The energy and decarbonisation ambitions are reflected in the Commission's Climate and Energy Policy Package for 2030 (EU, 2014). They include abating greenhouse gas emissions in 2030 by at least 40% from the 1990 level, raising the share of renewable energy to at least 27%, and increasing energy efficiency by at least 27% (EU, 2012). The 2030 ambitions are set as milestones on the path to the decarbonised 2050 economies of Europe, as expressed in the Roadmaps (EU, 2011a; EU, 2011b). Norway has recently launched its new climate policy goals for 2030 and beyond in line with the EU (Ministry of Climate and the Environment, 2015).

While the introduction and reformation of energy policy instruments take place rapidly, the knowledge of how several energy policy instruments and goals interact lags behind. Recent studies have revealed that the targets and policy instruments are partly overlapping and contradicting (Böhringer and Rosendahl, 2010; Huntington and Smith, 2011; Aune et al., 2012; Flues et al., 2014). The Energy Modelling Forum (EMF 25) study in the Energy Journal (Huntington and Smith, 2011) compares different kinds of energy efficiency policies and carbon policies to reduce emissions of climate gases. The main lessons learned from these studies are that carbon taxation is much more efficient to curb carbon emissions than energy efficiency policies, while the reduction in energy use is larger with energy efficiency measures compared to carbon taxation. With carbon taxation the possibility of substitution between fuels gives less reduction in energy use, but larger reduction in carbon emissions. However, the knowledge of energy efficiency policies interact with other instruments is still scarce (Oikonomou et al., 2008; Meran and Wittmann, 2012).

In this paper we analyse two issues: what is the effect of energy efficiency targets for residential energy use and how these targets interact with carbon policies. We scrutinise two different interpretations of the 2030 energy efficiency ambitions: a cap on residential energy use and a cap on residential energy intensity.[1] The main focus in our analysis is the so-called rebound effect, i.e., counteracting effects on energy use caused by energy efficiency efforts.

---

[1] Norwegian energy efficiency policies have so far been based on technology standards for buildings, subsidies for implementation of more efficient technologies, metering systems, energy labelling, and investment support (Ministry of Petroleum and Energy, 2012). The existing Norwegian tax on electricity use in households and some industries is mainly for fiscal purposes (Ministry of Finance, 2007).

Saunders (2015) recommends computable general equilibrium (CGE) models as the most suitable tool for studying rebound effects of energy efficiency policies, as they are able to take into account general productivity growth as well as various market interactions and rebound effects. By means of CGE analysis we consider rebound effects, economic welfare costs, as well as the effects on economy-wide CO_2 emissions.

The traditional approach in the literature analysing residential energy efficiency policies has been to increase energy efficiency exogenously, implying that energy efficiency policies make energy more productive in providing comfort and other services to the households; see e.g., Hanley et al. (2009) and McKibbin et al. (2011). A drawback with traditional energy efficiency studies is that the costs of obtaining the productivity rise are usually disregarded. In contrast, we implement energy efficiency policies as a cap on consumers' energy use and not as an exogenous increase in energy productivity.

Moreover, we account for investments in technological improvements as a response to policies. In traditional CGE models such investments are, in principle, captured by the substitutability between capital and energy: by investing in new buildings or equipment, the energy use can be reduced. As climate change and energy security have become increasingly important in the making of policies, the development of and investments in energy efficient technologies take place at much higher speed than previously, and policy intervention explains increasingly more of both energy and capital price dynamics. We believe that engineering experts' knowledge on immature or yet undeveloped technologies and their insight on probabilities, costs and potentials carry more relevant information than historical evidence (reflected in substitution elasticities estimated on time series data). Therefore, we combine an economy-wide perspective with bottom-up information on costs and potentials for investing in energy efficiency technologies in residential buildings. The modelling is based on detailed information of energy investment possibilities derived from the bottom-up model TIMES-Norway (Lind and Rosenberg, 2013; Rosenberg and Espegren, 2014).[2] A few previous CGE contributions have used such data for representing abatement costs of emissions to air, see e.g., Dellink (2005), Fæhn and Isaksen (2015) and Kiuila and Rutherford (2013).

The rebound literature (Saunders, 2000; Saunders 2015; Turner, 2009; Gillingham et al., 2013) often classifies the drivers of rebound of residential energy efficiency improvements along the following lines (see e.g. Turner (2009) for a comparable classification):

---

[2] This approach resembles the classical engineering approach to economic production functions (Chenery, 1949; Sav, 1984).

i) Pure efficiency effect – demand for energy is reduced as less physical energy is required to give a certain comfort level for the household;
ii) Direct price effect – as energy use in physical terms becomes more efficient, the effective price of energy is reduced and the demand for energy increases;
iii) Substitution effect – relative energy prices are changed and demand for the more efficient energy good will increase;
iv) Income effect – lower effective price on energy will give a positive income effect on all consumer goods and services;
v) Production and competition effects – energy intensive firms will benefit the most from lower market price on energy;
vi) Macroeconomic effects – price effects in the energy goods markets will influence the markets for all other goods and services, especially production and consumption of energy intensive goods. Interactions between supply and demand in several markets will determine the final effects on energy prices and demand for energy goods.

The direct price effect ii) and the substitution effect iii) are often called the direct rebound effects while the literature differs in what is called indirect rebound effects. For example Greening et al. (2000) include all income, costs, market and macroeconomic effects in the term indirect rebound effects.

The pure energy efficiency effect i) is present in our analysis, as well as the direct price effect ii), but with opposite sign than in the above-mentioned studies (because of the increased shadow price of the energy cap, in contrast to the effects of costless increases in energy efficiency). Since residential energy use is restricted – at a cost – in our analysis, the demand for other types of energy goods increases, which is the opposite of the substitution effect iii). The energy efficiency policies also have a negative effect on total consumer expenditure and the income effect iv) is negative. Lower residential demand for electricity gives a substantial fall in the market price of electricity, benefitting the energy intensive industries most. We find that the electricity rebound is 37-40% with our base assumptions.

The results of our analysis also confirm that instruments designed to save energy are ineffective in abating CO_2. Our results are even more pessimistic: Energy efficiency policies increase the CO_2 emissions and when applied simultaneously with carbon pricing, the problem is aggravated. The main explanation is the high share of electricity in total energy use. As only three per cent of the energy use in buildings (excl. industries) in Norway is based on fossil fuels (Ministry of Petroleum and Energy, 2009), the energy efficiency targets will primarily affect electricity use. As households reduce electricity use, energy-intensive trade-exposed (EITE) industries expand. Importantly, even if the energy use in the EITE industries is also primarily electricity, they have substantial process emissions. As opposed to most CGE studies, we account for such CO_2 emissions (other examples are e.g., Bednar-Friedl et al., 2012, and Fæhn and Isaksen, 2015).

The energy restrictions posed on households are costly: the shadow price corresponds to an equivalent tax of around 200%, depending on the policy design. In addition, welfare costs are reinforced as the expanding EITE industries are relatively unproductive. This arises from the relatively low carbon prices faced by the EU ETS emission sources compared to non-EU ETS emission sources, and also from other concessional terms enjoyed by the EITE industries. Moreover, a cap on energy intensity is a more stringent regulation than a cap on energy use, with higher welfare costs.

The paper is organized as follows. Section 2 gives a theoretical background for the energy efficiency policies and effects. Section 3 presents the computable general equilibrium model we use and the modelling of energy efficiency technologies. Numerical simulations of the policy alternatives are presented in section 4. Finally, section 5 concludes.

2 Theoretical background

We consider a representative consumer that maximizes the utility (H) of dwelling services (D) and energy (E) consumption

(1) $\mathrm{H} = \mathrm{u}(\mathrm{D}, \mathrm{E}), \qquad \mathrm{u}_{\mathrm{i}}' > 0, \mathrm{u}_{\mathrm{ii}}'' < 0,$

given the budget constraint

(2) $\mathrm{P^E E} + \mathrm{P^D D} = \mathrm{Y}$

$\mathrm{P^E}$ and $\mathrm{P^D}$ are the consumer prices on energy and dwelling services, respectively, which are exogenous for the consumer, and Y is income (equal to consumer expenditure). As a simplification we disregard consumption of all other goods.

We consider two different energy efficiency policies: i) a cap on energy use and ii) a cap on the energy/dwelling intensity. The caps, determined by $\alpha < 1$, are calculated relative to a baseline projection of energy and dwelling consumption, $\mathrm{E_{ref}}$ and $\left(\frac{\mathrm{E}}{\mathrm{D}}\right)_{\mathrm{ref}}$ respectively, that are treated as exogenous relative to the cap. The different policies are represented by the following constraints on energy use:

(3) $\mathrm{E} = \alpha \mathrm{E_{ref}}$

(4) $\frac{\mathrm{E}}{\mathrm{D}} = \alpha \left(\frac{\mathrm{E}}{\mathrm{D}}\right)_{\mathrm{ref}}$

The consumer maximizes utility with respect to dwelling services and energy consumption, given the budget constraint and either of the two energy efficiency policies. This gives the following first order conditions:

i) Cap on energy use (equation 3)

(5) $u'_E - \gamma P^E - \mu = 0$

(6) $u'_D - \gamma P^D = 0$

γ is the marginal utility of income (shadow price of the budget constraint in equation (2)) and μ is the shadow price of the energy efficiency cap. With no cap on energy use, μ is zero and the first order conditions in equations (5) and (6) are reduced to the standard result that the marginal utility of energy relative to the marginal utility of dwellings equals the relative price between energy and dwellings. For given consumer prices and income we have the following results: With a cap on energy use the consumption of energy will be lower than without any cap, see equation (5), while the consumption of dwelling services is independent of the cap, see equation (6).

ii) Cap on energy/dwelling intensity (equation 4)

(7) $u'_E - \gamma P^E - \mu \frac{1}{D} = 0$

(8) $u'_D - \gamma P^D - \mu \left(\frac{-E}{D^2}\right) = 0$

With a cap on the energy/dwelling intensity, represented by the last term on the left-hand side in equations (7) and (8), we see from equation (7) that energy consumption will be lower than without a cap, but larger than in the situation with an energy cap (as long as D>1), see equation (5). From equation (8) it follows that the first-order effects of a cap on the energy/dwelling intensity increase the consumption of dwelling services (the last term on the left-hand side is positive), compared to a situation with no cap.

In the numerical simulations presented in section 4 we analyse these policies using a CGE model with many markets and interaction effects. The energy efficiency policies will interact with the carbon price and energy goods prices through income and price effects that will generate economy-wide rebound effects that may counteract the first-order policy effects derived by this simplified model analyses. We calculate energy, emission and welfare effects in section 4.

3 The computable general equilibrium (CGE) model

3.1 Numerical model

We use a multi-sector CGE model for the Norwegian economy developed to analyse energy and environmental policies and strategies, SNOW-No[3] (Greaker and Rosnes, 2015). The model is developed in GAMS/MPSGE (GAMS, 2014; Rutherford, 1999).

Our model features a representative household that receives income from three primary factors: labour, capital and natural resources (fossil fuels). Labour and capital are mobile between sectors, while fossil fuel resources are specific to fossil fuel production. Total supply of labour and capital are given.

The production technologies of commodities are captured by nested constant elasticity of substitution (CES) cost functions; see Figures 1 and 2. For most commodities, the input shares of capital, labour, energy and intermediate products provided by other sectors are price dependent. For fossil fuels, all inputs except the sector-specific fossil fuel resource are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution.

We model CO_2 emissions from both energy use and industrial processes. Energy-related CO_2 emissions are linked in fixed proportions to the use of fossil fuels, with CO_2 coefficients differentiated by the specific carbon content of fuels. Abatement can take place by fuel switching, substitution of other goods for energy, or by scaling down production and/or final consumption. CO_2 emissions from industrial processes are linked to the output of the sector. Abatement of process emissions within existing production technologies can only take place by reducing production activities.[4]

Final consumption demand is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investments (a given demand for savings) and exogenous government provision of public goods and services. Total income of the representative agent consists of net factor income and tax revenues net of subsidies.

---

[3] SNoW-No: Statistics Norway's World model – Norway

[4] This assumption may be relaxed in the future with new carbon capture technologies.

Figure 1. Nested CES structure of production technology

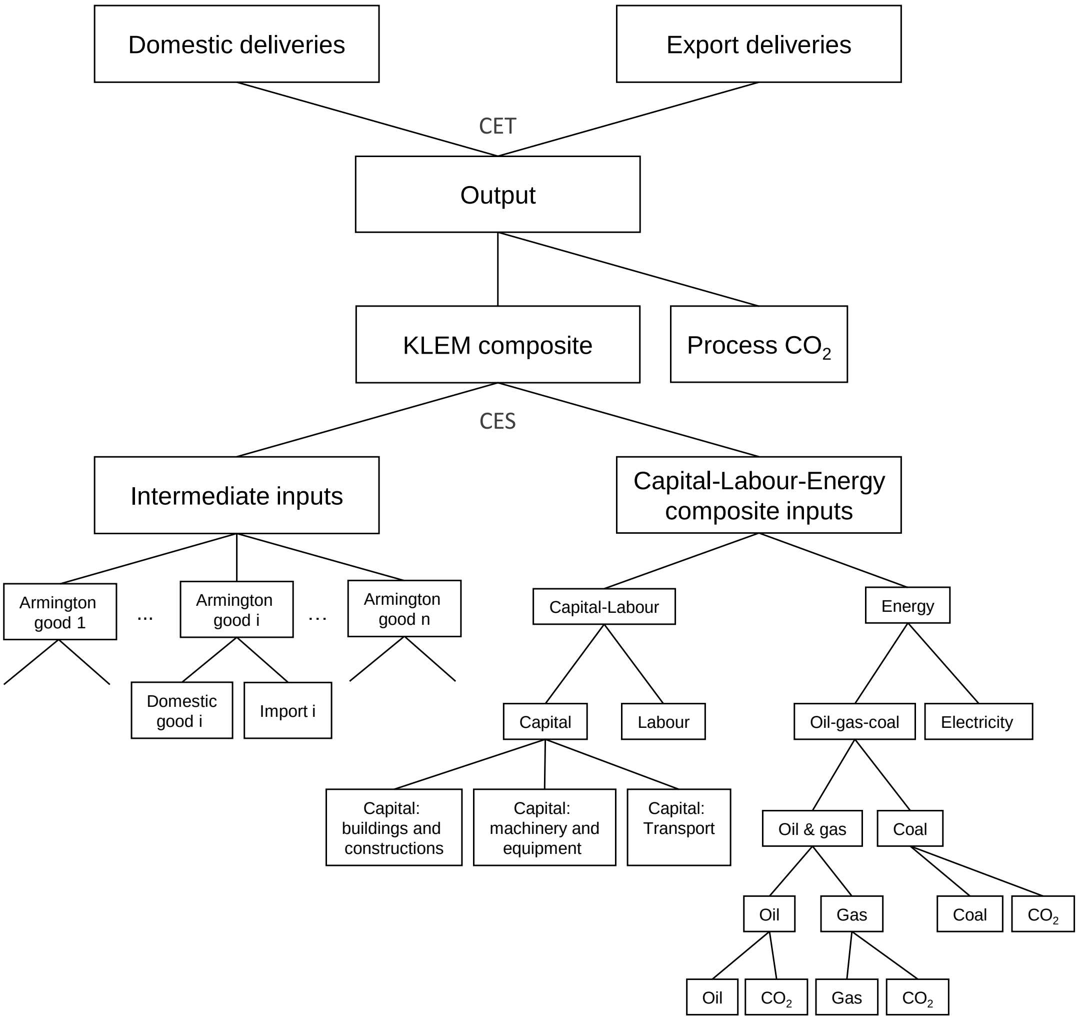
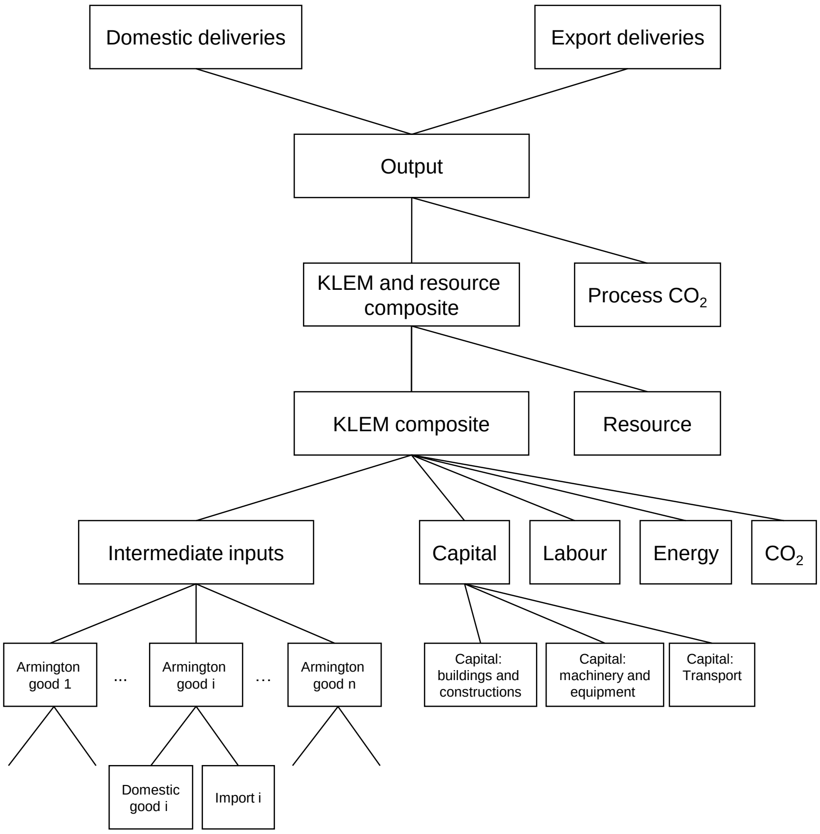
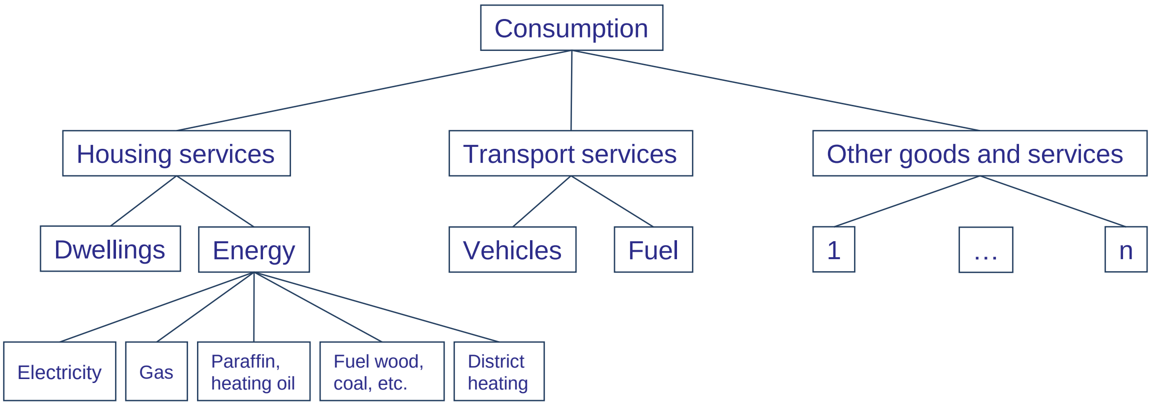


Figure 2. Nested CES structure of production technology for fossil fuel production



Consumption demand is represented by a three-level CES preference structure (see Figure 3). At the top level, aggregates of housing services, transport services and other goods are combined. At the second level, a CES function describes the substitution possibilities between dwellings and energy used in housing services; in the transport composite fuels and other transportation related goods are combined; and in the third composite all other goods and services are combined.

Figure 3. Nested CES structure of household consumption



We model a small open economy, and the rest of the world is exogenous (interest rate, world market prices etc). All goods used in the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported good from other regions (Armington, 1969). Export is determined by a constant elasticity of transformation (CET) function between domestic and export market deliveries. Factor prices and prices of deliveries domestically are all determined by domestic market equilibrium. Together with a given balance of payments, the real exchange rate that is consistent with domestic consumption will be determined (Horridge et al., 2013). The consumer price index is numeraire.

3.2 Modelling energy efficiency investments in housing

We combine the CGE model with detailed bottom-up data on potential technologies that are available to improve energy efficiency. As mentioned in the introduction, a few previous CGE contributions have used such data for representing abatement costs of emissions to air. Dellink (2005) introduces economy-wide abatement sectors for various emitted compounds. Fæhn and Isaksen (2015) model abatement of carbon emissions as a separate activity within each industry. Kiuila and Rutherford (2013) model abatement of CO_2 in private transportation and propose methods for modelling abatement as an activity within a CES structure, with the two substitutable inputs abatement capital and CO_2 emissions.

We apply a similar method as Kiuila and Rutherford (2013). However, our challenge is to include residential energy efficiency technology options. The analogue to Kiuila and Rutherford (2013) would be to include energy efficiency as a separate activity that has energy and energy efficiency equipment as substitutable inputs. However, our model already includes substitution possibilities between energy and dwelling capital in consumption, and modelling energy efficiency investments as a separate activity would lead to double-counting. Therefore, we exploit the CES composite of services from dwelling capital and energy use (see Figure 3) to account for energy efficiency options by calibrating a substitution elasticity that corresponds to technical energy efficiency data. We elaborate on the data, estimation and calibration of the substitutability in Section 3.3.

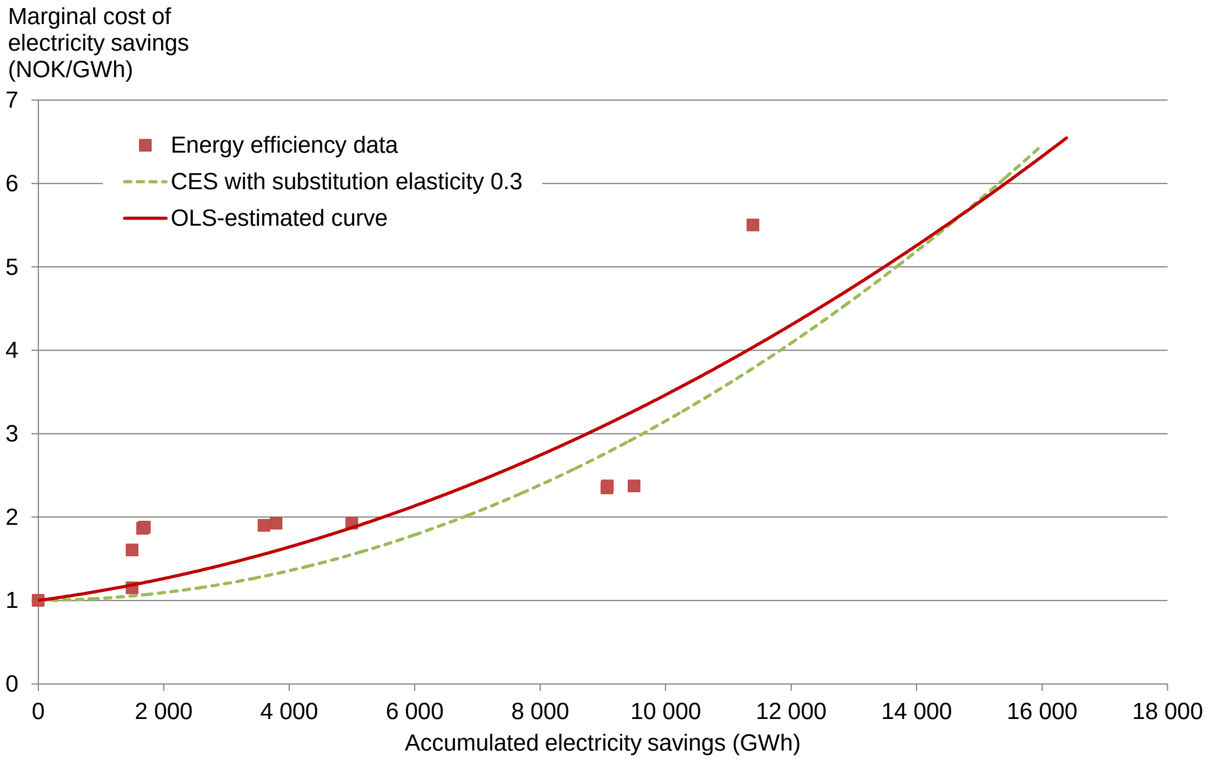
3.3. Data, estimation and calibration

Substitutability in housing services

The substitution elasticity between dwellings and energy in households is quantified in two steps. In the first step, we use Norwegian bottom-up data from Rosenberg and Espegren (2014) on energy efficiency costs and saving potentials of various measures available for households to estimate the marginal cost curve for energy efficiency improvements. Measures include information campaigns, monitoring equipment, rehabilitation and insulation of roofs, walls and floors, rehabilitation and replacement of outer doors and windows, new electric equipment and ventilators, and post-installation or integrated installation in new buildings of solar energy collectors. The costs include direct costs of purchase, installation and maintenance of the equipment, as well as the possible adjustments needed to keep the quality of the housing service unaltered. Total costs of energy efficiency efforts also account for the counteracting energy cost savings.

The dots depicted in Figure 4 reflect the data for each included measure, ranked according to costs (vertical axis). An OLS-estimated curve (second order polynomial) based on these data points constitutes a marginal cost curve for energy efficiency measures (the solid line). The cheaper measures include information campaigns, small-scale equipment and monitoring. In the upper part of the marginal cost curve are insulation and solar collecting projects. Accumulated energy saving potentials (for given levels of housing services) can be read along the horizontal axis.

Figure 4. Marginal costs of electricity savings and calibrated substitution



The second step is to calibrate the substitution between dwellings and energy that best fit the estimated OLS curve. The result is indicated by the dashed line in Figure 4 with a CES substitution elasticity of

0.3. The interpretation is that one per cent increase in dwelling capital gives energy savings of 0.3 per cent for a given level of the composite housing services (see Figure 3). The empirical literature is scarce on estimates of this substitution elasticity. Quigley and Rubinfeld (1989) estimate US annual rental value of housing in a demand system where dwelling comfort is a function of purchased energy and a vector of housing attributes consisting of heating systems, insulation, structures and the vintage of the building. Their constant elasticity of substitution estimate is 0.14, i.e., about half of that suggested by our estimate. This supports the hypothesis that the future technological potential as estimated on the most recent information is higher than estimations based on previous periods due to the rapid technological development taking place.

Some caveats of this method should be mentioned. First, the calibration relies on scarce, uncertain and subjective information and disregards some of the historical evidence. We explore the consequences by sensitivity analysis of the substitution elasticity; see Section 4.6. Further, Saunders (2015) questions whether CES is an appropriate functional form. At the outset, it would be better to use a more flexible functional form. The smoothed marginal cost curve presented in Figure 4 shows a fit with data of $R^2=0.62$.

A common challenge with the use of this kind of technical data is that several measures appear with negative costs; see for instance Hourcade et al. (2006) and Dellink (2005). When energy savings are included, several of the measures in Rosenberg and Espegren (2014) also come out with negative costs. In principle, at least three explanations for negative costs are possible. One is that these measures should be expected to be realised irrespective of energy efficiency policies and should be regarded as part of the baseline. The second is that cost components are left out of the calculations. A third is that there are market barriers to implementation, implying that while social costs are correctly negative, private costs are positive.[5] This calls for separate modelling of social and private costs and implies that targeted policies are necessary to overcome the market failures, see Florax et al. (2011). The explanation is crucial for how the negative costs should be treated. We rely on the first explanation and interpret all measures that would be profitable in the baseline as part of the baseline.[6] This applies to about half of the potential measures found in Rosenberg and Espegren (2014).

---

[5] Studies point to various barriers to energy efficiency investments, including imperfect information, credit rationing for the investors, lack of infrastructure, non-rational consumer choices, and learning externalities (Fleiter et al., 2011; Økstad et al., 2010; Giraudet et al., 2012). If these are market failures in an economic sense, so that private profitability is lower than social, policy responses are required (Florax et al., 2011). There are a number of second best policies (energy taxes, direct regulations like technology standards and caps on energy use, and subsidies to investments in new technologies etc.) that are available to deal with such imperfections.

[6] For a study exploring the last two explanations, see Giraudet et al. (2012).

Quantifying the rest of the model

The CGE model is calibrated to Norwegian National Accounts data for 2011. The dataset includes 41 industries, based on the standard GTAP classification (Narayanan et al., 2012), but adjusted to Norwegian data availability. The list of industries is included in Appendix A.

The energy goods comprise coal, crude oil, natural gas, refined oil products and electricity. In addition, the consumer can choose between the following sources for space heating: electricity, district heating, gas, paraffin and heating oil, coal, fuel wood and pellets. This disaggregation is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability. We distinguish between three commercial transportation sectors (air, water and land transport) as well as private transport. The main emission-intensive and trade-exposed (EITE) industries – pulp and paper industries, chemical products, non-metallic minerals, iron and steel products, non-ferrous metals – all form separate industries with different emission intensities. Process emissions from the EITE-industries, together with oil and gas extraction and transportation, are the main CO_2 sources in Norway, since electricity is produced mainly by hydropower.

The responses of agents to price changes are determined by a set of elasticities. Substitution elasticities in the nested CES structures for production technologies are based on econometric estimates in Andreassen and Bjertnæs (2006), Graham et al. (1999), Krichene (2002), in addition to other pertinent literature as collected in the GTAP database (Narayanan et al, 2012). In addition, the substitution elasticities in the consumer model are based on Bye et al. (2008). The only exception is the substitution elasticity between dwelling services and energy in the housing services aggregate that is calibrated, see above. The Constant Elasticity of Transformation between domestic sales and deliveries at the foreign market, and the Armington elasticities of substitution between domestic goods and imports are all set to 4, which is in the upper part of estimates (McDaniel and Balistreri, 2002) as this is most relevant for a small open economy as Norway.

4 Numerical analysis

4.1 The EU-2030-policy baseline

Our projection for 2030 is based on estimates for the Norwegian economy by Ministry of Finance (2013), but adjusted to account for the more recent decisions of EU's and Norway's 2030 climate policy targets.[7] Important drivers are growth rates for labour (0.7% p.a.) and capital (2% p.a.), together with technology-neutral efficiency improvements (0.6% p.a.).[8] In line with official projections, we adjust the resource base so that production of crude oil and natural gas are reduced by 25% compared to 2011, and adjust the exogenous balance of payment accordingly.

Recently, the Norwegian government decided to integrate its 2030 climate policy with the new targets of the EU (Ministry of Climate and the Environment, 2015). Norway is negotiating with the EU to be part of the flexible European burden-sharing agreement for non-EU ETS emissions. In addition, Norway will continue its participation in the EU ETS.[9] We base our estimates of the European 2030 carbon prices and energy prices on simulations from a European energy market study including the European 2030 targets (Aune et al., 2015). The EU ETS price increases to 37 EUR/ton CO_2 in order to meet the 43% emission reductions target. Since the Norwegian emissions form a small share of the EU ETS this price is treated as exogenous. Regarding the carbon price in the sectors outside EU ETS, the terms for Norway are not settled yet. If we assume full flexibility within the non-EU ETS sectors across borders, all non-EU ETS sources will face the same EU-wide carbon price. We use this assumption. The 30% emission reduction target for the non-EU ETS sectors then yields a price of 230 EUR/ton CO_2.

The European electricity price increases by 3.7% p.a. (Aune et al., 2015). It influences the electricity price in Norway, since differences between the domestic and European prices may occur due to transmission capacity limits. Domestic electricity production is limited upwards (but not downwards) due to limited availability of suitable renewable projects. Other world market prices are assumed to increase by 1.8% p.a. from 2011 with the following exceptions for particularly trade-exposed and carbon-policy affected goods: crude oil and natural gas (0.9% p.a.), non-ferrous metals (1% p.a.), iron and steel (1.7% p.a.), chemical products (1.2% p.a.), and non-metallic minerals (1.7% p.a.).[10]

Norwegian CO_2 emissions reach 50.3 million tons in 2030. This corresponds to an annual increase of 0.7% from 2011. 56% of the emissions originate from the ETS sources and 44% from the rest of the economy.

---

[7] In Section 4.5 we also construct a baseline in a regime without the new 2030 targets in order to isolate the effects of the carbon policy from the energy efficiency policy.

[8] In the case of residential energy use this adjustment accounts for the inclusion of energy efficiency measures that become profitable without additional policy incentives.

[9] No decisions are taken yet regarding renewable energy targets in Norway or in the EU. Hence, we disregard renewable targets of the EU and Norway in our scenarios.

[10] All these world market price projections are based on Ministry of Finance (2013).

4.2 Energy efficiency policy scenarios

The Norwegian energy efficiency targets for 2030 are not settled yet. In this study we base the policy assumptions on the proposals of the European Commission, as Norway traditionally follows the EU climate policies closely even when there are no legal obligations to do so in the EEA legislation. The Commission (EU, 2014) proposed a 30% energy savings target for 2030, following a review of the Energy Efficiency Directive (EU, 2012). The European Council, however, endorsed an indicative target of 27% to be reviewed in 2020 having in mind a 30% reduction target.

In our energy efficiency policy scenarios we only consider Norwegian targets. Furthermore, we restrict the focus to policies in the residential sector.[11] Since such targets are far from settled yet, we have interpreted the political signals in two different ways: either as a cap corresponding to 27% reduction in residential energy use or as a 27% cap on residential energy intensity, both relative to a 2030 baseline. We start by analysing the cap on energy use in section 4.3, before we compare the two alternative energy efficiency policies in section 4.4. In section 4.5 we discuss the interaction between carbon policies and the residential energy efficiency policies, while section 4.6 presents a sensitivity analysis.

4.3 Cap on energy use

Costs

Economic welfare measured by Equivalent Variation (EV) drops by 1.0% compared to the baseline as a result of the 27% cap on residential energy consumption; see Table 1, first column of results. These costs reflect first of all the costs directly borne by the households because of the energy use restriction. They are represented by the high shadow price of the energy cap. The shadow price corresponds to an equivalent energy tax of 175%, i.e. nearly a tripling of the energy price (see Table 1)

The shadow price depends on the extent to which the households are able to reduce their energy use by investing in energy efficient equipment that can provide them with the same utility of housing services with less energy input. We find that such substitution, in isolation, leads to a 3.2% increase in dwelling investments. However, the cost of housing services increases sharply due to the energy cap and both substitution and income effects result in *lower* demand for housing services and lower demand for dwellings, i.e. consumers choose less valuable houses (move or rent out parts of their houses). The

---

[11] EU has different targets for energy efficiency in the transport sector, especially related to CO_2 (EU, 2012). These measures are quite different from the kind of policies we are focusing on in this paper. We leave this for future research.

demand for dwellings drops by 3.2% in the new equilibrium; see Table 1. Along with the 27% cap on residential energy use, the result is a fall in the utility of housing services of 5.8%.

As a consequence of lower electricity demand by households, the domestic electricity price falls. This, along with lower labour and capital prices caused by reduced demand for dwellings, reallocates resources to other parts of the economy, primarily to the EITE industries. This increases the welfare costs, due to the fact that the EITE industries are leniently taxed initially. They have lower payroll tax rates and lower carbon prices than the non-EU ETS sources. These tax wedges imply that reallocation of resources to the EITE industries contributes negatively to welfare.

On the other hand, two other effects contribute positively to welfare: First, dwellings are leniently taxed in Norway (Bye and Åvitsland, 2003) and lower consumption of housing services (including dwellings) increases efficiency. Second, as housing demand drops, consumption is diverted towards more transport activities. These are highly taxed initially (both for environmental and fiscal reasons) and welfare effect of this reallocation is, therefore, positive.

Table 1. Results of energy efficiency policies. Percentage change from the respective baseline

	High carbon pricing regime (EU 2030 policy)		**Low carbon pricing regime**	
	Energy use cap	**Energy intensity cap**	**Energy use cap**	**Energy intensity cap**
Economic indicators:				
Welfare	-1.0	-1.3	-0.9	-1.1
Utility of Housing services*	-5.8	-6.5	5.9	6.6
Utility of Dwellings*	-3.2	-3.8	-3.1	-4.6
Utility of Energy use in housing*	-27.0	-29.7	-27.0	-29.6
Production (GDP)	0.0	0.1	0.0	0.0
Production in EITE-industries	15.0	18.6	10.9	12.8
Prices:				
Real electricity price	-15.5	-17.5	-10.5	-11.9
Real wage rate	-5.7	-6.4	-5.4	-6.2
Real rental rate	-7.5	-8.6	-7.0	-8.1
Shadow price of energy efficiency cap (rate)**	175	210	164	194

* The table reports values of the housing composite and its components; see Figure 3.

** The shadow price is measured as the necessary tax rate to reach the cap (on energy use in housing or energy intensity).

Energy use, rebound effects and CO_2 emissions

Since more than 90% of residential energy use in the baseline is electricity, we restrict the rebound analysis to electricity rebound. Electricity rebound is calculated as the increase in electricity use in the rest of the economy divided by the fall in residential electricity use.

The cap on residential *energy* consumption corresponds to a 26.7% drop in household *electricity* use from the baseline; see first column of results in Table 2. There is no direct electricity rebound in household consumption, but substantial indirect rebound effects (substitution, market and competitiveness effects, as explained in the introduction) that follow the fall of the domestic electricity price. These are especially pronounced in the EITE industries, which are also stimulated by the labour and capital price reductions. Eventually, electricity use in the EITE industries increases by 35.2%, while electricity use in the economy as a whole is reduced by 9.0%, since other industries than the EITE increase electricity use by 4.7% (Table 2). This corresponds to an economy-wide rebound effect of 37% from the initial electricity demand reduction in households.

As only a small share of energy use in housing services consists of fossil fuels, the direct reduction in CO_2 emissions from residential energy is small; see Table 2. The households reallocate consumption to other goods and services, and the subsequent transport increase by households causes a small increase of CO_2 emissions. The largest CO_2 effect is seen in EITE industries, which increase their process emissions by 1.7 million tons. All in all, domestic CO_2 emissions increase by 1.2 million tons, or 2.4% from the baseline.

Table 2. Results of energy efficiency policies: Change from baseline in electricity use and CO_2 emissions

	High carbon pricing regime (EU 2030 policy)		**Low carbon pricing regime**	
	Energy use cap	**Energy intensity cap**	**Energy use cap**	**Energy intensity cap**
Electricity use, mill. 2011-NOK and (%)				
Households	-2.3 (-27%)	-2.6 (-29%)	-2.4 (-27%)	-2.6 (-30%)
EITE industries	0.6 (35%)	0.7 (44%)	0.4 (17%)	0.5 (20%)
Other	0.3 (5%)	0.3 (5%)	0.1 (2%)	0.2 (3%)
Total	**-1.5 (-9%)**	**-1.5 (-9%)**	**-1.8 (-10%)**	**-2.0 (-11%)**
Total rebound (%)	37 %	40 %	23 %	25 %
CO_2 emissions, mill. tons				
Households, residential	-0.2	-0.3	-0.3	-0.3
Households, transportation	0.1	0.1	0.3	0.3
EITE industries	1.7	2.1	1.2	1.4
Other	-0.3	-0.4	0.0	0.0
Total	**1.2**	**1.6**	**1.2**	**1.4**
Total CO_2 emissions (%)	2.4	3.1	1.8	2.1

4.4 Cap on energy use vs. cap on energy intensity

Welfare costs are higher with the energy intensity cap than with the cap on energy use; see Table 1 (second column of results). The energy intensity cap of 27% leads to a fall in residential energy use of 29.7%. In other words, the energy intensity cap is stricter and equivalent to a cap on energy use of 29.7%. Thus, the cost effects for households are more pronounced. This is mirrored in a higher shadow price on the cap: the shadow price now corresponds to a 210% tax on residential energy use (Table 1). Lower residential electricity demand leads to a larger drop in the domestic electricity price. From the theoretical model in section 2 it follows that the first-order effect on residential energy demand of both types of energy efficiency policies is negative compared to a situation without any policies, while the first-order effect on demand for dwellings is unaltered with a cap on energy use and positive with a cap on energy intensity. These results are confirmed by the numerical simulations for the use of energy. But, as the numerical model also accounts for composition, price and income effects, demand for dwellings falls in both policy cases, though less so when the use, rather than the intensity, is capped; see Table 1. The drops in electricity, capital and labour prices are larger and reallocations to the EITE production more pronounced. Compared to a cap on residential energy use, total welfare and income fall more.

Residential electricity demand falls more with a cap on energy intensity (29.4%, Table 2). The reallocation to the EITE industries cause slightly larger indirect electricity rebound effects (substitution, market and competitiveness effects) amounting to 40% of the initial electricity cut of households.

Th**e** use of transport fuels in the households is not much affected by the nature of the energy cap. However, the total CO_2 emissions increase by 1.6 million ton or by 3.1% as opposed to the 2.4% increase in the case with a cap on energy use, see Table 2.[12] This is mainly explained by larger process emissions of CO_2 from the EITE industries.

4.5 Interaction between energy efficiency policies and carbon policy

In order to identify the impact of the interaction between energy efficiency policies and carbon policies, we have simulated the same energy efficiency reforms in another regime with low carbon prices, i.e., without taking into account the recent EU and Norwegian 2030 climate policy decisions. This low carbon pricing regime is based on what were the adopted or announced forthcoming climate policies in 2011. In the non-EU ETS sectors, carbon tax rates are retained at today’s level (20-40 EUR/ton CO_2 in real terms). Since 2008, Norway has been part of the EU ETS and here we follow the Ministry of Finance (2013) projection of a relatively low allowance price of 20 EUR/ton in 2030. Due to lower carbon prices in 2030, compared to in the main regime analysed above, international commodity prices are lower as well. Following Ministry of Finance (2013), the electricity price is 10%

---

[12] However, increased domestic EITE production will probably give less leakage of carbon emissions to other countries. Thus, in a global perspective the national effects will be counteracted.

lower, while international prices of EITE industries are between 0.5 and 1.5% lower in 2030 than in the main regime. This is due to lower prices in the EU, with which about 85% of Norway's international trade in EITE goods takes place. However, since prices in the rest of the world remain unchanged, the competitiveness of Norwegian firms increases slightly. With lower carbon prices, lower electricity prices and better competitiveness for EITE industries, Norwegian emissions are 28% higher in this regime (before energy efficiency policies are introduced) than in the main baseline where we have high carbon price.

Comparing the results of the energy efficiency policies in this low carbon price regime with the results from the analysis above (EU 2030 policy, i.e., high carbon pricing regime) identifies the interaction effects of the energy efficiency policies with the 2030 carbon pricing policies. Both sets of results are presented in Table 1 and Table 2.

The welfare costs of introducing energy efficiency policies are higher with high carbon pricing (EU 2030 policy regime). It is less attractive to substitute fossil fuels for electricity in households when the carbon price is high. This is reflected in higher shadow prices of the energy efficiency caps and a larger electricity price fall. The EITE industries expand more, and since the relative difference between their CO_2 price and that of non-EU ETS industries is more exacerbated, this implies higher welfare costs. So does a smaller increase in transportation (which is indicated in Table 2 as a smaller increase in the CO_2 emissions).

We also observe that the electricity rebound is higher when energy efficiency policies interact with a high carbon price, see Table 2. With the energy use cap the electricity rebound is 14 percentage points higher, and 15 percentage points higher with energy intensity cap. Energy prices (especially the electricity price) fall more as a consequence of the households' more cautious energy use. This reinforces the reallocation of energy and other resources to the EITE industries. In the high carbon policy regime, thus, domestic emissions increase more in the wake of the energy efficiency policies towards households than if the 2030 carbon policy were not in place.

4.6 Sensitivity analysis

We have analysed the importance of substitution possibilities in housing services. Table 3 presents the results of a cap on energy use in two additional cases: when the substitution elasticity in housing services is zero and when it is doubled from the base assumption of 0.3 to 0.6.[13]

---

[13] Qualitative effects are similar with an energy intensity cap.

A substitution elasticity of zero can be interpreted as a situation with prohibitively high investment costs, implying that residential energy can only be saved by cutting back on consumption of housing services. Thus, demand for dwellings drops by 27% and consumption shares of other goods and services increase. Final demand is shifted more markedly towards services and transportation, and we find a corresponding reallocation of industrial factor use. In particular, compared to the main case the expansion of the EITE industries is smaller; see Table 3.

The lack of technological options increases the shadow price of the cap significantly compared to the main case with substitution elasticity of 0.3. This is the main explanation for the substantially higher welfare cost. Welfare is also affected by interaction effects with existing price wedges. Smaller expansion of the EITE industries, substantially lower demand for dwelling services and stronger demand for transport services are reallocations that modify the welfare costs. We also find a smaller economy-wide electricity rebound in this case, reflecting first of all a much weaker electricity demand from the EITE industries than in the main scenarios.

When the substitution elasticity is doubled from 0.3 to 0.6, the shadow price of the energy efficiency policies is brought down. As a result of larger investments in energy-efficient dwellings and modified composition and income effects of the policies, the demand for dwellings increases. The lower shadow price of the cap when substitutability is doubled implies a smaller welfare loss. However, the economy-wide electricity rebound increases to 62% and the rise in CO_2 emissions doubles. Both these implications are explained by a larger EITE expansion.

Table 3. Sensitivity analysis: Effects of cap on energy use with different substitution elasticities in housing services. Percentage change from respective baselines

	Low elasticity (0)	Base elasticity (0.3)	High elasticity (0.6)
Economic indicators:			
Welfare	-2.3	-0.9	-0.6
Dwellings	-27.0	-3.2	1.7
Residential energy use	-27.0	-27.0	-27.0
EITE production	5.3	15.0	24.6
Prices:			
Electricity price	-22.4	-15.5	-13.4
Real wage rate	-16.0	-5.7	-2.3
Real rental rate	-25.2	-7.5	-1.8
Shadow price of energy cap (rate)*	421	175	95
Emissions and rebound effects:			
Total CO_2-emissions	0.3	2.4	4.7
Electricity rebound	17 %	37 %	62 %

* Shadow price is measured as the necessary tax rate to reach the cap.

5 Concluding remarks

A well-known result from studies of climate policies is that instruments designed to save energy are inefficient in abating CO_2. Our results are even more pessimistic: Energy efficiency policies increase CO_2 emissions, and simultaneously introducing carbon pricing only aggravates the problem. The main explanation is the high share of electricity in total energy use in Norway. Energy use in dwellings is almost entirely based on electricity. As households reduce electricity demand, energy-intensive and trade-exposed industries (the EITE industries) can access electricity and other resources at lower prices. Rebound effects within households are small, but economy-wide, indirect rebound is significant because the EITE industries expand. The economy-wide rebound effect is in the middle of previous findings (Gillingham et al., 2013).

These effects would have been dampened if energy efficiency policies were applied to all energy users in the economy. However, since the EITE industries have large process emissions of CO_2 that are independent of energy use, extending the energy efficiency policies to all energy use would improve, but probably not remove the adverse emission impacts. The effect will depend on the substitution possibilities between electricity and fossil fuels in the EITE industries.

Capping energy intensity rather than energy use increases the stringency of the policies and welfare costs are therefore higher in that case. The costs of the reforms are also reinforced as the EITE industries are relatively unproductive and expand more. This arises from the relatively low carbon prices faced by the EU ETS emission sources, and also from other concessional terms enjoyed by the EITE industries, like lenient rates of electricity and payroll taxes.

We combine the CGE analysis with available, case-relevant bottom-up information on energy-saving investment costs. The bottom up information contains anticipated future costs and potentials of available technological adaptations. It is important to emphasise the uncertainty of this information. The calibration to experts' guesstimates sets aside evidence from previous experience and relies on scarce and subjective information. The potential benefit is that we capture recent indications on future development trends in energy technologies. In CGE contexts, the more common representation of energy efficiency improvements is as free, autonomous productivity parameter shifts. We find it pivotal to account for the costs of such productivity achievements. The sensitivity analysis shows that increasing the substitution elasticity increases rebound effects of both electricity and fossil fuels. As higher substitutability reduces the costs of energy efficiency investments, this sensitivity analysis approaches the assumption made in previous CGE studies of costless energy efficiency improvements.

When accounting for costs of investing in energy efficiency, both price and income effects restrict consumption of other energy and energy-based goods, indicating too large rebound estimates in previous literature assuming autonomous energy efficiency improvements.

Our conclusions hinge on the operationalization we have chosen of the energy efficiency policies. The benchmarking, the targets, the extension and the timing are all elements to be determined in forthcoming political processes. However, this is not an argument for postponing analyses until policies are settled. On the contrary, ex ante knowledge of alternative policy designs is valuable input to such processes.

Bottom-up information of energy efficiency tends to include potential measures with costs below zero. We have interpreted these as projects that will be realized along the baseline scenario without additional policy measures. However, if there are some kinds of market barriers to energy efficiency investments like imperfect information, credit rationing for the investors, lack of infrastructure or learning externalities, the modelling should rather reflect the negative costs as private costs exceeding social costs. This could possibly alter the results and policy implications.

The inclusion of residential energy efficiency investment costs is a first step towards including new abatement options. Extending this approach to other energy use and to abatement options not linked to energy efficiency improvements would give a more complete representation of costs, rebound effects, carbon emissions and interaction among policy targets and policy instruments.

References

Andreassen, L. and G. H. Bjertnæs (2006): Tallfesting av faktoretterspørsel i MSG6 (Quantifying demand for inputs in the MSG6 model). Notater 2006/7, Statistics Norway.

Armington, P.S. (1969): A Theory of Demand for Producers Distinguished by Place of Production. IMF Staff Papers 16(1), 159–78.

Aune, F.R, H.M. Dalen, and C. Hagem (2012): Implementing the EU renewable target through green certificate markets. Energy Economics 34, 992–1000.

Aune, F.R, R. Golombek and H.H. Le Tissier (2015): Phasing out nuclear power in Europe. CREE Working Paper 05/2015, Oslo, Norway.

Bednar-Friedl, B., T. Schinko and K.W. Steininger (2012): The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment. Energy Economics 34, 168–180.

Bye, B., T. Fæhn, T.R. Heggedal, K. Jacobsen, B. Strøm (2008): An innovation and climate policy model with factor-biased technological change: A small, open economy approach. Reports 2008/22, Statistics Norway.

Bye, B. and T. Åvitsland (2003): The welfare effects of housing taxation in a distorted economy: a general equilibrium analysis. Economic Modelling 20, 895–921.

Böhringer, C. and K. E. Rosendahl (2010): Green Promotes the Dirtiest: On the Interaction between Black and Green Quotas in Energy Markets. Journal of Regulatory Economics, 37 (3), 316–25.

Chenery, H. B. (1949): Engineering production functions. Quarterly Journal of Economics 63, 507–31.

Dellink, R. B. (2005): “Modelling the Costs of Environmental Policy: A Dynamic Applied General Equilibrium Assessment”. New horizons in environmental economics, Edward Elgar Publishing, Cheltenham UK and Northhampton MA, USA.

EU (2011a): Communication from the European Commission. A Roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112

EU (2011b): Communication from the European Commission. Energy Roadmap 2050. COM(2011) 885

EU (2012): Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency.

EU (2014): Climate and Energy Policy Package for 2030 (http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm)

Fleiter, T., E. Worrell, W. Eichhammer (2011): Barriers to energy efficiency in industrial bottom-up energy demand models—A review. Renewable and Sustainable Energy Reviews 15, 3099–3111.

Florax R.J.G.M, H.L.F. de Groot and P. Mulder (eds.) (2011): “Improving Energy Efficiency through Technology: Trends, Investment Behaviour and Policy Design”. Edward Elgar Publishing, Cheltenham UK and Northhampton MA, USA.

Flues F., A. Löschel, B.J. Lutz and O. Schenker (2014): Designing an EU energy and climate policy portfolio for 2030: Implications of overlapping regulation under different levels of electricity demand. Energy Policy 75, 91–99.

Fæhn, T. and E.T. Isaksen (forthcoming): Diffusion of climate technologies in the presence of commitment problems. Forthcoming in Energy Journal, http://dx.doi.org/10.5547/01956574.37.2.tfae

GAMS (2014): GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 24.4.3. Washington, DC, USA, 2014.

Gillingham, K., M.J. Kotchen, D.S. Rapson, G. Wagner (2013): The rebound effect is overplayed. Nature 493, 475–476.

Giraudet, L.-G., C. Guivarch and P. Quirion (2012): Exploring the potential for energy conservation in French households through hybrid modeling, Energy Economics 34, 426–445.

Graham, P., S. Thorpe, L. Hogan (1999): Non-competitive market behaviour in the international coking coal market. Energy Economics 21, 195–212.

Greaker, M. and O. Rosnes (2015): Robuste norske klimamålsetninger (Robust Norwegian climate goals). Samfunnsøkonomen nr. 1-2015, 67–77.

Greening, L.A, D.L. Greene, C. Difiglio (2000): Energy effiency and consumption – the rebound effect – a survey. Energy Policy 28, 389–401.

Hanley, N., P.G. McGregor, J.K. Swales, K. Turner (2009): Do increases in energy efficiency improve environmental quality and sustainability? Ecological Economics 68, 692–709.

Horridge, M., A. Meeraus, K. Pearson and T.F. Rutherford (2013): Solution Software for Computable General Equilibrium Modeling. Chapter 20 in Dixon, P.B. and D.W. Jorgenson (eds.) "Handbook of Computable General Equilibrium Modeling" Vol. 1B, Elsevier.

Hourcade, J.-C., M. Jaccard, C. Bataille, F. Ghersi (2006): Hybrid modeling: New answers to old challenges. The Energy Journal 27 (Special issue 2), 1–12.

Huntington, H. and E. Smith (eds.) (2011): Strategies for Mitigating Climate Change through Energy Efficiency: A Multi-Model Perspective. The Energy Journal 32 (Special Issue 1).

Kiuila, O. and T.F. Rutherford (2013): The cost of reducing CO_2 emissions: Integrating abatement technologies into economic modelling. Ecological Economics 87, 62–71.

Krichene, N. (2002): World crude oil and natural gas: a demand and supply model. Energy Economics 24, 557–576.

Lind, A. and E. Rosenberg (2013): TIMES-Norway Model Documentation, IFE/KR/E-2013/001, Kjeller, Norway.

McDaniel, C.A. and E.J. Balistreri (2002): A Discussion on Armington Trade Substitution Elasticities. Office of Economics Working Paper No. 2002-01-A, U.S. International Trade Commission, Washington, DC, USA

McKibbin, W.J., A.C. Morris, and P.J. Wilcoxen (2011): Subsidizing Household Capital: How Does Energy Efficiency Policy Compare to a Carbon Tax? The Energy Journal 32 (Special Issue 1), 111–127.

Meran, G. and N. Wittmann (2012): Green, Brown, and Now White Certificates: Are Three One Too Many? A Micro-Model of Market Interaction. Environmental and Resource Economics 53, 507–532.

Ministry of Climate and the Environment (2015): Ny utslippsforpliktelse for 2030 – en felles løsning med EU (New reduction commitments for 2030 – a common solution with the EU), Meld. St. 13 (2014-2015) (White paper).

Ministry of Finance (2007): En vurdering av særavgiftene. NOU 2007:8.

Ministry of Finance (2013): Perspektivmeldingen 2013 (Long-term perspectives on the Norwegian Economy 2013). Meld. St. 12 (2012-2013) (White Paper).

Ministry of Petroleum and Energy (2009): Energieffektivisering. Del 1 Hovedrapport. Lavenergiutvalget.

Ministry of Petroleum and Energy (2012): Energiutredningen – verdiskaping, forsyningssikkerhet og miljø. NOU 2012:9.

Narayanan, G.B., A. Aguiar, R. McDougall (2012): Global Trade, Assistance, and Production: The GTAP 8 Data Base. Center for Global Trade Analysis, Purdue University.

Oikonomou, V., C. Jepma, F. Becchis and D. Russolillo (2008): White Certificates for energy efficiency improvement with energy taxes: A theoretical economic model. Energy Economics 30, 3044–3062.

Quigley, J. M. and D. L. Rubinfeld (1989): Unobservables in Consumer Choice: Residential Energy and the Demand for Comfort. Review of Economics and Statistics 71, 416–25

Rosenberg, E. and K.A. Espegren (2014): CenSES energiframskrivinger mot 2050. Institutt for energiteknikk. IFE/KR/E-2014/003.

Rutherford, T.F. (1999): Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax. Computational Economics 14, 1–46.

Saunders, H. D. (2000): A view from the macro side: rebound, backfire, and Khazzoom-Brookes. Energy Policy 28, 439–449.

Saunders, H. D. (2015): Recent evidence for large rebound: elucidating the drivers and their implications for climate change models. The Energy Journal 36, 23–48.

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

Turner, K. (2009): Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Economics 31, 648–666.

Økstad, E., L.P. Bingh, B.A. Christensen, G. Sørmo, B. Strøm, N. Hallenstvedt, K. Grjotheim, (2010): Tiltak og virkemidler for å redusere klimagassutslipp fra norsk industri. TA 2594, Klima- og forurensningsdirektoratet, Oslo, Norway.

Appendix A: The numerical model

Table A1. List of industries in the model

Industry	Code
Agriculture	AGR
Forestry	FRS
Fishing	FSH
Coal	COA
Oil & gas	CRU
Minerals n.e.c.	OMN
Food products – meat	MEA
Vegetable oils and fats	VOL
Dairy products	MIL
Food products n.e.c.	OFD
Beverages and tobacco products	B_T
Textiles	TEX
Wearing apparel	WAP
Leather products	LEA
Wood products	LUM
Paper products, publishing	PPP*
Petroleum, coal products	OIL
Chemical, rubber, plastic products	CRP*
Mineral products n.e.c.	NMM*
Ferrous metals	I_S*
Metals n.e.c.	NFM*
Metal products	FMP
Motor vehicles and parts	MVH
Transport equipment n.e.c.	OTN
Machinery and equipment, incl. electronic equipment	MEE
Manufactures n.e.c.	OMF
Electricity	ELE
Gas manufacture, distribution	GAS
Water	WTR
Construction	CNS
Trade	TRD
Transport n.e.c.	OTP
Water transport	WTP
Air transport	ATP
Communication	CMN
Financial services n.e.c.	OFI
Insurance	ISR
Business services n.e.c.	OBS
Recreational and other services	ROS
Public Administration, Defense, Education, Health	OSG
Dwellings	DWE

* Energy-intensive trade-exposed (EITE) industries

Table A2. List of consumption goods in the model

Food and non-alcoholic beverages
Alcoholic beverages and tobacco etc.
Clothing and footwear
Dwellings
Heating: Electricity
Heating: Gas
Heating: Paraffin and heating oil
Heating: Fuel wood, coal etc.
Heating: District heating
Furnishings, household equipment and routine household maintenance
Health
Transport: Transportation services excl. fuel
Transport: Fuel
Communication
Recreation and culture
Education
Restaurants and hotels
Miscellaneous goods and services