Energy technology and energy economics:

Analyses of energy efficiency policy in two different model traditions

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Energiteknologi og energiøkonomi: Analyser av energipolitikk i to ulike modelltradisjoner

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For studier av energi- og klimapolitikk er modeller nyttige og utbredte verktøy både i teknologi- og økonomifaget. Denne artikkelen tar utgangspunkt i et samarbeid mellom teknologer og økonomer som har hver sin modelltradisjon, selv om de over tid har tatt innover seg mange trekk fra hverandres fag. Ved bruk av en modell fra hver tradisjon får vi fram ulike historier om hva som skjer som følge av et krav om redusert energibruk i husholdningene. Analysen viser behovet for å belyse effekter av energipolitikken fra flere vinkler når viktige politiske beslutninger skal tas.

Energy technology and energy economics: Analyses of energy efficiency policy in two different model traditions

Brita Bye[a], Kari Espegren[b], Taran Fæhn[c], Eva Rosenberg[d], Orvika Rosnes[e]

Abstract
Ambitious energy efficiency goals are among the key responses to Europe's energy and climate challenges. To gain knowledge about the impacts of policies, two main families of models are widely used: energy system models – with emphasis on modelling technologies, and economic general equilibrium models – with emphasis on modelling markets and behaviour of economic agents. We study the same policy – an energy saving target – in two different models that are representative for the two modelling traditions in order to identify their similarities and differences. We implement the energy policy as a cap on energy purchased by residential sector. Our study illustrates that it is necessary to consider the effects of energy policy from several perspectives and use different scientific approaches before taking important political decisions. While the economic general equilibrium model allows for both energy efficiency investments and reduced demand for energy services as behavioural responses, the latter option is omitted by assumption in the energy system model. The response in the energy system model is wholly due to substitution between different technologies and energy carriers. The most striking consequence is that household demand for electricity remains virtually unaltered in the energy system model, held up by large investments in heat pumps. In the general equilibrium model, in contrast, the cap is almost entirely met by cutting household demand for electricity, with considerable impacts in the rest of the economy.

Keywords: Energy Efficiency Policy; Energy Efficiency (in buildings); Computable General Equilibrium; CGE Model; Energy System Model

JEL classification: C63, C68, D58, Q43, Q48, Q58

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1 Introduction

The EU 2030 climate and energy framework (EC, 2014) and the recent "Winter Package" for clean energy transition (EC, 2016) both emphasize improved energy efficiency as one of the key responses to Europe's energy and climate challenges. In order to gain knowledge about the impacts of energy efficiency policies, models are useful and widespread tools. Two main families of models have been developed for energy and climate policy analyses. The first one, *energy system models*, is based on optimisation of technology choices in production, distribution and use of energy. The other one, *economic general equilibrium models*, models markets where equilibrium prices and quantities are the result of interactions among optimising economic agents.

The purpose of our analysis is to gain knowledge about the similarities and differences between the two modelling approaches in energy policy analyses. How similar are the models in their perceptions of reality and their policy implications? To answer this, we study the same policy – an energy saving target for residential sector – in two state-of-the-art models developed within the two different modelling approaches.

The research communities within the technological sciences and economics have gradually recognised the need for more refined models, acknowledged each other's strengths and how the two approaches can complement each other. The work of the UN Intergovernmental Panel on Climate Change[1] has played a particularly important role in increasing interdisciplinary understanding. In the fields of global climate change and carbon policies a fair amount of model comparisons has been published that comprise both energy system models and economic general equilibrium models, see Weyant and Kriegler (2014) for a recent overview.

[1] See http://www.ipcc.ch

However, there is still a long way to go to systematically identify what are overlaps and what are complementarities between the models in order to learn from each other and extract the best of both traditions.

The aim of this study is to contribute to this knowledge by comparing energy policy outcomes in two models of the different traditions in a *national* perspective. Our case is Norway, who closely follows the EU's efforts in the energy and climate policies. The EU has not yet decided on their energy efficiency policy designs or exact targets for 2030 (EC, 2016). The Norwegian Ministry of Petroleum and Energy (2016) indicates in its White Paper on Energy overarching energy intensity goals for Norway, but it contains no specific 2030 targets for energy consumption, energy savings or energy efficiency. All policy signals on energy efficiency both in Norway and in the rest of Europe do, however, pay particular attention to the potential in residential buildings. Therefore, we focus on households and study the impact of energy efficiency policy using two models that are representative for the two approaches: the energy system model TIMES-Norway (Lind and Rosenberg, 2013) and the economic computable general equilibrium (CGE) model for Norway, SNOW-NO (Bye et al., 2018). We operationalise the energy efficiency policy as a cap corresponding to 27% reduction in consumption of purchased energy by the residential sector in 2030 compared to a baseline scenario.[2] Such a cap can be implemented by a white certificate system for households' energy purchases (Lees, 2008).

TIMES-Norway's principal strength is the rich array of technological measures that are available or expected to become available in the future. In particular, several technologies that produce energy are specified. Also, households can invest in energy production technologies,

[2] 27% corresponds to the indicative energy efficiency improvement goal in EC (2014). Recently, the Commission has suggested a goal of 30% improvement from a historical benchmark.

for example heat pumps and solar panels. In SNOW-NO technologies are modelled as averages with relatively little detail and mostly based on past or present knowledge.

The principal strength of SNOW-NO is that the interaction of all markets of the economy is modelled. Households consume a large variety of goods and services. They can change both the level and the composition of demand in response to policies. Accordingly, they can reduce their demand for energy services (e.g., heat or comfort). In TIMES-Norway, as in most energy system models, demand for energy services is predefined. Energy use in households can only be reduced through technological adaptations.

Our main conclusion is that these differences between the two models generate markedly different responses to a cap on purchased energy in the residential sector, especially in the electricity market. In TIMES-Norway, household demand for electricity remains virtually unchanged, held up by large investments in heat pumps that use electricity. By contrast, the cap is almost entirely met by cutting household demand for electricity in the general equilibrium model. While SNOW-NO has less technology flexibility, it represents far more of the substitution possibilities in total household demand. The result is a substitution of other goods and services for energy, particularly electricity which dominates the households' energy demand. The effects on the economy via the electricity market are, thus, large in SNOW-NO, but almost non-existing in TIMES-Norway.

Our analysis reveals the need to examine energy policy and market developments from different angles when important political decisions have to be taken. First, it sheds light on several aspects of the energy policy impacts. Second, it provides a quality check of important model drivers and reveals the possible outcomes when there is great uncertainty about which factors are important drivers of the results.

2 The models

Both models are representative, state-of-the-art examples of their respective traditions. TIMES-Norway is a dynamic bottom-up optimisation model of the Norwegian energy system, developed by the Institute for Energy Technologies (IFE) on assignment from the Norwegian Water Resources and Energy Directorate (NVE). SNOW-NO is a CGE model representing the total Norwegian economy, developed by Statistics Norway. Both models have been documented in earlier publications, see Lind and Rosenberg (2013) and Bye et al. (2018). In the following subsections, we will briefly sum up the models' main characteristics before elaborating in detail on how the households' energy use and residential investment behaviour are modelled.

2.1 The energy system model TIMES-Norway

TIMES-Norway has a rich description of technologies and is flexible with respect to the choices of technologies and energy sources in energy production, transmission and use. It covers all land-based energy use in Norway. The energy system is modelled on the basis of official energy statistics[3] for the base year 2010, and energy is measured in physical energy units. There are five national regions/electricity price zones and electricity trade among the national regions as well as with neighbouring countries is modelled. Figure 1 gives an overview of model inputs, outputs and modules. The production side involves several production and transmission technologies. The demand side consists of four main groups: households, manufacturing, transport and the service sector. These are broken further down into sub-groups and demand types (heating, cooking etc.).

[3] http://ssb.no/energi-og-industri/statistikker/energibalanse/aar-endelige

The model optimises the energy system by minimising the total system costs under the constraints set by the modeller, including the predefined energy service demands that must be met (such as heating, lighting etc.); see exogenous input in Figure 1. The fixed energy service demand is met by production by various technologies and energy carriers and by import. Distribution of electricity and district heating are modelled as several grids with defined capacities, investment and operation costs and grid losses. For a given energy service demand level, changes in relative prices of energy carriers will lead to substitution among the energy carriers, while the level of total energy use may change by e.g., implementing energy efficiency measures. The (minimised) total system cost is an output of the model.

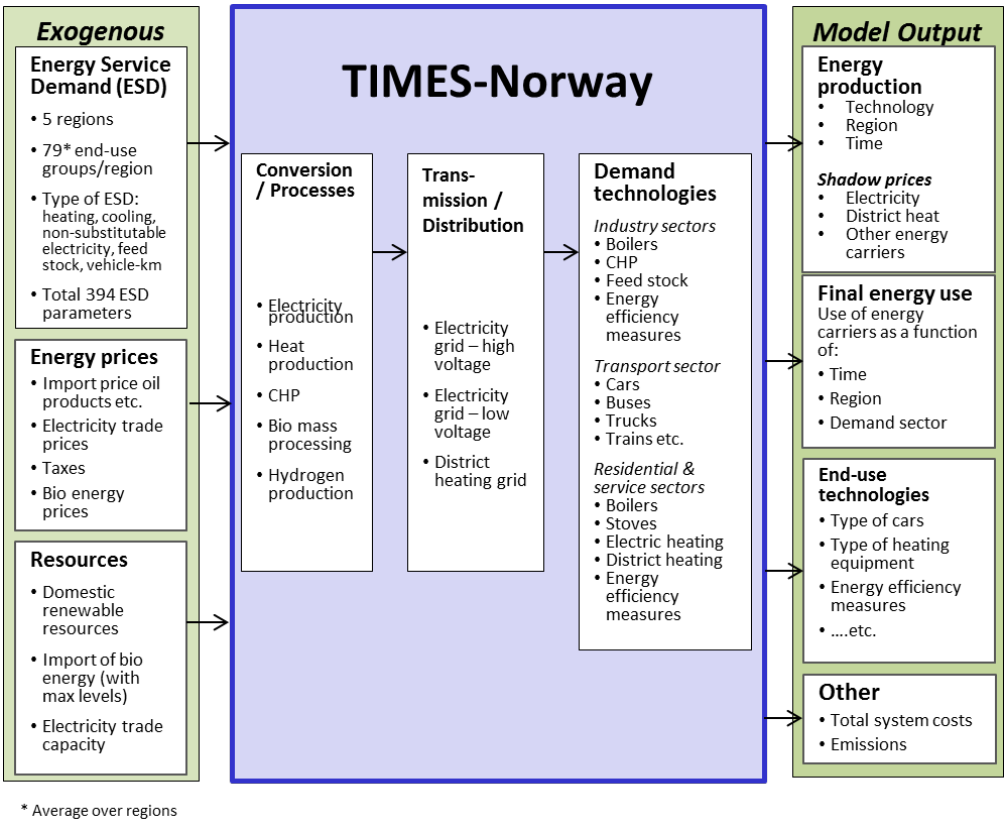

Figure 1 **TIMES-Norway**

2.1.1 Households' energy use and investment behaviour in TIMES-Norway

Households' energy use is largely driven by the exogenous demand for various energy services. The energy services specified in dwellings are space heating, hot tap water, lighting, and services from electric appliances. Households' demand for heating services can be met by combining energy use with existing technologies or by investing in new technologies. All the technologies are described in terms of investment and operating costs, efficiency, technical life time, existing capacity and potential, and energy carriers they use. Demand for energy services for the various purposes varies during the year, week and day, but the time profiles are constant from year to year.[4] TIMES-Norway calculates the optimal mix of technologies and energy carriers to meet the given demand for energy services. Different technologies have different efficiencies, which implies that the amount of energy required for the same service depends on the technology chosen. The households in TIMES-Norway use both purchased energy (like electricity, district heating, etc.), solar and ambient energy (heat pumps), and other, non-marketed, energy sources (e.g., firewood).

Households can implement various measures to adjust energy use when faced by a cap on purchased energy, as in our policy example. Measures with different potentials and costs can be implemented both in existing and in new buildings. A distinction is also made between measures in single-family, multi-family and leisure houses. Potential measures are presented in Table 1.

[4] The model contains several time periods: 52 weeks per year and 5 time periods per week (weekdays 7-11, weekdays 11-17, weekdays 17-23, nights 23-7 and weekends).

Regulations	Energy efficiency measures			Energy production	
Current requirements: – Technical building regulations – Ban on incandescent bulbs – etc. Future requirements: – Building regulations – Appliance requirements – etc.	Investment: Heating – Insulation of existing buildings – New doors / windows – Draught excluders – Water-saving shower heads – Water-heaters – Heating system – Ventilation systems – Control and regulation – Energy monitoring	Investment: Electrical appliances – Ventilation – Control and regulation – Energy monitoring – Energy-efficient equipment	Behavioural: – Standby – Turn out lights – Operation and use of household appliances – Efficient airing out	Production with: Heat pumps – Liquid to water – Air to air Solar panels (PV) Solar panels (thermal) – Hot water – Combi water and heat	Improved efficiency through: – New wood-burning stove – New boiler – Electric radiators replacing boiler – Etc.

Table 1 **Potential measures in households**

Regulations are measures that are imposed upon households as a result of existing or future requirements or prohibitions. These measures are essentially different from the remaining, see below, as they are absolute constraints without explicit costs in the model.

Energy efficiency measures include households' options to reduce energy use in dwellings without changing the energy service in terms of comfort, heat, light etc. Measures of this type may be investments in the dwellings (insulation, new doors etc.), heating appliances or electrical appliances (lighting, cooking appliances, fridges, televisions, etc.). For such investments to occur in the cost-minimisation in the model, the investment costs must be offset by energy cost savings. Among energy efficiency measures we have also grouped *behavioural* measures other than technological investments that can save energy. These are typically less costly and can be triggered by information programmes or similar.

Energy production investments include investments in equipment that produces energy in the dwelling as well as in improvements of the efficiency of the equipment. These include equipment that can exploit solar and ambient energy, like solar panels and heat pumps. Two

types of heat pumps are modelled: air to air pumps that can reduce the use of energy for heating purposes by 25%, and liquid to water pumps that can reduce the use of energy for heating purposes by 45%. The latter requires the existence of (or investment in) a heat distribution system in the dwelling.

2.2 The economic general equilibrium model SNOW-NO

SNOW-NO is a multi-sector CGE model for the total Norwegian economy, see Bye et al. (2018). SNOW-NO computes annual equilibrium levels for supply, demand and domestic prices for a number of goods, services and production factors (labour, capital, energy), as well as emissions of greenhouse gases and welfare costs. Main input data are the input-output tables in the Norwegian National Accounts. All quantities are measured in money-metrics, i.e. the expenditures in fixed base-year prices; this also applies to energy use. The model is developed in GAMS/MPSGE (GAMS, 2014; Rutherford, 1999).

There are 41 different industries. Private producers maximise profit and can change both the production level and the composition of input factors, including energy products, depending on changes in relative prices. Similar to TIMES-Norway, there is export and import of energy. As a small country, Norway is assumed not to affect world market prices, these are therefore exogenous in SNOW-NO. Public sector production is exogenous. Consumers are represented by one representative household that maximises utility. Household demand for the various goods and services depends on relative prices and the household's income level. Economic welfare costs are measured as the change in utility of the representative household, since the representative household owns all resources in the economy.

2.2.1 Households' energy demand and investment behaviour in SNOW-NO

The household demand system in SNOW-NO is modelled by a Constant Elasticity of Substitution (CES) nested preference structure (Varian, 1992).[5] Consumption consists of three substitutable groups of goods, one of which is *housing service*s (see Figure 2). Substitution possibilities between different goods are represented by the (constant) substitution elasticities. The elasticity of substitution determines how the relative consumption of goods changes as the relative prices change. The larger the value of the elasticity, the easier it is to substitute one good for another.

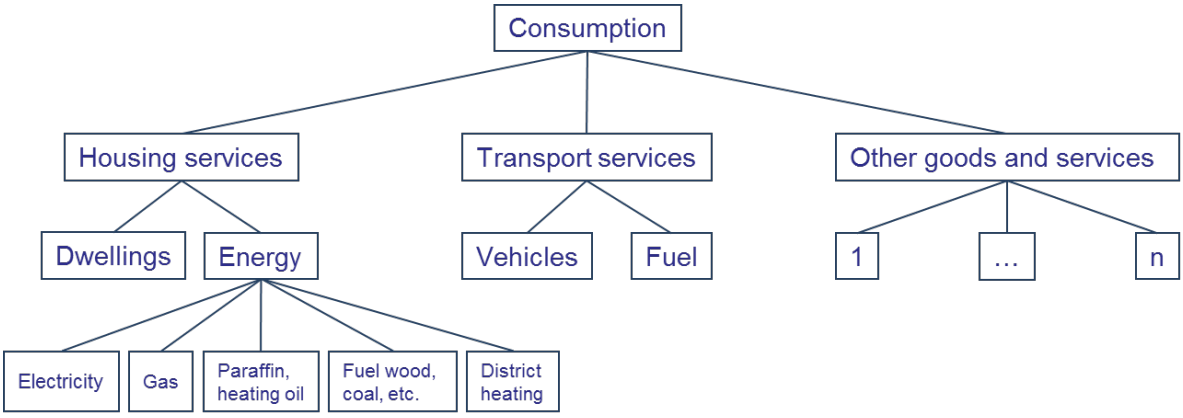

Figure 2 Consumption structure in SNOW-NO

Housing services is an aggregate of energy consumption and of dwelling capital and can be regarded as the comfort level that energy and dwelling capital in combination can provide. The housing services concept in SNOW-NO is comparable to the concept of energy services for heating in TIMES-Norway.

As is common in CGE models, the energy technologies are mostly represented by average technologies, based on past and present knowledge, rather than expectations of future developments. However, compared to most CGE models SNOW-NO has moved in the direction of energy system models in modelling anticipated future technology options for

[5] The CES function is standard in CGE models and in particular in models in the MPSGE format, Rutherford (1999).

energy efficiency improvements in housing. We use data on investment costs and energy saving potentials of different residential energy efficiency measures from TIMES-Norway to estimate the substitution elasticity between energy and dwelling capital. This substitution elasticity will express the necessary investments in the dwelling in order to reduce energy use without sacrificing comfort. Figure 3 shows the energy saving potential of energy efficiency investment measures from Table 1, ranked according to costs (Rosenberg and Espegren, 2014).[6]

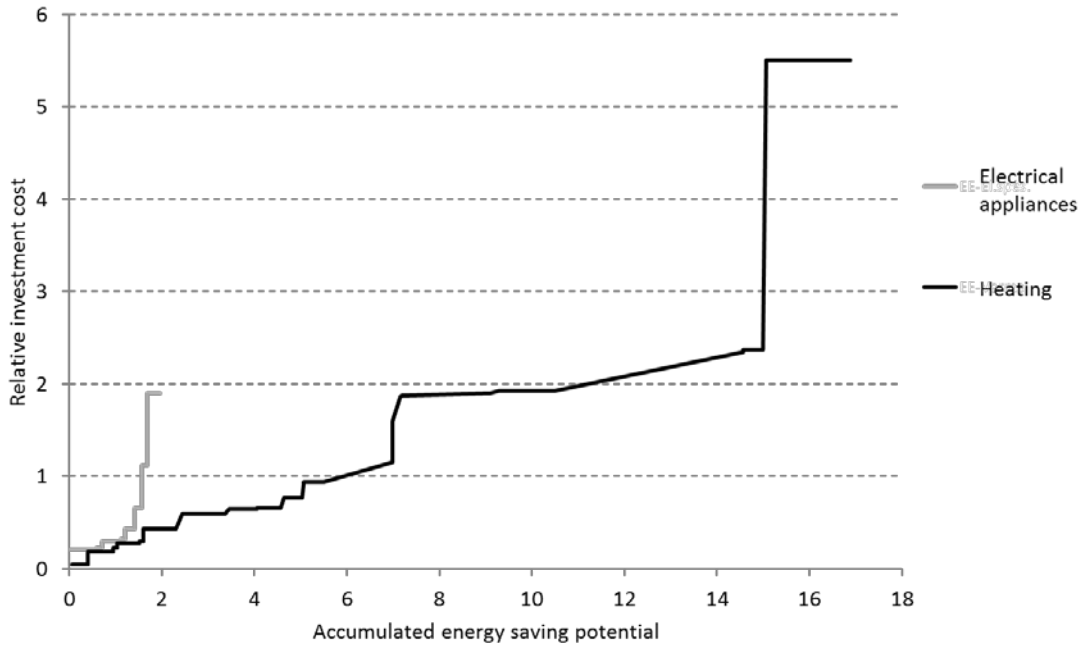

Figure 3 **Relative investment costs (annuity relative to energy price) and energy saving potential (TWh, accumulated)**

Since we focus on the energy services for heating, we leave energy efficiency measures associated with electrical appliances (marked grey in Figure 3) out of our data set.[7] Furthermore, all measures with costs less than the alternative cost of buying one unit of energy (i.e., measures with relative costs below 1 in Figure 3), have been omitted from our data set. This is because the rational economic agents in SNOW-NO will invest in such

[6] Investment costs are measured as annuities. We have used 5% as the economic discount rate.

[7] In SNOW-NO, energy demand for electrical appliances is not modelled separately.

profitable energy efficiency technologies without further incentives by the authorities. Therefore, these measures cannot be available as a response to the policy change we are studying.

Given these assumptions, 2/3 of the original dataset for energy efficiency measures associated with heating remains for estimation of the substitution elasticity.[8] Application of the ordinary least squares method yields an estimated substitution elasticity of 0.3 between use of energy and dwelling capital. An interpretation of the substitution elasticity is that an increase in the price ratio between energy and dwelling capital by 1 per cent will reduce the ratio between consumption of energy and dwelling capital by 0.3 per cent. Figure 4 shows the estimated curve, along with the original data on energy efficiency measures.

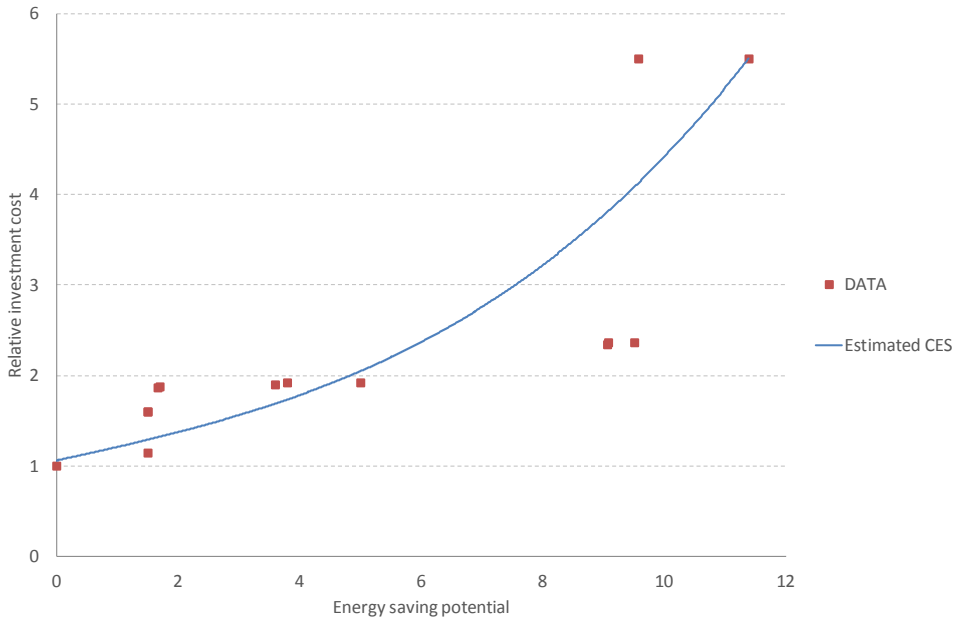

Figure 4 **Relative investment costs (annuity relative to energy price) and energy saving potential (TWh, accumulated): Data and the estimated CES curve**

[8] We derive the following relative demand function (in log-linear terms) for energy and dwellings from the CES utility function: $\ln(E/D) = \alpha + \beta \ln(P^D/P^E)$. *E/D* is the relative demand for energy *E* to dwellings *D*, P^D/P^E is the relative price of dwellings P^D to energy P^E, β is the substitution elasticity and α is the intercept of the log-function, see Bye et al. (2018) for further details.

3 Analyses of the energy efficiency policies

In order to study the effects of the energy saving requirement for the residential sector in the two different models, we first create baseline scenarios up to the year 2030. Then we examine the outcomes of a policy aimed at reducing household energy consumption for heating purposes by 27% in 2030 in the two models, operationalised as a cap on households' purchased energy.

3.1 The baseline scenarios

The baseline scenarios are intended to represent developments from now until 2030 in the absence of the cap. Developments in overall GDP, household consumption, productivity and international markets roughly follow the trends in the Norwegian Government's Long-Term Perspectives (Norwegian Ministry of Finance, 2013). Assumptions of particular importance for both models are those about global market prices for various energy carriers such as fossil fuels and bioenergy, and about political decisions that have already been taken (but not necessarily implemented yet). In both models, energy efficiency measures that become profitable within 2030 as a result of already decided policies will be part of the baseline scenarios. The TIMES-Norway results show that the behavioural measures listed in Table 1, together with some investment measures (such as draught excluders and control and regulation measures), are examples of profitable measures that are carried out already in the baseline scenario. The SNOW-NO baseline scenario shows similar results in terms of energy efficiency measures that are implemented.

Based on the consumption trends from Norwegian Ministry of Finance (2013), the exogenous projection of future demand for energy services in TIMES-Norway is increasing towards 2030 (see Rosenberg and Espegren, 2014). Households' use of purchased energy for heating purposes is nonetheless at the same level in the baseline scenario in 2030 as in 2010 due to

energy efficiency measures and increased energy production in households by new heat pumps. Since total consumption (including energy services) increases in SNOW-NO in the period until 2030 and alternative energy production technologies (such as heat pumps) are not available, energy consumption increases in the baseline scenario in SNOW-NO; see Bye et al. (2018). However, the absolute level of energy use in the baseline does not affect the relative changes that follow from a change in policy, so the analyses of relative effects are comparable.

3.2 Effects of a cap on residential energy use

The cap on energy use is imposed on residential energy purchases for heating purposes. Similar requirements are not introduced in other sectors of the economy. The results from the simulations of the cap in the two different models are given in Table 2.

	SNOW-NO	TIMES-Norway
Domestic price of electricity*	-15.5	-1
Household electricity consumption*	-26.7	1
Household energy consumption*	-27.0	-27
Demand for housing services/Demand for energy services**	-5.8	0
Use of dwelling capital	-3.2	n.a.
Utility	-1.0	n.a.
System costs	n.a.	3

* Measured as purchased electricity and purchased energy. Comparable variables in SNOW-NO and TIMES-Norway.
** 'Housing services' in SNOW-NO corresponds to 'energy services' in TIMES-Norway.

Table 2 Effects of a 27% reduction in residential energy purchases. Percentage change from the 2030 baseline scenario

In TIMES-Norway, households' demand for energy services is the same as in the baseline by assumption. Hence, the cap on energy use does not lead to a reduction of heating services. Instead, energy efficiency measures and investments in energy production equipment will be carried out until the energy saving requirement is met. Figure 5 shows the composition of energy use for heating purposes in both the baseline and policy scenario. The first observation

is that larger emphasis will be put on energy efficiency measures, such as new water heaters, improved ventilation systems and insulation that will become profitable. Second, it is optimal to increase the households' use of heat pumps substantially. This enables the households to produce a larger share of its energy need by exploiting ambient energy. One important implication of this adaptation is that household *electricity* consumption rises, if only marginally (1%), despite the cap, see Table 2. The reason is that heat pumps use electricity. The cap on purchased energy is met by reducing the use of district heating and bioenergy (particularly firewood) instead.

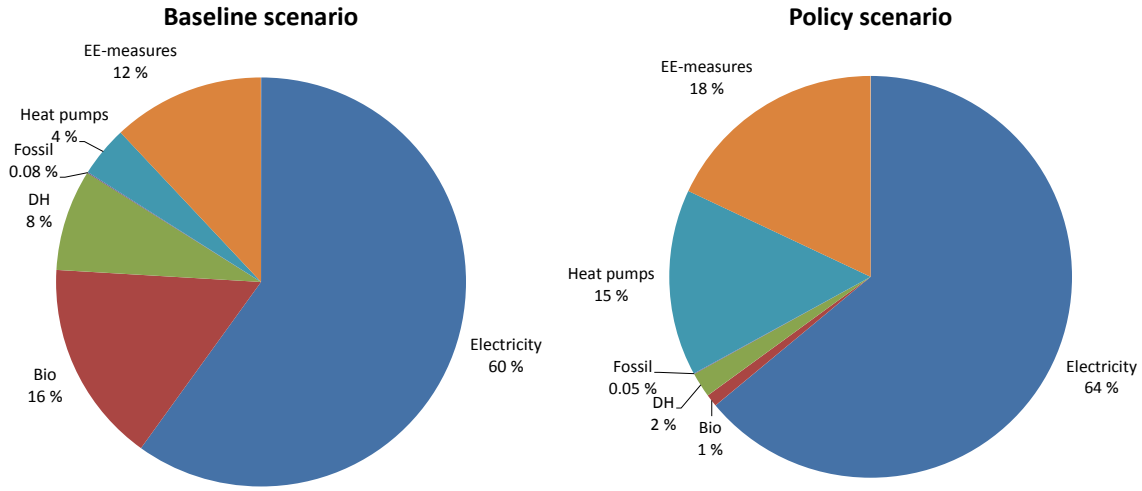

Figure 5 **Composition of energy for heating purposes (incl. energy efficiency measures and heat pumps) in households in TIMES-Norway in the baseline scenario and in the policy scenario, 2030**

In TIMES-Norway, demand for energy services is given not only for households, but for all sectors. When household electricity consumption remains virtually the same, prices in the electricity market do not change noteworthy either. As a result, the changes in energy consumption, production technologies and energy efficiency in the other sectors of the economy are limited. Power production remains the same.

The results are very different in the CGE model. In SNOW-NO, the effect on households' electricity consumption is much stronger: electricity use in households drops by 26.7%. As a

response, electricity prices fall sharply. There are several reasons for this. Most importantly, substitution from electrical heating to heat pumps is not an option in SNOW-NO. There is substitution between energy and dwelling capital, and between different energy goods, but no substitution between different capital goods using the same energy carrier (see Figure 2). Furthermore, energy consumption in households is dominated by electricity. Therefore, even if the demand for all energy carriers drops, the impact is largest for electricity.[9]

While SNOW-NO has less technological flexibility than TIMES-Norway, it has more flexibility to adjust the level of consumption of housing services. In other words, if people find it less costly (in terms of utility) to leave rooms unheated, rent out part of their houses or move to smaller dwellings than to buy the energy necessary to keep up comfort and heating at the baseline levels, they will do so. And the model indicates that they will: Table 2 reports a 5.8% drop in the demand for housing services as opposed to zero (by assumption) in TIMES-Norway.

Turning to energy efficiency measures in SNOW-NO, we find fairly similar outcomes as in TIMES-Norway regarding investments in efficiency improvements. This is as expected, as our estimation of the substitution elasticity between the use of energy and dwelling capital in SNOW-NO is based on data of investment options from TIMES-Norway. The energy efficiency investments can be identified as the gap between the 3.2% reduction in use of dwelling capital and the 5.8% reduction in housing services. If no energy efficiency measures were available, the only effect on dwelling capital would be a reduction proportional to that of demand for housing services. Energy efficiency investments in insulation and more efficient

[9] Note that the dominance of electricity is more pronounced in the SNOW-NO model than in TIMES-Norway (93% vs. 77%). While the latter is calibrated to physical energy data and measures all energy flows in energy units, the former is calibrated to National Accounts data and measures energy quantities in money-metrics. It follows that SNOW-NO only includes energy that is bought in markets (has prices). This is partly the explanation to the differences in electricity market outcomes between the two models, but it is not the major explanation.

heating equipment replace energy use. It is an empirical question to what extent technological and behavioural adaptations are considered as options by the agents. However, it is important to remember that both models may have omitted relevant response mechanisms.

The fall in electricity prices in SNOW-NO that follows the substantial reduction in household electricity demand leads to major market repercussions in the rest of the economy (contrary to the electricity market outcome in TIMES-Norway). First of all, the electricity price fall benefits the power-intensive process industry which increases its electricity use considerably. The industry also profits from reduced capital prices since demand for housing and construction services decline. Net exports of electricity also increase (imports fall and exports increase) to re-establish market equilibrium. Total domestic production of electricity in 2030 is the same as in the baseline due to assumed constraints, just like in the TIMES-Norway simulations. However, as imports fall, total electricity use in the economy is reduced 9%.

As seen from Table 2, the quantity cap on energy consumption in SNOW-NO reduces household utility by 1%. Household utility is the model's metric for economic welfare costs of the policy; see Section 2. As all income will finally accrue to the household, the change in utility captures both the direct utility loss due to the cap the households face, and also the indirect effects of the adaptations of all the model agents. Given that only the households face energy restrictions in the policy experiment, this is a significant fall in welfare.

Utility is, by assumption, constant in the energy system model TIMES-Norway, as all energy services are given. TIMES-Norway computes the total system costs, defined as the minimised investment and operating costs, accumulated over the entire analysis period, to meet the exogenous demand for energy services in Norway. System costs increase 3% as a result of the cap. The increase of total system costs reflects the costs of implementing a number of

measures that were not profitable in the baseline scenario and, hence, implies a loss for the economy.

Costs tend to be lower, the more flexibility that is built into the model. The two models have complementary flexibility characteristics. In the energy system model TIMES-Norway there are more options for technological adaptations and more detailed specifications of their practical implications. In the economic model SNOW-NO relatively more flexibility is modelled in the households' consumption patterns and levels, as they will respond to all price and income changes. Thus, some of the immediate loss that consumers experience as a result of the energy use constraint is mitigated through shifting consumption towards goods that have become relatively cheaper, see Bye et al. (2018). Similar flexibility applies to producers/firms. Resources that are released when households' demand for energy and dwelling capital falls will, therefore, benefit other sectors of the economy and reduce overall costs to the society.

4 Conclusions

We have analysed energy efficiency policy using an energy system model and an economic computable general equilibrium model. Our analysis illustrates that the two modelling approaches may yield quite different results. This reflects the fact that the models were developed for different purposes. Whereas technology-rich energy system models can provide a detailed picture of energy-related investments and compositional changes due to a policy in the partial setting, economic general equilibrium models are developed to look at all markets and market agents' behaviour in interaction, so as to provide a good picture of both direct and indirect effects of policy.

We examine the outcomes of an energy saving requirement. The most striking difference between the two model outcomes occurs in the electricity market. The energy system model TIMES-Norway shows that households' electricity consumption may remain roughly the same even with stringent requirements for reductions in households' energy purchases. In contrast, the same policy leads to a sharp fall in households' electricity consumption in the economic computable general equilibrium model for the Norwegian economy, SNOW-NO. These deviating results stem from fundamental differences between the two scientific modelling traditions. They complement each other by emphasising different empirical aspects of the technological and economical world.

Our analysis yields some general conclusions: We need to use the different scientific approaches together in order to shed light on a broader range of the effects of energy policy. Model analyses provide useful information for policy-makers, producers, distributors and consumers of energy about the possible effects of policies and market developments. In particular, it gives public planners an idea of areas where policy instruments, public investment or other initiatives are called for. Mutual understanding and exchange of knowledge across disciplines and over a range of issues are important for generating consistent and realistic pictures of developments in the field of energy.

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References

Bye, B., T. Fæhn and O. Rosnes (2018): Residential energy efficiency policies: Costs, emissions and rebound effects. Energy 143, pp. 191–201. DOI 10.1016/j.energy.2017.10.103

EC (2014): Climate and Energy Policy Package for 2030; The European Commission (http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm)

EC (2016): Clean Energy For All Europeans, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, COM (2016) 860 final, European Commission, Brussels, 30.11.2016

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

Lees, E. (2008): Evaluation of the energy efficiency commitment 2005 – 2008. Report to DECC

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

Norwegian Ministry of Finance (2013): Perspektivmeldingen 2013 [Long-term Perspectives on the Norwegian Economy 2013], Meld. St. 12 (2012–2013). (In Norwegian with summary in English)

Norwegian Ministry of Petroleum and Energy (2016): Kraft til endring – Energipolitikken mot 2030 [Power for change – energy policy towards 2030], Meld. St. 25 (2015–2016) (In Norwegian only).

Rosenberg, E. and K.A. Espegren (2014): CenSES energiframskrivinger mot 2050 [CenSES energy projections to 2050]. Norwegian Institute for Energy Technology. IFE/KR/E-2014/003 (In Norwegian only).

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. DOI 10.1023/A:1008655831209

Varian, H.R. (1992): Microeconomic Analysis. 3rd edition. W.W. Norton & Company, New York, London

Weyant, J. and E. Kriegler (2014): Preface and introduction to EMF 27, *Climatic Change* 123:345–352, Special Issue on "The EMF27 Study on Global Technology and Climate Policy Strategies". DOI 10.1007/s10584-014-1102-7