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INTRODUCTION OF HYDROGEN IN THE NORWEGIAN ENERGY SYSTEM

Institute for Energy Technology

Institute for Energy Technology

Address	KJELLER NO-2027 Kjeller, Norway	HALDEN NO-1751 Halden, Norway
Telephone	+47 63 80 60 00	+47 69 21 22 00
Telefax	+47 63 81 61 06	+47 69 21 22 01

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Abstract

The overall aim of the NorWays project has been to provide decision support for the introduction of hydrogen as an energy carrier in the Norwegian energy system. The NorWays project is a research project funded by the Research Council of Norway. An important task has been to develop alternative scenarios and identifying market segments and regions of the Norwegian energy system where hydrogen may play a significant role. The main scenarios in the project have been:

- Reference: Based on the assumptions of World Energy Outlook with no new transport technologies
- HyWays: Basic assumptions with technology costs (H_2) based on results from the HyWays project
- No tax: No taxes on transport energy ("revenue neutral")
- CO_2 reduction: Reduced CO_2 emissions by 75% in 2050

Three regional models have been developed and used to analyse the introduction of hydrogen as energy carrier in competition with other alternatives such as natural gas, electricity, district heating and biofuels. The focus of the analysis has been on the transportation sector.

Keywords: Hydrogen, MARKAL, energy system analysis, vehicles

	Name	Date	Signature
Author(s)	Eva Rosenberg Audun Fidje Kari Aamodt Espegren	2008-12-30 2008-12-30 2008-12-30	Eva Rosenberg Audun Fidje Kari Aamodt Espegren
Reviewed by	Preben Vie	2008-12-30	Preben J.S. Vie
Approved by	Per Finden	2008-12-30	Per Finden

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1 Summary

The overall aim of the NorWays project has been to provide decision support for the introduction of hydrogen as an energy carrier in the Norwegian energy system. The NorWays project is a research project funded by the Research Council of Norway with industrial co-financing from Statoil, Hydro, (StatoilHydro), Statkraft and Hexagon.

The main goals of the NorWays project have been to develop alternative scenarios and identifying market segments and regions of the Norwegian energy system where hydrogen may play a significant role as well as to develop regionalized models for analyzing the introduction of hydrogen as energy carrier in competition with other alternatives such as natural gas, electricity, district heating and biofuels.

IFE's part of the project includes the development of a generic regional MARKAL model constructed to represent a general region, neither adapted to special local conditions nor to a specific situation. Based on this generic model, IFE developed regional models for Rogaland, Telemark and Oslo. Rogaland and Telemark is modelled with an urban and a rural area, while Oslo only has an urban area. The MARKAL models have been used in order to analyse the entire energy system and compare hydrogen technologies to other possibilities. The analysis focuses on how taxes, restrictions and energy prices have an impact on the production and use of hydrogen.

Assumptions and scenarios

The basic assumptions described in this report are based on the results from the HyWays project and an important input to this project is the deployment of hydrogen cars at different times and hence the investment cost of vehicles. The basic assumptions from HyWays include a substantial reduction in technology costs compared to the present costs.

The scenario analysis assesses how policy instruments can contribute to an early introduction of hydrogen. To be able to achieve huge reductions in CO_2 emissions in Norway, the transportation sector needs a shift from fossil fuels to low or no CO_2-emission fuels. Thus, the main focus in the analysis has been on the transport sector, especially cars, to identify the parameters and conditions that are important to make a profitable transition to hydrogen cars.

The main scenarios in the project have been:

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The reference scenario based on the Baseline of World Energy Outlook is included in order to compare the results with the situation of today.

There are large uncertainties about future technology costs and energy prices. Thus, to assess the effects of the assumptions used, we have analysed the different scenarios in combination with a sensitivity analysis of energy prices and investment costs.

Analysis results

In the analysis we have not controlled or restricted the introduction of new technologies. This resulted in a fast implementation of new technologies as soon as they were profitable. In reality this is not the case, and normally there will be a delay in the introduction of new technologies.

In the HYWAYS scenario all cars in Rogaland and Telemark use hydrogen in 2050. In Oslo, however, there are no hydrogen cars in the HYWAYS scenario, due to more expensive hydrogen in Oslo than in the other regions. Plug-in hybrids are introduced in Oslo from 2020, and in 2050 all cars are plug-in hybrids.

The effects of changes in ***investment costs*** are in general more important for the type of car than for the type of hydrogen production technology. If the investment cost of hydrogen cars is as described in the HYWAYS-scenario, hydrogen cars are used if hydrogen can be produced at a reasonable cost. If the cost of plug-in hybrids is reduced by 20 % more than assumed in the HYWAYS-scenario, plug-in hybrids will be used instead of hydrogen cars. If the costs of hydrogen cars are increased, less hydrogen will be used for transportation and hydrogen will be introduced later.

The effect of the CO_2 reduction scenario is an earlier introduction of hydrogen cars, combined with hydrogen production from renewable energy. A large reduction in CO_2-emissions is only obtained with strong political limitations on CO_2-emissions. Another effect of the CO_2 reduction scenario is that SMR-plants with CCS will be profitable with the presence of industry with possibilities for CCS (as in Telemark),

Changes in relative energy price give different results. A higher natural gas price results in a delayed introduction of hydrogen, where less hydrogen is produced from SMR and more from electrolysis. A higher natural gas price combined with a higher electricity price gives more biodiesel, while a higher electricity price in combination with a high hydrogen price is in favour of plug-in hybrids. No energy taxes give a delayed introduction of hydrogen cars and hence more gasoline and natural gas cars are used.

The different regions analysed give different results with regard to hydrogen production technology and use of hydrogen. An important regional difference is the availability of hydrogen as a by-product. If available, this will give an earlier introduction of hydrogen cars and use of cheaper and less efficient hydrogen combustion cars. Secondly, central electrolysis plants are profitable in regions with a surplus of electricity. Industrial use of natural gas is important in order to decrease the energy cost of SMR-plants. When no cheap energy is available, this is in favour of more energy efficient vehicles, like battery electric- and plug-in hybrid cars.

2 Introduction

The overall aim of the NorWays project has been to provide decision support for introduction of hydrogen as an energy carrier in the Norwegian energy system. The Norwegian energy system is characterized by high dependence on electricity, mainly from hydropower. However, over the last decades Norway has become a large exporter of oil and natural gas. Since the electricity demand and a large share of the heating demand are covered by hydropower, considerable reductions of CO_2 emissions in the transportation sector are very important.

Important objectives of the NorWays project have been to carry out analysis and evaluation of scenarios and market segments for introduction of hydrogen. Active participation of stakeholders has been an important working methodology of the project in order to ensure consensus and feedback from industrial participants related to selection processes, assumptions, and reliability of results. This work supports the main goals of the NorWays project; developing alternative scenarios and identifying market segments and regions of the Norwegian energy system where hydrogen may play a significant role as well as developing suitable, regionalized models for analyzing the introduction of hydrogen as energy carrier in competition with other alternatives such as natural gas, electricity, district heating and bio-fuels.

When introducing hydrogen into the energy system the local energy resources, the demographic structure, environmental aspects and the future requirement for security of supply are important parameters to take into account. Three regions in Norway have been selected for detailed analysis. The report includes a description of criteria used for the selection of geographical regions. Variations in the regions with respect to energy resources, energy demand, population density etc were taken into account.

The project includes the development of a generic regional MARKAL model, constructed to represent a general region, neither adapted to special local conditions nor to a specific situation [Rosenberg and Espegren 2006]. Based on this generic model, three regional models were developed, and these are presented in this report together with analysis results. The model structure of the regional MARKAL models is described, with focus on market segments where hydrogen may play a significant role in an early market introduction phase.

The report describes a methodology for an interaction with an infrastructure model developed in this project. The infrastructure model optimizes the build-up of a hydrogen supply infrastructure for a given demand development and have a higher level of detail than MARKAL for analysis of hydrogen in the transportation segment.

Finally, the report presents results from the analysis of a reference scenario, the basic assumptions of the HYWAYS-scenario, a “tax neutral” scenario and a scenario with limitations on CO_2-emissions. In addition sensitivity analysis of the importance of energy prices and technology costs are presented.

3 Selection of geographical regions

The intention of choosing different regions for the analysis in the NorWays project has been to assess how the resource availability and energy end-use demand in different regions can influence the introduction of hydrogen in the energy system, both with respect to production and use of hydrogen. To be able to choose three different and interesting regions, a set of criteria characterising the energy system was identified, such as energy demand, electricity production, untapped resources, energy infrastructure and geographical conditions.

In the selection of regions, variations in characteristic regarding local energy resources and energy end-use demand were emphasised, in order to evaluate how these variations influence the analysis results. For instance, regions with a large potential of wind power, will be able to produce zero-emission hydrogen based on electricity from wind power, while areas with landing of natural gas, as well as possibilities for CO_2 handling and storage, can produce hydrogen from natural gas. In some regions hydrogen is also available as by-product from industrial processes.

Energy end-use and population density are important when deciding on regions for detailed modelling and analysis. Regions with high population density, high density of cars and large fleets of vehicles are likely to become regions for early introduction of hydrogen. Transportation is the sector where hydrogen is most likely to be introduced first, as large reductions in CO_2-emissions can be obtained in this sector. Today energy demand in the transportation sector is mainly covered by use of fossil fuels. In a short-term perspective these fuels can be substituted by bio-fuels and in a long-term perspective by hydrogen fuelled vehicles or plug-in hybrids. Thus, regions with a high car density are of interest in this study.

Based on the available information about the different regions in Norway and discussions of the most important factors in workshops, we concluded with the three regions of Rogaland, Telemark and Oslo.

The main reason for selecting Telemark was due to the regions industrial production with a high energy demand and with available hydrogen as by-product from the industry. Oslo was selected as it has the highest population density and also the highest density of cars in Norway. The main reason for selecting Rogaland was the landing of natural gas, the local gas grid and the possibility of deposition of CO_2. The huge potential for wind power in Rogaland was also important. In all the selected regions the knowledge is high and involvement is strong as Stavanger, Grenland and Oslo are part of the HyNor-project. Rogaland and Telemark have currently one hydrogen fuelling station each. Hynor is the hydrogen highway in Norway established in 2003, and part of the Scandinavian hydrogen highway partnership.

The counties Hordaland, Møre and Romsdal and Finnmark were considered as possible regions for the NorWays project, but they where however not selected for the detailed analysis. These counties can be of interest for a later study. Remote areas have not been considered, but could represent an early niche market for introduction of hydrogen.

Appendix 1 provides information and data on the selected criteria, believed to be the most crucial for an early introduction of hydrogen, divided on each region/county.

4 Regional MARKAL models

4.1 Model structure

MARKAL (an acronym for MARKet ALocation model) is a mathematical model of the energy system. MARKAL is a linear programming tool, a bottom-up model with a detailed representation of the energy sector of the economy. The MARKAL model consists of a detailed description of the energy system, both technically and economically, with resources, energy carriers, conversion technologies, and energy demand. The model is demand driven, thus the forecasted energy demand is given exogenously and the demand is satisfied over the modelling periods at least costs.

The model can be used for a wide range of applications such as strategic planning of future energy supply options, analysis of least-cost strategies, energy policies and measures, examination of the collective potential of technologies and resources, and evaluation of different research strategies for energy technologies. In a MARKAL model, the time period has equal intervals, typically five years. The analyzing period for the three regional models is from 2010 to 2050, with five years intervals.

The MARKAL model provides a framework for representing a regional energy economy. The reference energy system (RES) in MARKAL consists of:

- Demand for energy services
- Available energy sources (mining or imports)
- Sinks (exports)
- Technologies
- Commodities

The main boundaries is set by the available sources and demand for energy services represented by respectively supply and demand curves. The available commodities are:

- Energy carriers
- Energy services
- Materials
- Emissions

The regional models are divided into urban and rural areas in order to analyse different production and transport alternatives and demand variations. The model differentiates between a car used in urban and rural areas in order to take into account the variations in drive cycles. Further, there are limitations on options for new technologies in the rural areas, e.g. we have not allowed hydrogen pipelines to rural areas. Production of hydrogen can be either as a large scale plant with transport to urban and/or rural areas or local production, see Figure 1. Hydrogen is modelled as an energy carrier with day-night and seasonal storage adapted from the HyWays-project [Martinus 2006].

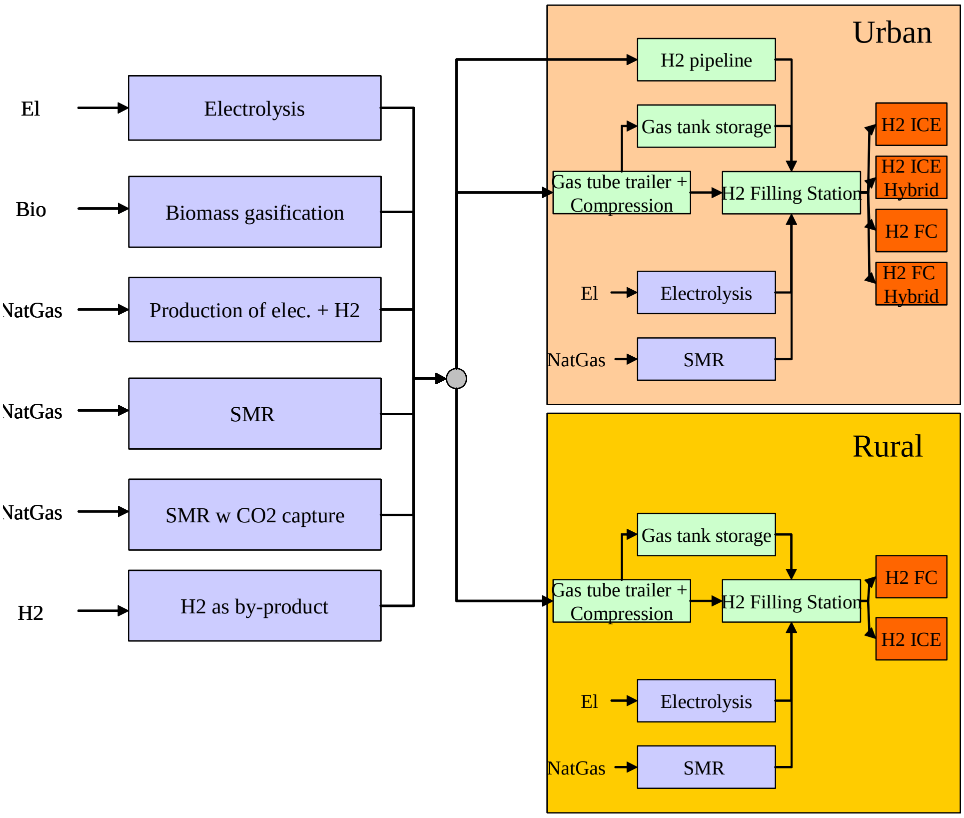

Figure 1 Modelling of hydrogen in the regional models.

4.2 Demand

The models have 29 different demand sectors, 1 in agriculture, 5 in services, 8 in industry, 6 in households and 9 in transport. These demand sectors have one to three different energy services, e.g. heat, non-substitutable electricity, vehicle km etc. The different sub-sectors are described in more detail by Rosenberg and Espegren [2006].

The energy demand is given as net energy for all purposes where nothing else is stated. In the road transport sector, demand is given as annual vehicle-km for cars and buses in each area, while demand of freight transport, ship and others is in kWh.

The foresight of energy demand is based on the work done in [NOU 2006:18], but with modifications of the demand in the household sector and in some industry sub-sectors. Industry companies modelled as separate units in the regional models are assumed to have a constant demand for energy during the entire period. The growth in energy demand in the household sector is based on a constant use of energy per capita and a growth in population based on the middle scenario of Statistics Norway for each region. The increase in household energy demand will then be 14 % in Telemark, 40 % in Oslo and 35 % in Rogaland. For more details see [Rosenberg and Espegren 2006]. The development in energy demand used in the MARKAL model is shown in Figure 2.

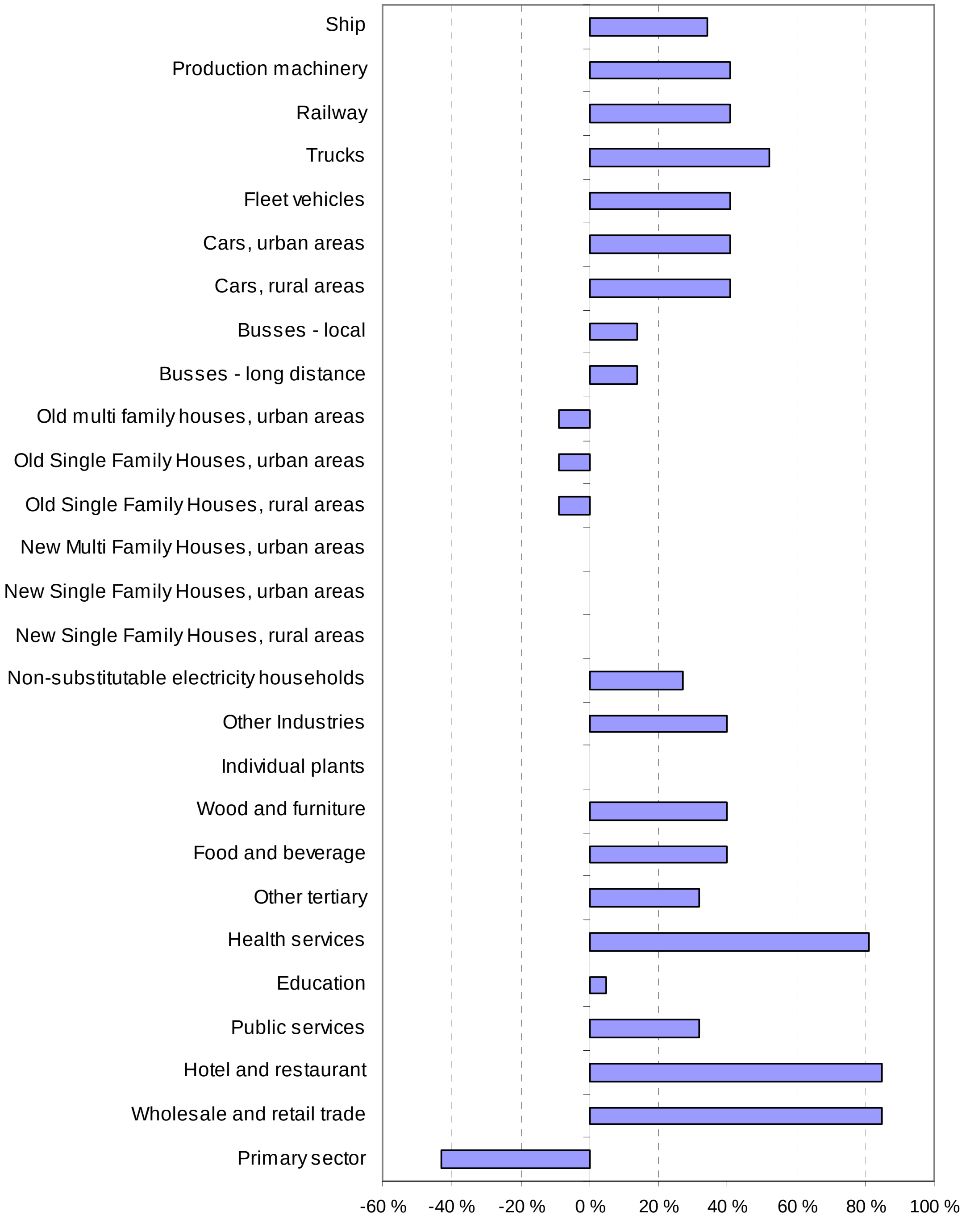

Figure 2 Development in energy demand of all sub-sectors in the MARKAL- regional models (% change from 2005 to 2050). The growth in the household sector is an average for Norway and the growth in new dwellings is not shown since they start with zero demand.

4.3 Energy prices

The energy prices used in the basis scenario are presented in Table 1 and in Figure 3-Figure 4.

The price of imported and exported electricity is based on a quota price of 25 €/ton CO2. The price of import and export of electricity fluctuate both by season and by day/night. Prices are based on forwards in Germany (EEX) and evaluation within the NorWays project. It is assumed a fluctuation of 10 €/MWh over the season for the whole analysis period. The fluctuation day/night is assumed to be 25 €/MWh. An overview of electricity prices is presented in Figure 3.

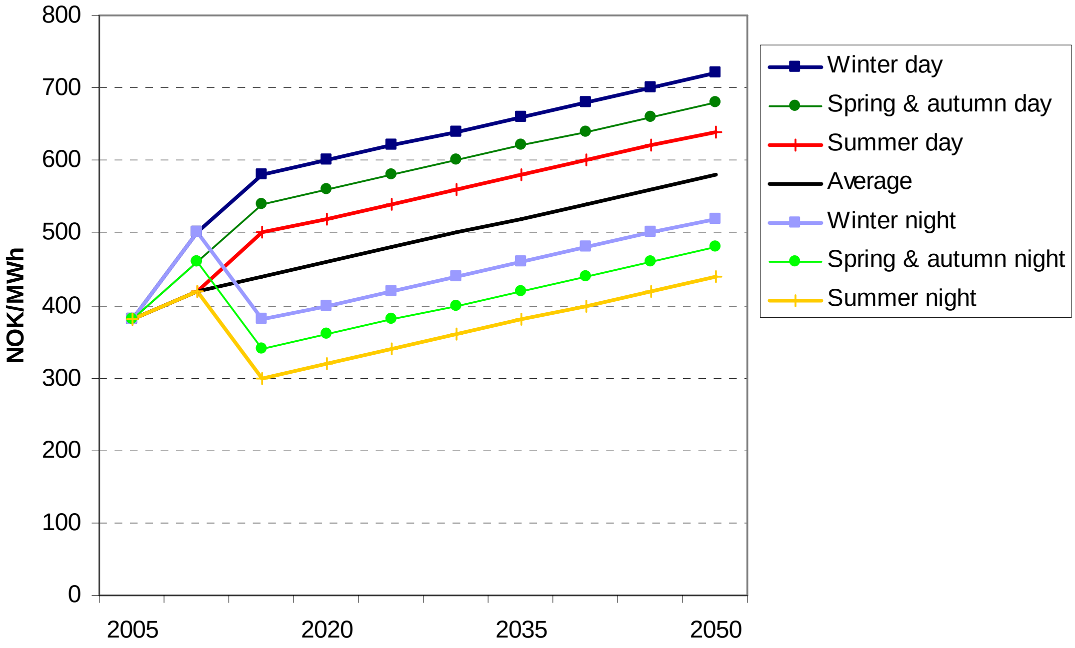

Figure 3 Electricity prices (import and export) 2005-2050 (NOK/MWh)

The price of hydrogen by-product from industry is assumed to be 10% higher than natural gas delivered to industry, as this is considered as a possible substitute for the industry.

The import price of natural gas and ethane is predicted as natural gas in WETO-H2, where the natural gas is expected to be 100 $/ boe in 2050. A linear interpolation of the price is used together with an exchange rate of 6 NOK/$.

All different petroleum products are predicted as crude oil in WETO-H2, where the crude oil price is expected to be 110 $/barrel in 2050. Other products of petroleum are predicted with the same slope as prices from WETO-H2, i.e. the production/delivery cost is kept constant.

The increased price of different biomass products is based on the same slope as for electricity. The price in 2005 is based on Norwegian statistics. Figure 4 shows different biomass prices.

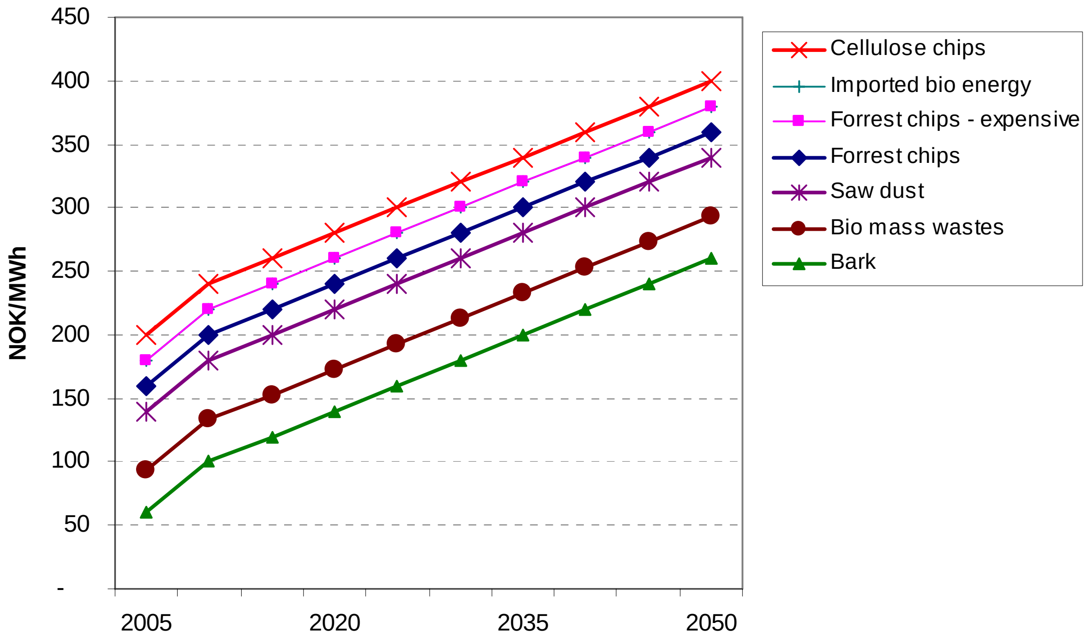

Figure 4 Biomass prices 2005-2050 (NOK/MWh)

A comparison of some different energy prices is shown in Figure 5.

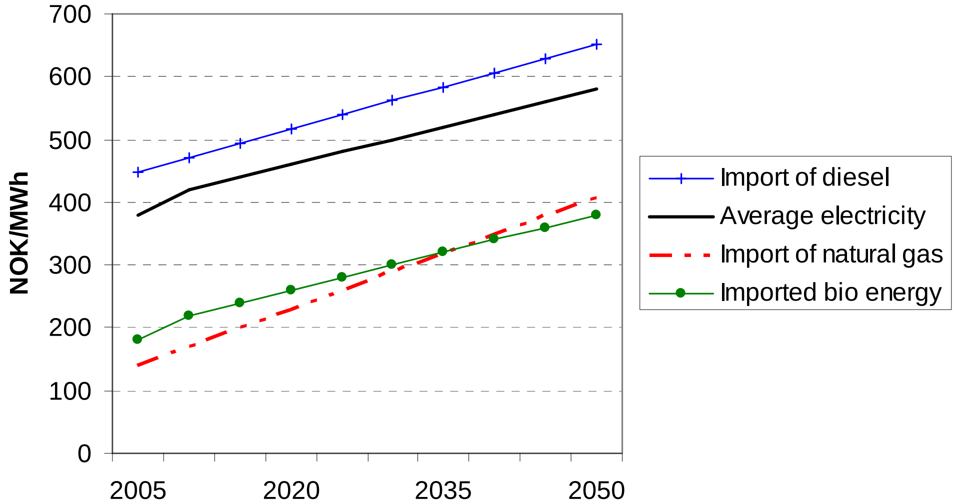

Figure 5 Comparison of energy prices 2005-2050 (NOK/MWh)

In Table 1 the energy prices used in the model, the increase over the analysing period and which driver is used to forecast the energy price is listed.

Table 1 Energy prices (NOK/MWh)

Technology	2005	2010	2020	2030	2050	Increase 2005-2050	Driver
Bio diesel 2. generation	900	922	967	1011	1100	200	El
Biomass	180	220	260	300	380	200	El
Biomass - Pellets	230	253	299	345	436	206	El
Coal (hard coal)	92	96	100	103	103	11	Coal
Coke	140	146	151	157	157	17	Coal
Electricity autumn day	380	460	560	600	680	300	El
Electricity autumn night	380	460	360	400	480	100	El
Electricity average (25 €/ton CO2)	380	420	460	500	580	200	
Ethane	458	487	544	601	715	257	NG
Ethane combi pipe	458	487	544	601	715	257	NG
Ethanol	991	1013	1058	1102	1191	200	El
Hydrogen by-product from industry	145	176	237	298	420	275	NG
Kerosene	539	561	607	652	742	203	Oil
LPG	458	481	526	571	661	203	Oil
Marine diesel	492	520	575	631	742	250	Oil
Natural gas - pipe	132	160	215	271	382	250	NG
Natural gas - ship	141	170	230	289	408	267	NG
Oil - heavy distillate, stationary use	372	395	440	485	575	203	Oil
Oil - light distillate(diesel), transport	448	471	516	561	652	204	Oil
Oil - light distillate, large	425	450	500	550	650	225	Oil
Oil - light distillate, small	520	540	581	621	702	182	Oil
Gasoline	420	443	488	533	623	203	Oil
Rape methyl ether	891	913	958	1002	1091	200	El

In Table 2 the taxes used in the model are presented. They are based on the taxes in 2007 and it is assumed that these taxes will be the same the entire period from 2005 to 2050 in the basic assumptions. The VAT is added to household use and is increasing according to increasing energy prices. Wood fire logs are only used in households, and thus the price includes VAT and is not given separately as a tax. The same is the case for bio-ethanol that is only used by cars. VAT on hydrogen use in cars is estimated to a cost of 250 NOK/MWh, based on “all-inclusive costs” from the infrastructure model. Diesel used by machinery does not have any taxes. Natural gas cars are assumed to be taxed as gasoline cars. VAT is included in order to model the different energy costs for different end-users competing for the same energy carrier, e.g. electricity in industry and households.

The level of CO_2 allowances is based on a CO_2 cost of 200 NOK/ton CO_2. In the period 2008-2012 it will be given free CO2 quotas corresponding to 87% of the emissions in 1998-2001, and it is thus assumed that 13% of the energy use has to pay the CO_2 allowance. This system is assumed to continue until 2050.

The grid tariff is added to count for the consumer costs of electricity use, since the model does not include this.

Hydrogen and bio fuels have no taxes except VAT in the basic assumptions.

Table 2 Taxes in the model, based on the level of taxes in 2007 (NOK/MWh)

Energy	Tax/Subsidy	2005	2050
Oil	CO2 tax on heating oil	54	54
	Energy tax on mineral oil	42.9	42.9
	Sulphur tax on mineral oil	7	7
	VAT on mineral oil and kerosene in households	130	180
NGS	CO2 allowances NGS(energy sector, some industry)	40	40
	CO2 tax NGS	41.5	41.5
	VAT on NGS households (incl. cars)	100	200
LPG	CO2 allowances LPG (energy sector, some industry)	48	48
	CO2 tax LPG	46.9	46.9
	VAT on LPG households (incl. cars)	100	200
Diesel	Autodiesel tax	302	302
	CO2 tax Autodiesel	54	54
	VAT on autodiesel	200	250
Gasoline	Gasoline tax	462	462
	CO2 tax gasoline	89	89
	VAT on gasonline	240	294
Electricity	Tax on electricity	102.3	102.3
	Tax on electricity, reduced rate (industry)	4.5	4.5
	VAT on electricity in households	170	220
	Grid tariff	200	200
	Grid tariff (industry)	73	73
Bioenergy	VAT on pellets	60	110
Hydrogen	VAT on hydrogen use in cars	250	250

VAT in Norway is 25 %.

4.4 Technology costs and efficiencies

Each demand sector has a number of demand technologies fulfilling the exogenously given demand. Most of the technology data is based on previous MARKAL models, with some minor updating [Ettestøl 2006] and [Rosenberg et.al. 2006].

Technology data like investment cost, operational cost, efficiency, life-time etc. for most transport technologies as well as production technologies for hydrogen are gathered in a common spreadsheet used by all parts of the NorWays project (Interface.xls), from here denoted NorWays Interface. The input to this spreadsheet is mainly based on the HyWays project [HyWays], and where available, the widely accepted dataset of the CONCAWE-EUCAR-JRC [CONCAWEWtW].

In the HyWays project the data was collected in the E3database tool [E3database]. All financial calculations in the E3database are based on an interest rate of 8%, and a depreciation period of 20 years (except cables and pipelines which are depreciated over 40 and 50 years, respectively).

The NorWays Interface is updated/adjusted compared to the E3database by the NorWays project for some technologies, in particular hydrogen production technologies. Exchange rates of 1$ = 6 NOK and 1€ = 8 NOK have been used.

Furthermore, forecasts have been established within the NorWays project. The investment cost of vehicles does not include the Norwegian nonrecurring tax. All modelling activities conducted within NorWays have applied the NorWays Interface (MARKAL, Infrastructure Analysis and Energy Chain Calculations).

4.4.1 Vehicles

The only vehicles modelled in detail are cars, busses are modelled partly. Trucks can only chose between fossil diesel and bio diesel.

In urban areas it is possible to choose among all the different types of cars, while in the rural areas it is more restricted. Since the benefit of a higher efficiency of electric cars and hybrid cars with combustion engines is most important in urban traffic, it is assumed that there are no electric or hybrid cars (with combustion engines) in rural areas as shown in Figure 6.

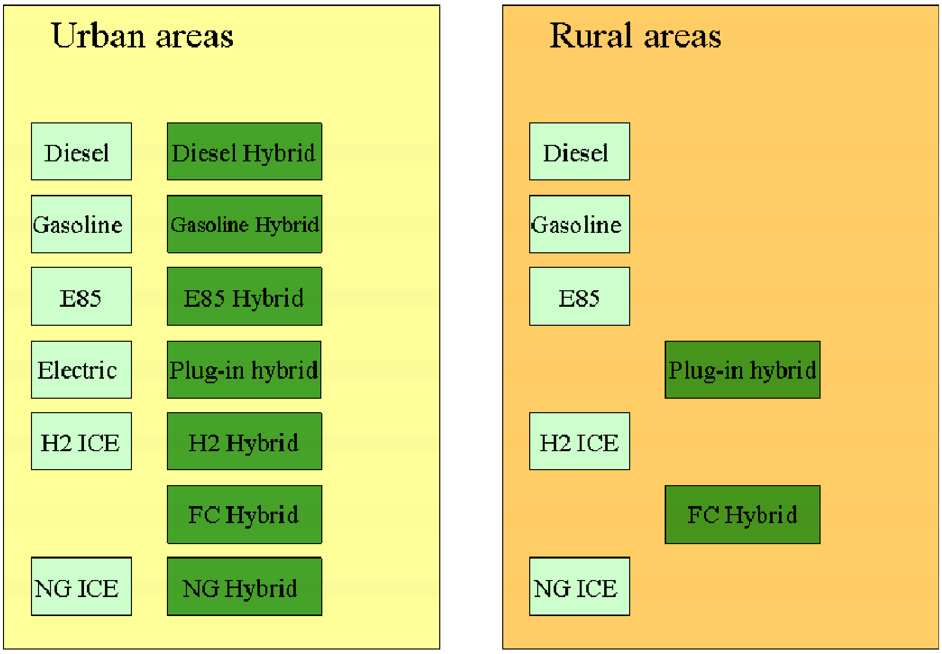

Figure 6 Available car technologies in urban and rural areas

The lifetime is 15 years for all transport technologies, except for fleet vehicles that have a lifetime of 5 years. The annual average mileage used is 14 000 km/car and for fleet vehicles 63 000 km/car [NOU 2004b].

The first year of availability of each transport technology is presented in Table 3. Demonstration technologies may be available earlier at a higher cost.

Table 3 First year of availability of each transport technology

	Fleet vehicles	Car - urban	Car - rural	Bus - local	Bus - long distance	Trucks	Ship	Rail-way	Machi-nery
Diesel	2005	2005	2005	2005	2005	2005	2005	2005	2005
Gasoline	2005	2005	2005						
Natural gas - CNG	2005-2010 [1)]	2005-2010 [1)]		2005-2010 [1)]		2005-2010 [1)]	2005		
El	2005	2005						2005	
E85	2005	2005	2005						
H2 ICE	2010	2010	2010	2010	2010		2020		
H2 FC	2020	2020	2020	2020		2020	2030		
Hybrid gasoline	2005	2005							
Hybrid diesel	2010	2010				2010 [2)]			
Hybrid ethanol	2010	2010				2010 [2)]			
Hybrid CNG	2010-2015 [1)]	2010-2015 [1)]							
Hybrid H2	2015	2015		2015					
Hybrid H2 FC	2020	2020							
Plug-in hybrid	2010	2010	2010						

[1)] Year of availability is dependent on county (2005 in Rogaland and 2010 in Telemark and Oslo)
[2)] Available for delivery trucks in urban areas

The investment cost used in the model (from Interface.xls) is presented in Figure 7 and in Table 4. The costs prior to the year of availability in the model are excluded from the figure. The learning curves are based on the work done in HyWays and Figure 8 shows the investment cost as a function of the production volume. [HyWays]

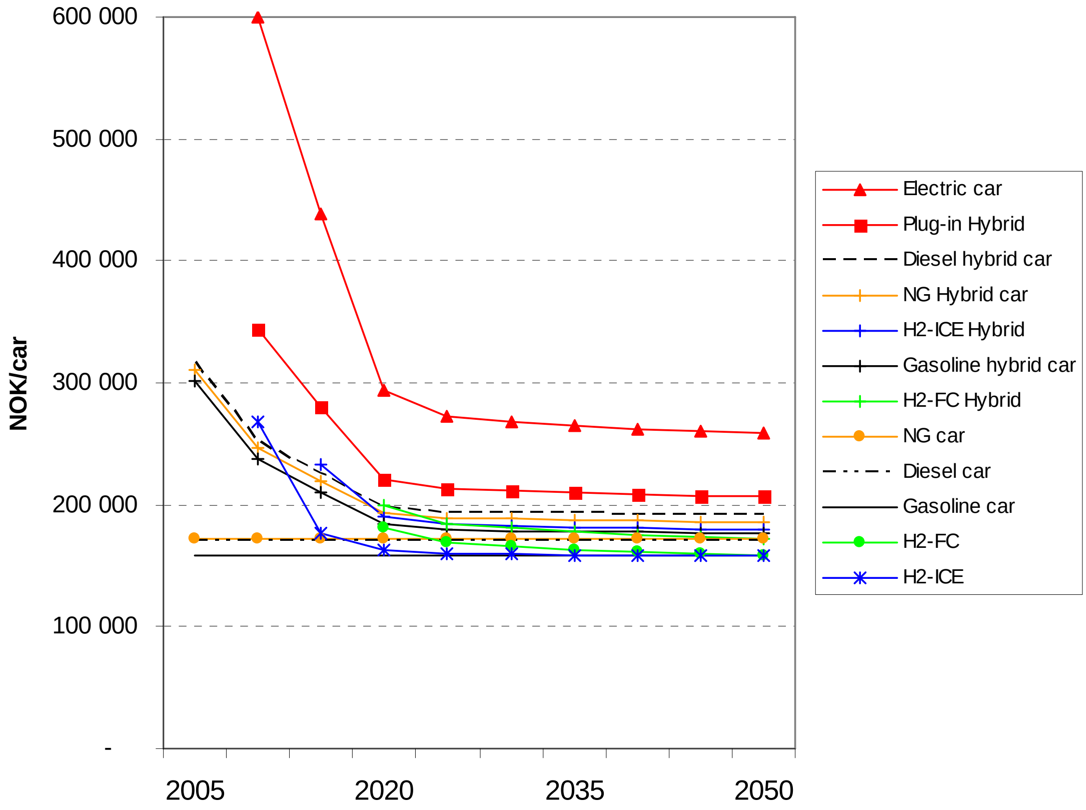

Figure 7 Investment costs for different types of cars in the period 2005-2050 (NOK/car)

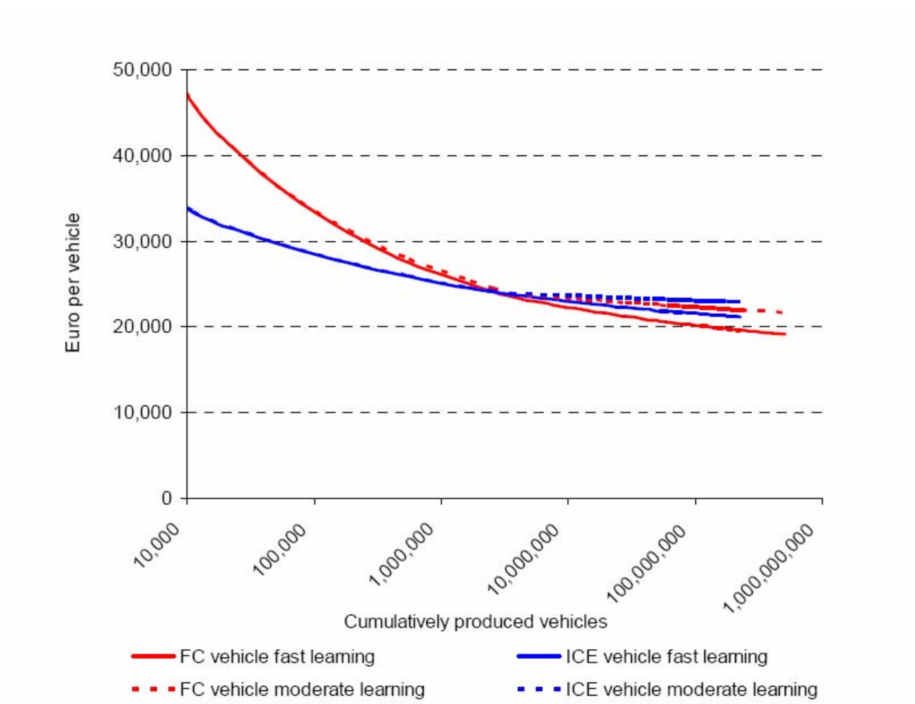

Figure 8 Learning curves from HyWays (Source: HyWays, The European Hydrogen Roadmap, www.hyways.de)

Table 4 Investment costs for different types of cars in the period 2005-2050 (NOK/1000 vehicle-km/year)

	2010	2020	2030	2050
H2-FC car	-	12 919	11 824	11 304
H2-FC Hybrid car	-	14 208	12 921	12 325
H2-ICE car	19 196	11 605	11 405	11 299
H2-ICE Hybrid car	-	13 607	13 066	12 828
Gasoline/ E85 car	11 343	11 343	11 343	11 343
Gasoline hybrid car	16 927	13 117	12 776	12 643
Diesel car	12 206	12 206	12 206	12 206
Diesel hybrid car	17 962	14 151	13 810	13 677
NG car	12 293	12 293	12 293	12 293
NG Hybrid car	17 586	13 776	13 434	13 301
Plug-in Hybrid	24 555	15 821	15 076	14 786
Battery electric vehicle	47 145	24 850	22 985	22 259

Figure 9 shows the fixed operation and maintenance costs of the different cars. All cars with a combustion engine have the same fixed O&M costs and are presented as one line (including plug-in hybrid). The exception is the hybrid hydrogen fuel cell car that has the same fixed O&M costs as the hydrogen fuel cell car. The costs prior to the year of availability in the model are excluded from the figure.

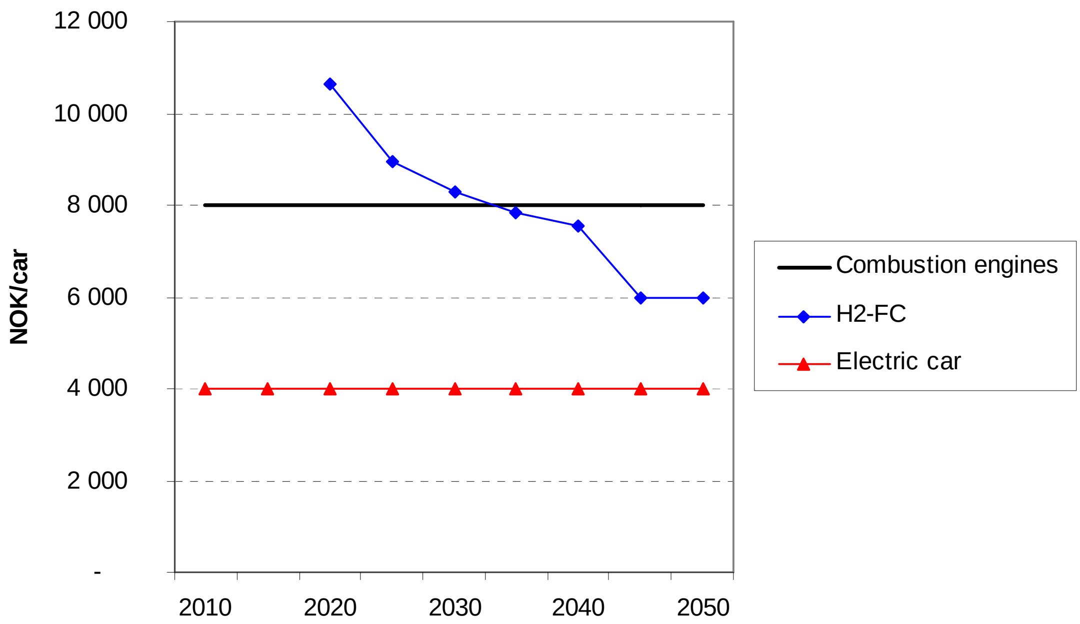

Figure 9 Fixed operational and maintenance costs for different cars in the period 2005-2050 (NOK/car)

The efficiency of combustion engines is different in urban and rural areas in the MARKAL analysis, see Figure 10. The efficiency in urban areas is based on an assumption that 70 % of the travel is in cities and 30% is longer distances in combination with the manufacturer information on efficiencies when driving in cities or at longer distances. In rural areas 30 % of the travel is assumed to be in cities and 70 % is longer distances. For a gasoline car this gives an efficiency in urban areas of 8.2 liter/100 km and in rural areas of 6.7 liter/100 km. The same relationship between rural and urban travel efficiencies is assumed for the natural gas combustion car and the hydrogen combustion car. In the basic assumptions, all efficiencies are kept constant during the whole period.

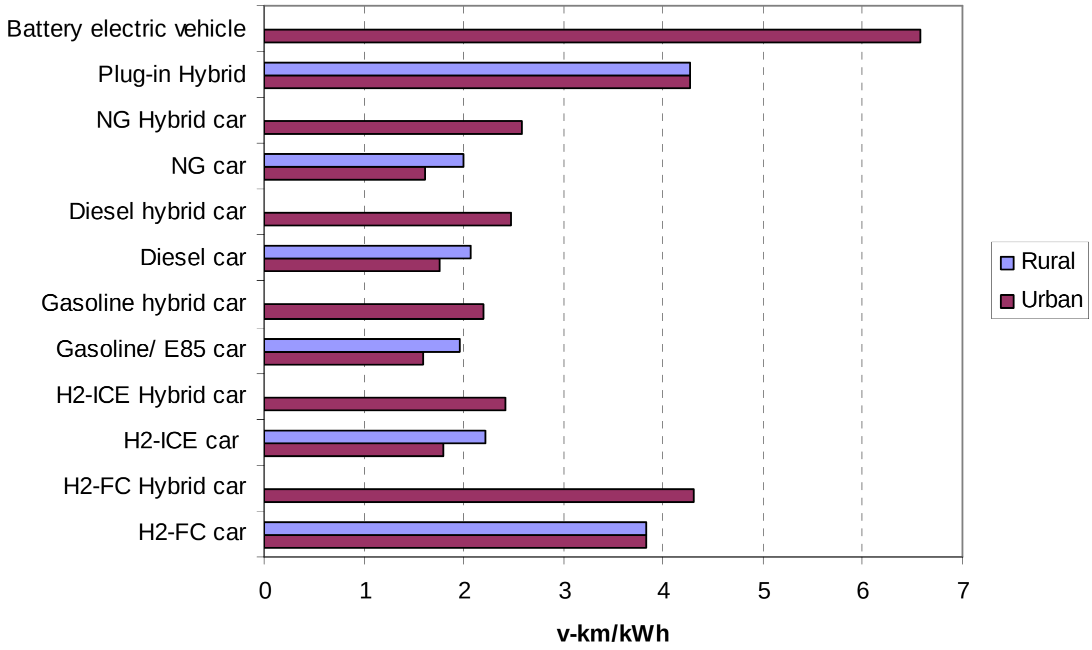

Figure 10 Car efficiency (constant in the period 2010-2050) given as vehicle km per kWh.

4.4.2 Production of hydrogen

Biomass

The cost of production of hydrogen by gasification of biomass in the MARKAL analysis is based on information from Mueller-Langer [2007] when it comes to large scale production and on “The H2 Economy Book” for small scale production. These figures differ from the CONCAWE study [CONCAWEWtT] used in the E3database, but are considered as the best to use in the base scenario in this study. The parameters of the CONCAWE study are constant during the entire period, while the figures used in the MARKAL analysis improves in the future. The investment costs in large plants are even lower in 2050 in the Mueller-Langer study than in CONCAWE study, but the efficiency never reaches the same high level as in CONCAWE study.

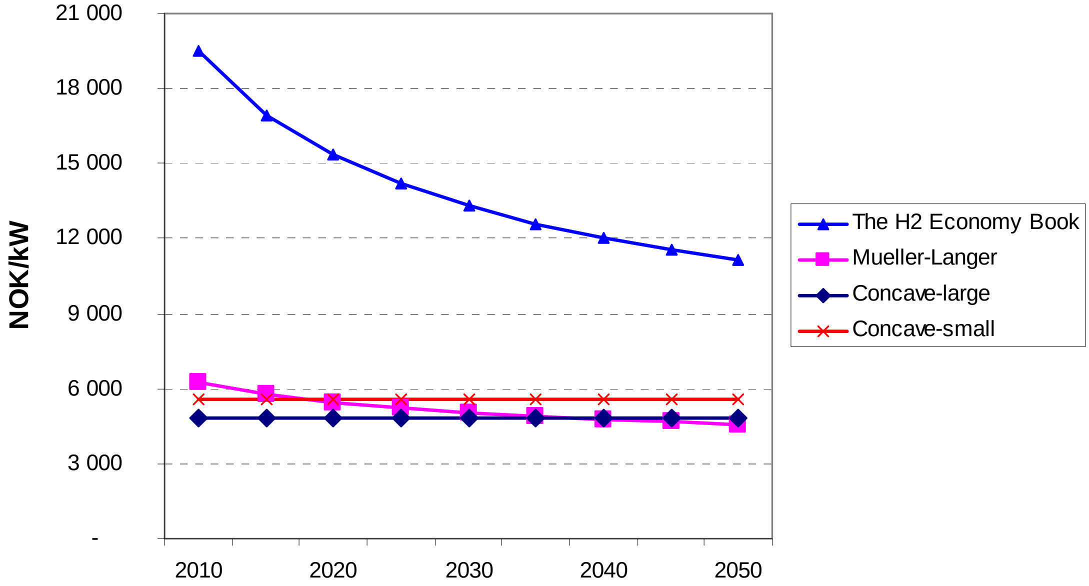

Figure 11 Comparison of investment costs for biomass gasification in CONCAWE and MARKAL (Mueller-Langer - The H2 Economy Book) (NOK/kW)

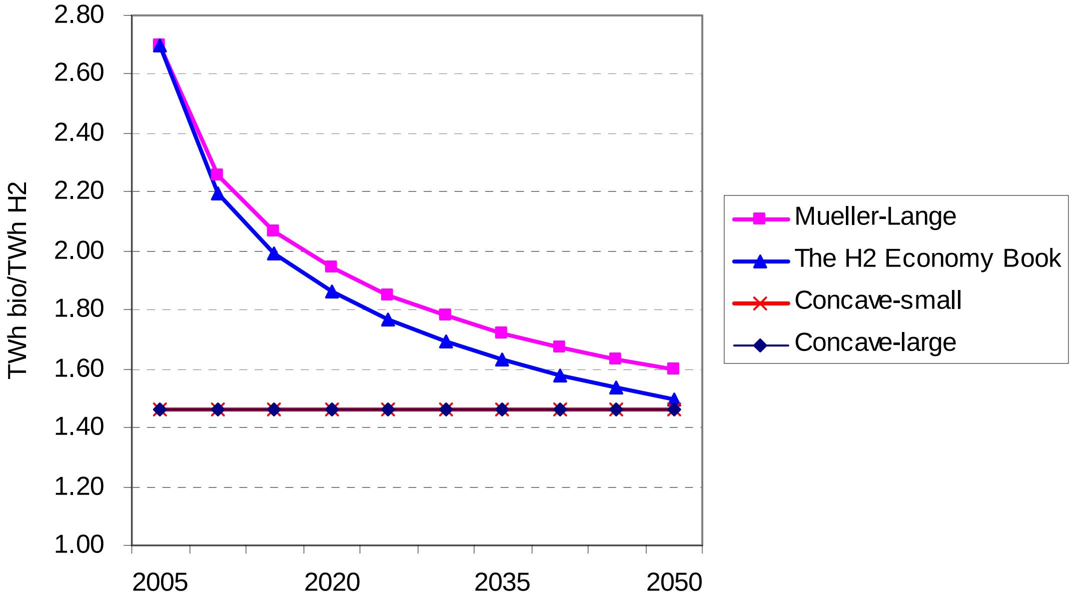

Figure 12 Use of biomass per produced hydrogen in CONCAWE and MARKAL model (Mueller-Langer - The H2 Economy Book) (TWh biomass / TWh H_2)

Comparison of different technologies for production of hydrogen

The investment costs of most hydrogen production technologies are expected to be considerable reduced from today up to 2050, see Figure 13.

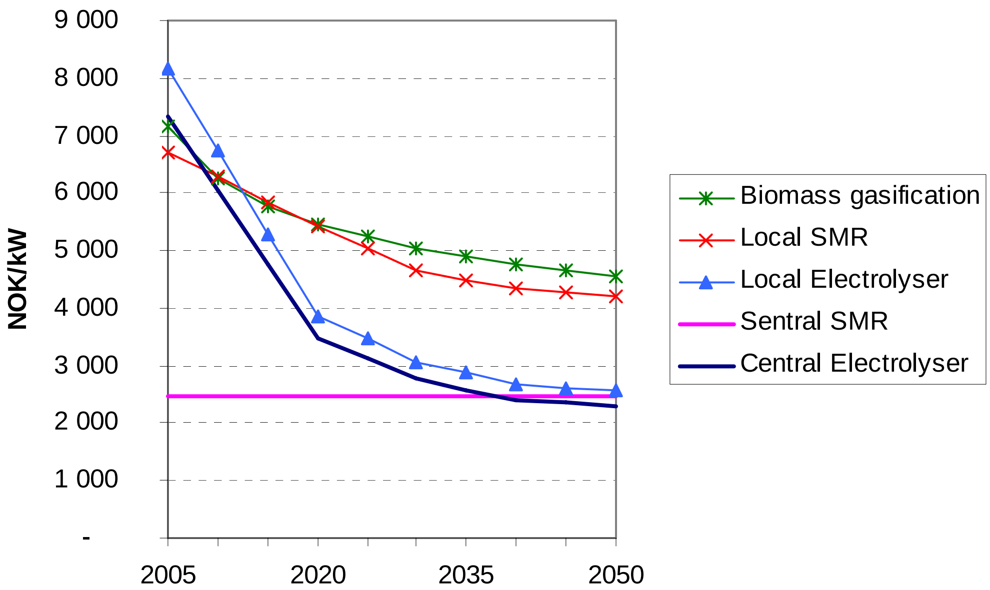

Figure 13 Investment costs of some hydrogen production technologies (NOK/kW)

The energy prices are expected to increase considerable during the period and in combination with reduced investment costs, this makes the energy price a more important variable the later the time period. To illustrate this, a comparison of the capital cost and energy cost of central electrolysers are shown in Figure 14. The electricity price is an average with a quota price of 25 €/ton CO_2. In this case the energy cost represents 86 % today and 96 % in 2050.

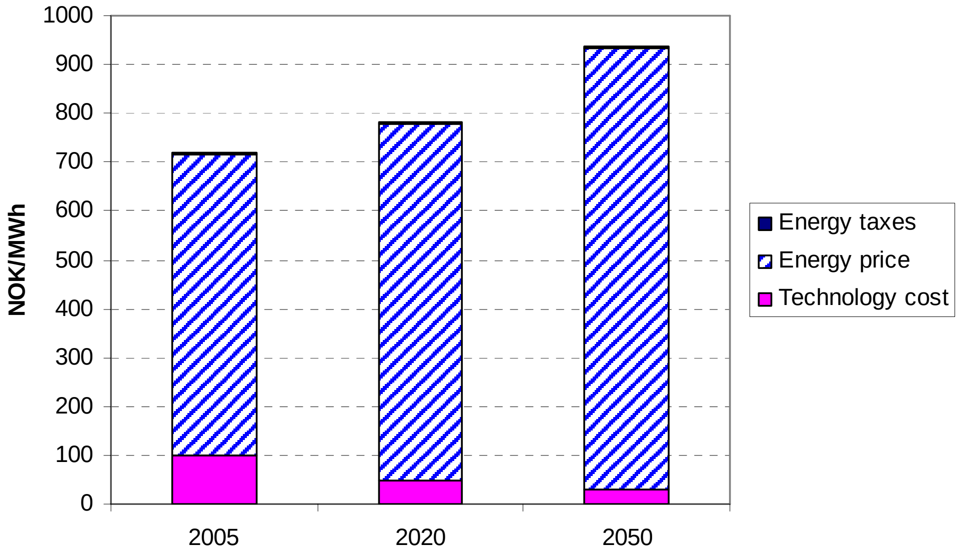

Figure 14 Production cost of hydrogen in a central electrolyser plant in 2005, 2020 and 2050 (NOK/MWh H_2)

The hydrogen production costs for some of the possible technologies that can produce hydrogen in the MARKAL models are presented in Figure 15. The cost is divided into investment cost, energy price and taxes. If the plant does not operate at full time, the investment cost per produced MWh hydrogen will increase, while the energy cost is unchanged.

The operation time of the hydrogen production plants is quite important, and in the figures here it is assumed to be fully utilised, while the MARKAL models makes a total optimization of all the alternatives that might result in reduced operation times.

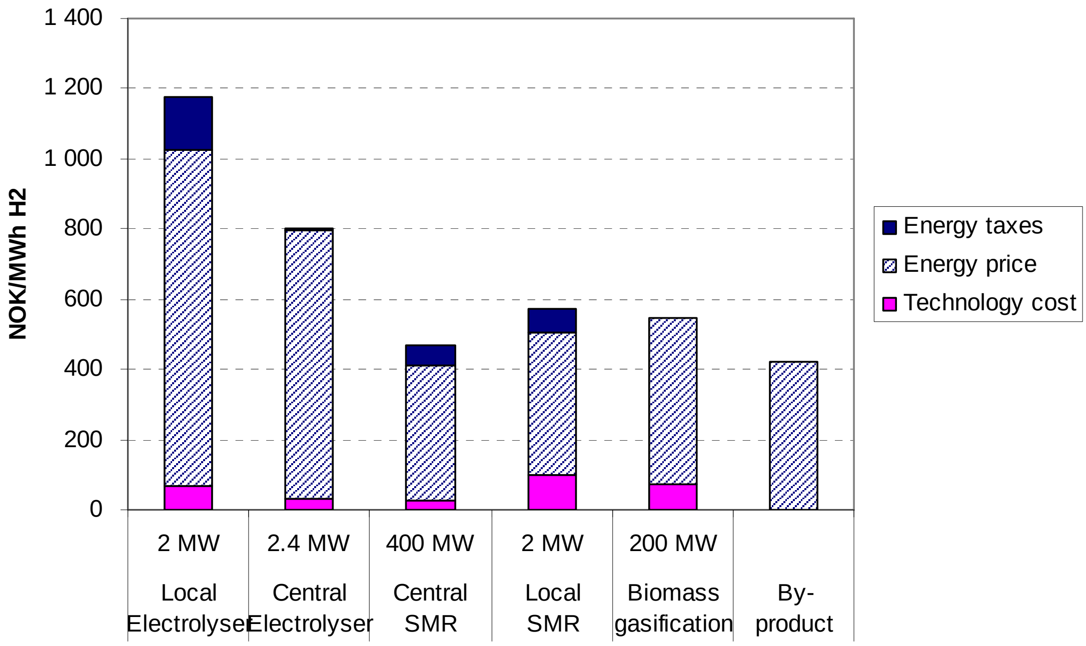

Figure 15 Hydrogen production costs for some technologies in 2020 in Telemark (the energy delivery cost varies in the different regions), NOK/MWh H_2

The production costs for hydrogen with different technologies are presented in Figure 16. The cost does not include delivery costs or taxes of energy and assumes full utilisation of the capacity. Hydrogen available as an industrial by-product is the cheapest alternative, however it is a restricted resource and of the regions considered, only available in Telemark. In 2020 production of hydrogen with SMR is assumed to cost approximately 350 NOK/MWh H_2. In 2050 with higher natural gas prices the production cost is estimated to 588 NOK/MWh H_2. A central electrolysis plant may produce hydrogen at a cost of approximately 730 NOK/MWh in 2020 increasing to 870 NOK/MWh in 2050. Large scale biomass gasification will with the given energy prices have a production cost of 612-696 NOK/MWh H_2.

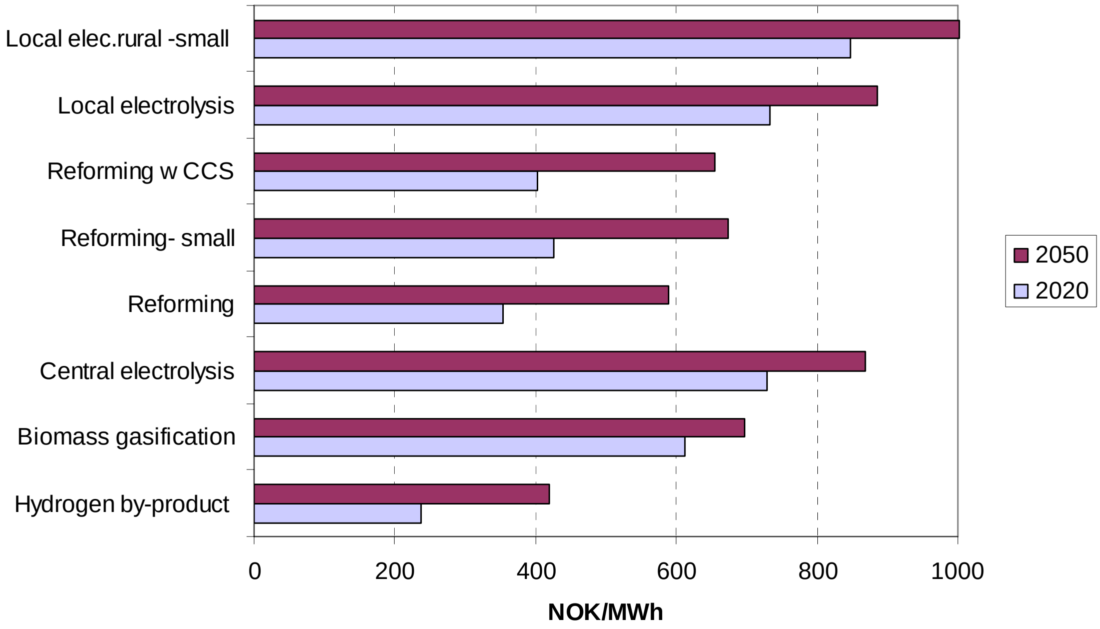

Figure 16 Example of production cost of hydrogen with different technologies (NOK/MWh)

5 Interaction with the Infrastructure model

5.1 Methodology

The infrastructure models developed within the NorWays project optimizes the evolution of a hydrogen supply infrastructure for a given demand development. The models have a higher level of detail of hydrogen technologies and infrastructure, as technical, geographical economical and commercial parameters are combined in the optimization routine, and are particularly useful for the screening and analysis of hydrogen in the transportation segment.

In the main runs, the infrastructure model is referring to the hydrogen penetration and demand assumptions from the NorWays report Viable Markets and Regions for introduction of hydrogen in the Norwegian energy system, scenario B [Svensson et.al, 2008]. To validate and calibrate the MARKAL assumptions on hydrogen distribution, an iteration routine between the infrastructure model H2INVEST and MARKAL has been performed where the infrastructure model would feed transport costs and distances to MARKAL and MARKAL would feed back the hydrogen demand for rural and urban areas to the infrastructure model. The infrastructure model H2INVEST is described in [NorWays D8b 2008].

The interaction between MARKAL and the H2INVEST model is in general as described in the following steps (and as shown in Figure 17):

1. Hydrogen technology data from the NorWays interface was implemented in the MARKAL and infrastructure model

2. Demand for hydrogen by filling station (based on results related to penetration rates of vehicles from HyWays) was used as a starting point for hydrogen demand in the Infrastructure model

3. Demand for hydrogen by region and type was calculated by MARKAL and the demand was entered into the Infrastructure model.

4. Updated costs and distances for transportation of hydrogen was calculated by the Infrastructure model and entered into MARKAL.

5. New iteration with revised cost assumptions (3-4) was carried out four times to obtain a converging solution.

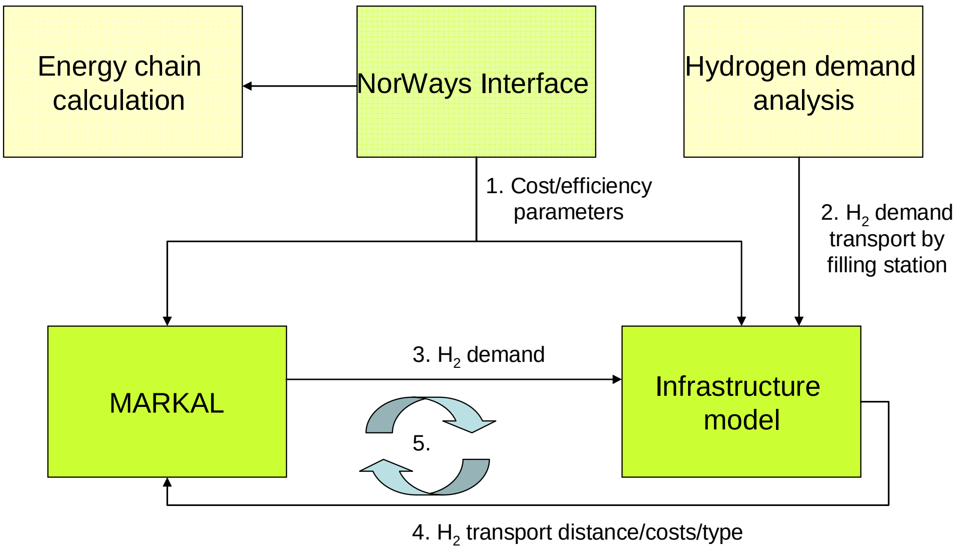

Figure 17 Linking of MARKAL and the H2INVEST models within the NorWays project

5.2 Results

As a starting point for the MARKAL model of Telemark the assumption for H_2 transport was pipeline transport (5 km) and trailer (20 km) in urban areas. In rural areas only trailer was an option, with distances of 50 and 100 km.

The results from the H2INVEST model of Telemark after a few iterations gave a total transport length by pipeline in urban areas of 10.2 km giving a total investment cost of 660 NOK/kW, which is twice as much as originally assumed. The average distance for trailer distribution of hydrogen in urban areas was 8.7 km and the costs and fuel consumption is changed to 750 NOK/kW and 0.004 kWh diesel/kWh H_2. In rural areas all hydrogen is transported by trailer and the average distance is 54 km in 2050. In the

MARKAL model one trailer with an average distance is used (one in urban and one in rural), instead of having a share of trailer transport at different distances (due to simplicity).

The iteration converged to a scenario where the hydrogen fuel cell car started by 2025 in the urban and 2030 in the rural areas and achieved 100% penetration by 2035 in the urban areas and by 2045 in the rural areas. This confirms that in a MARKAL scenario with realistic hydrogen distribution efforts, fuel cell cars become competitive against other technologies both in urban and rural areas.

The results from the iterations between the MARKAL and H2INVEST models for Telemark are also used in the MARKAL models for Rogaland and Oslo.

Another result of the interaction process is restrictions on the share of hydrogen used in urban areas that can be transported by pipeline. In Telemark and Rogaland at least 50 % has to be locally produced or transported by trailer and in Oslo this figure is 5 %.

6 Scenarios and sensitivity analyses

The main reason for developing scenarios in the NorWays project, is to analyze how hydrogen can be introduced in the Norwegian energy system. The scenario analysis assesses how policy instruments can contribute to an early introduction of hydrogen. To be able to achieve huge reductions in CO_2 emissions in Norway, the transportation sector needs a shift from fossil fuels to low or no CO_2 emission fuels. The scenario analysis shows how taxes, restrictions and energy prices have an impact on the production and use of hydrogen.

The scenario analysis also assesses the impact of availability and cost of different hydrogen end-use technologies (e. g. fuel cell vehicles) compared to other end-use technologies (e.g. plug in hybrids) and assesses the impact of the availability and cost of different resources for hydrogen production.

6.1 Overall description

There are large uncertainties about future costs and energy prices. Thus to analyse the effects of the assumptions used we have analysed several different scenarios in combination with sensitivity analysis of especially energy prices and investment costs.

The basic assumptions described in this report are referred to as the HYWAYS scenario. These assumptions are based on the results from the HyWays project. An important input to this project is the deployment of hydrogen cars at different times and hence the investment cost of vehicles.

No changes in energy policies are assumed except that a tax on natural gas driven cars is included. This is because it is unlikely from an environmental aspect too. It is shift from heavy taxed gasoline and diesel cars to natural gas cars without tax.

To compare the results with the situation today, a reference scenario based on the Baseline of World Energy Outlook [IEA 2008] is introduced. The baseline of WEO uses 3 % biofuels, and the rest is petroleum products. The share of gasoline and diesel is almost the same. For simplicity, it is assumed that the reference scenario in this project uses only petroleum products with the same share of gasoline and diesel as today.

Table 5 Analysed scenarios

Category	Scenario	Description
Reference	REF	A reference scenario based on the assumptions of WEO with no new transport technologies
Basic assumptions	HYWAYS	Basic assumptions with technology costs (H_2) based on the HyWays project
Taxes	TAXNO	No taxes on transport energy (“revenue neutral”)
CO2	CO2-R	Reduced CO_2 emissions by 75% in 2050, by 66% in 2030 and by 20% in 2020

Table 6 Sensitivity analyses

Sensitivity analyses	Description
Prices	**Changes in oil and natural gas prices**
OIL110-200	Higher oil prices from 2010, 200 $/bl in 2050, no change in natural gas price
OIL200	200 $/bl in 2015-2050, no change in natural gas price
OIL110-200-NG65-163	Higher oil prices from 2010, 200 $/bl in 2050, 70% of oil price increase reflected in natural gas price
OIL200-NG163	200 $/bl in 2015-2050, 70% of oil price increase reflected in natural gas price
Cars	**Changes in car parameters**
CARH2	Delayed cost reduction for H_2 cars by 10 years
CARPLUG	Sensitivity for investment costs of plug-in hybrids
CARSENS	Sensitivity for investment costs, operation and maintenance costs and efficiencies of cars
H2 production	**Changes in hydrogen production cost and availability**
H2PRODBIO	Sensitivity for biomass gasification
H2PRODEL	Sensitivity for investment costs of large electrolysers
H2PRODIND	More H_2 as by-product available from industry in Telemark
Biomass	**Different restrictions and costs of biomass technologies and use**
BIOIMP	Import of biodiesel is not allowed to the region
BIODSL	Sensitivity for investment cost of biodiesel production

6.2 Scenario – Tax neutral

A simple way of analysing the effects of taxes on transport energy is to delete all taxes in the model. Since less energy is used by e.g. electrical cars than gasoline cars this will not be the same as a revenue neutral tax system, but it is a simple way to show some of the effects of taxes on traditional energy like gasoline, diesel and natural gas while hydrogen, bio fuels and electricity has less or no taxes. The taxes in all other scenarios are those described in Table 2.

6.3 Scenario - Reduced CO_2-emissions

For the CO2-R scenario, a restriction on CO_2-emissions starting in 2020 with a reduction of 20% of the emissions in 1990, followed by a reduction of 66% in 2030 and a linear decrease to 75% reduction in 2050 is assumed. There are no restrictions before 2020.

In Rogaland the model does not include alternatives for reduction of CO_2-emissions for the use of raw materials in the metal industry (production of aluminium and ferro alloys) and the Kårstø plant. These emissions are therefore excluded from the scenario and the reduction is only applied on all other CO_2-emissions.

Table 7 Limitation on CO_2-emissions (1000 tons)

	1991	2020	2030	2050
Reduction		20 %	66 %	75 %
Oslo	1078	862	367	270
Rogaland	3213	2955	2362	2245
Telemark	2222	1 778	755	556

6.4 Sensitivity of prices of petroleum products

The sensitivity of higher prices of oil and natural gas is analysed in four different combinations. In all cases are the electricity price and the prices of biomass kept the same as in the basic assumptions and as presented in Table 1. It is the relative changes in prices that are most important in these analyses, not the absolute price of each energy carrier.

In the OIL100-200 scenario the price of crude oil is 100 $/barrel in 2010 and 200 $/barrel in 2050. The increase for crude oil is applied for oil products related to the oil price. This includes the price of heavy distillate, light distillates, diesel, gasoline and kerosene.

In the OIL200 scenario the price of crude oil is constant at 200 $/barrel in 2010 to 2050. In both these scenarios the prices of all other energy carriers like natural gas, electricity and biomass is kept constant.

In two alternative scenarios it is assumed that the natural gas price increase by 70% of the crude oil increase, i.e. the natural gas price in 2010 is 65 $/boe and 163 $/boe in 2050 in the scenario OIL100-200-NG65-163 and 163 $/boe in 2010-2050 in the scenario OIL200-NG163. In the model the import of natural gas and ethane by ship and pipeline is increased in the same way as the oil products.

Figure 18 illustrates the increased prices in the different scenarios. It is only the prices of diesel and natural gas delivered by ship that is shown, but the other products follow the same development. In the OIL100-200 and OIL200 the natural gas price is as in the basic assumptions.

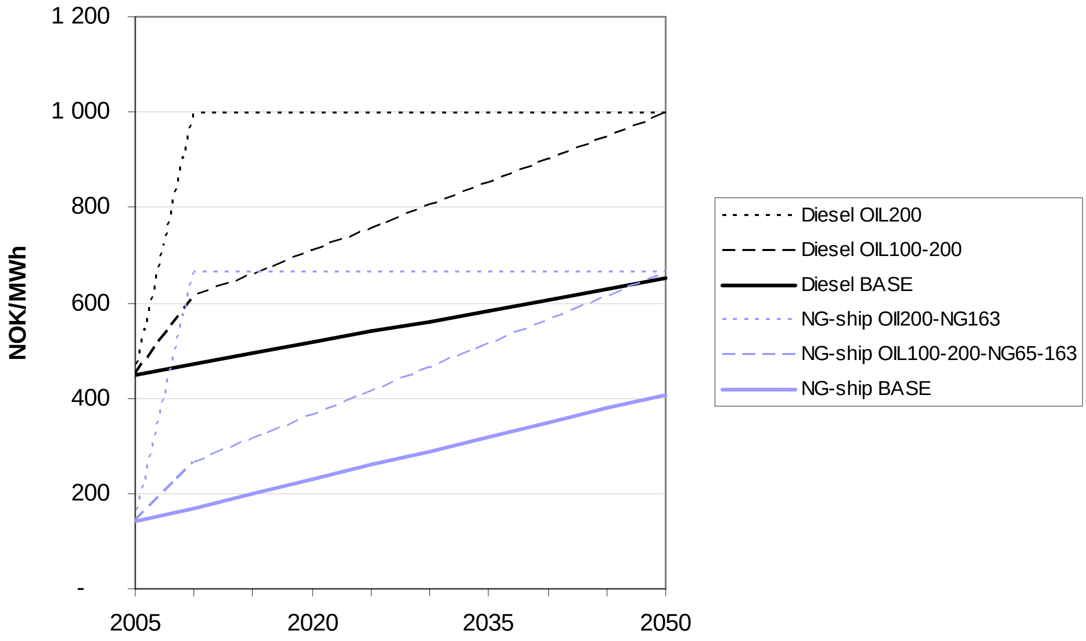

Figure 18 Prices of diesel and natural gas by ship in the basic assumptions, and the different alternatives with higher oil and natural gas prices (NOK/MWh)

6.5 Sensitivity of car parameters

CARH2 Delayed cost reduction for H_2 cars by 10 years

The cost reduction of hydrogen cars is postponed by 10 years, i.e. the cost in the basic assumption of 2010 is kept constant until 2020 and the cost of 2020 in the basic assumption is the scenario cost of 2030 etc. There are no changes for other vehicles that can use hydrogen, since they do not use hydrogen in the basic assumption.

CARPLUG Sensitivity for investment costs of plug-in hybrids

The investment cost of plug-in hybrid cars is reduced until the model chooses to use them in each region.

CARSENS Sensitivity for investment costs, operation and maintenance costs and efficiencies of cars

An alternative development of investment costs of most cars (all except gasoline, diesel and natural gas cars) is included in the Interface-sheet, used as a technology database in this project. The difference between the basic assumptions and the alternative investment costs is presented in Figure 19. The investment costs of battery electric vehicles and plug-in hybrids are reduced and the costs of hydrogen FC and ICE cars are increased. The investment costs of all hybrid cars are also decreased. In addition to changes in investment costs, the operation and maintenance costs of hydrogen fuel cell cars (incl. hybrid) are increased and the efficiency is reduced.

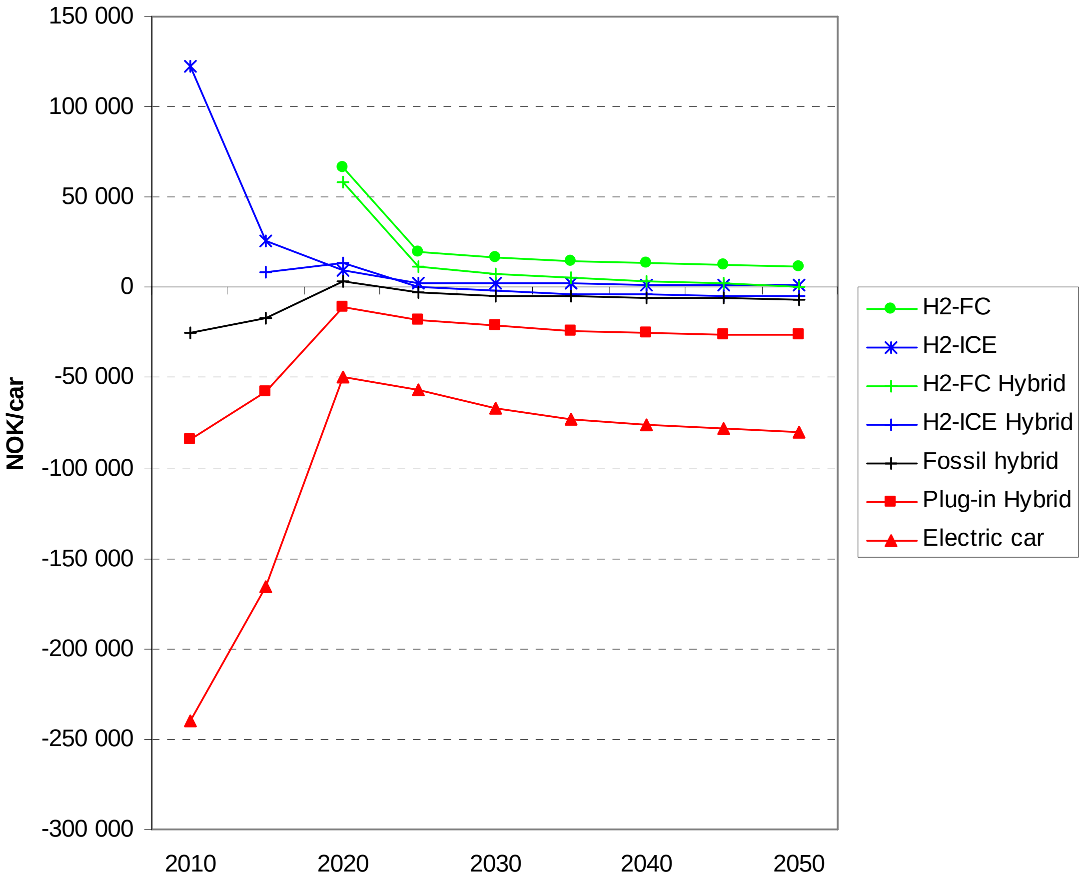

Figure 19 Changes in investment cost of cars in scenario CARSENS compared to the basic assumptions (NOK/car)

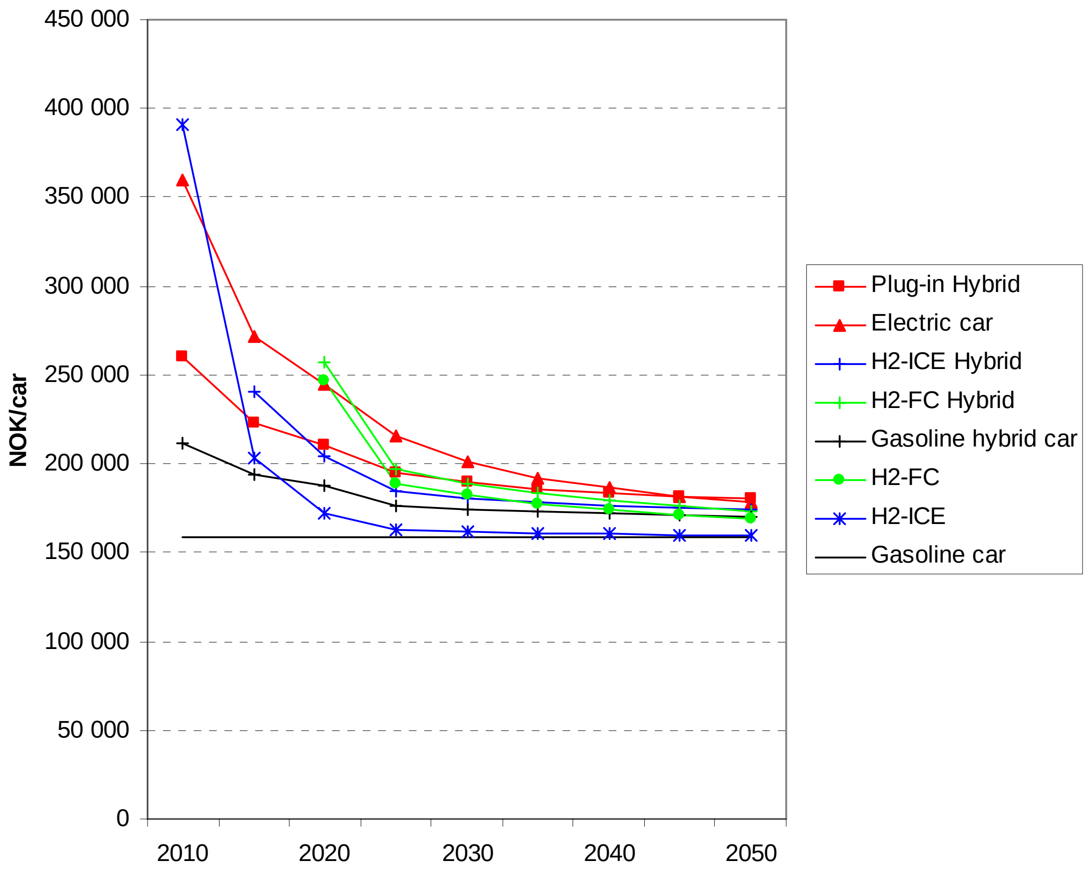

Figure 20 Investment costs of some of the cars in the CARSENS analysis 2010-2050 (NOK/car)

6.6 Sensitivity of hydrogen production cost

The sensitivity of the investment costs and efficiencies of hydrogen production from biomass gasification and from large electrolysers are analysed by decreasing the investment cost and/or increasing the efficiencies until the technology is chosen.

In Telemark there is also an alternative with more by-product hydrogen available from industry. In the basic assumptions available by-product is approximately 10000 Nm^3/hr, increasing to 44000 Nm^3/hr in the H2PRODIND scenario.

6.7 Sensitivity of restrictions and costs of biomass technologies and use

Each region has both own biomass resources and the possibility to import both biofuels and biomass from other regions (or abroad) in the basic assumptions. The consequences of not allowing import of biodiesel to the region is analysed, since biomass for biodiesel production might be a scarce resource and hence a region has to be able to produce biofuels from own resources if it is a sustainable alternative. In addition sensitivity analysis for investment cost of biodiesel production is analysed.

7 Results

The main focus of the analysis has been on car types and hydrogen production technologies and these analyses are described in detail in chapter 7.1 and 7.3. To complete the picture, the entire transportation sector is briefly described in chapter 7.2, as well as use of biomass in all sectors in chapter 7.4 and electricity production and use in chapter 7.5.

7.1 Cars

The three scenarios HYWAYS, TAXNO and CO2R are described first, followed by a sensitivity analysis of energy prices, technology costs and car efficiencies.

"Cars" includes both private and fleet vehicles, and the private cars are divided into use in urban and rural areas in the three analysed regions.

7.1.1 Scenarios

HYWAYS-scenario (basic assumptions)

Hydrogen cars will be introduced in 2020 in Rogaland and Telemark but not in Oslo, with the basic assumptions as shown in Figure 21. The gasoline cars of today will first be replaced by diesel cars with a high share of biodiesel in all regions. The introduction of hydrogen cars comes first in urban areas of Rogaland and Telemark. Due to lower hydrogen cost in Telemark, the combustion engine with lower investment cost and lower efficiency is used here, while the fuel cell cars are used in Rogaland where hydrogen is somewhat more expensive.

Due to higher production costs for hydrogen in Oslo (see chapter 7.3) no hydrogen cars will be used in Oslo. Until 2025 the model invests in diesel cars with a high share of biodiesel. From 2030 the investment costs of plug-in cars has become low enough to be the most economic choice (in combination with high efficiency and low energy cost). New fleet vehicles are plug-in cars already from 2020.

After 2020 all new cars in both rural and urban areas of Rogaland and Telemark are fuel cell cars and from 2030 it is invested in plug-in hybrids in Oslo, due to more expensive hydrogen.

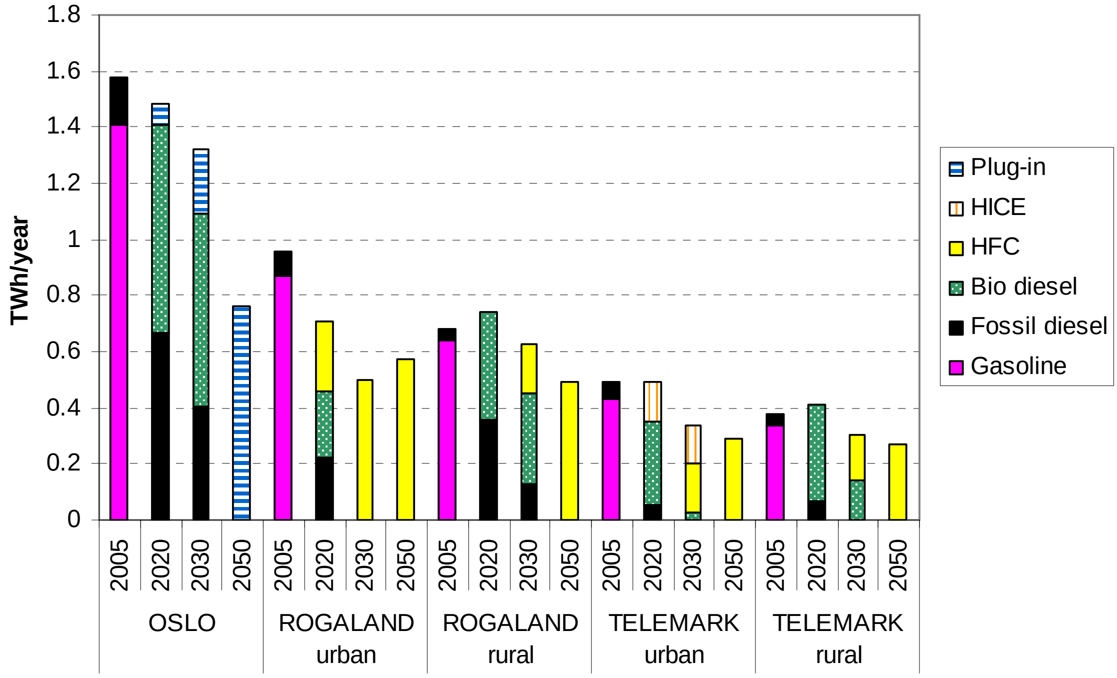

Figure 21 Energy use by car types 2005-2050 in the HYWAYS-scenario (TWh/year)

The energy consumption is reduced due to more efficient hydrogen fuel cell cars and plug-in hybrids in 2050 compared to combustion engines today, see chapter 7.1.3.

Biodiesel is used in all regions with the basic assumptions of the HYWAYS scenario. The models do not distinguish between biodiesel used by buses, cars or trucks and therefore it is assumed that the biodiesel share is the same in all types of road traffic. Biodiesel is further discussed in chapter 7.2.

Tax neutral scenario (TAXNO)

If all taxes are deleted from the models, more gasoline and natural gas will be used and the introduction of hydrogen cars is delayed. Natural gas cars will be used in the urban areas of Rogaland and Telemark, while gasoline is used in rural areas and in Oslo, due to lower energy prices without taxes and then the more expensive cars are not profitable. Biodiesel will not be used in any of the regions in the TAXNO scenario because biodiesel is only a competitive option due to reduced taxes.

In 2050 the use of hydrogen by cars are almost the same as in the HYWAYS-scenario with basic assumptions in Telemark.

In Rogaland hydrogen is only used to a small extent in urban areas in 2050, while all cars in both urban and rural areas used hydrogen in the HYWAYS-scenario. In rural areas of Rogaland only gasoline cars will be used in the TAXNO scenario. In urban areas it is first investments in natural gas cars and then in fuel cell cars.

In Oslo, hydrogen cars are used in the TAXNO-scenario but not in the HYWAYS-scenario, due to cheaper natural gas for hydrogen production in a central SMR-plant.

New car technologies are only competitive in the mid-term if there are high tax differences between fossil fuels and other fuels (hydrogen, electricity and bio-fuels).

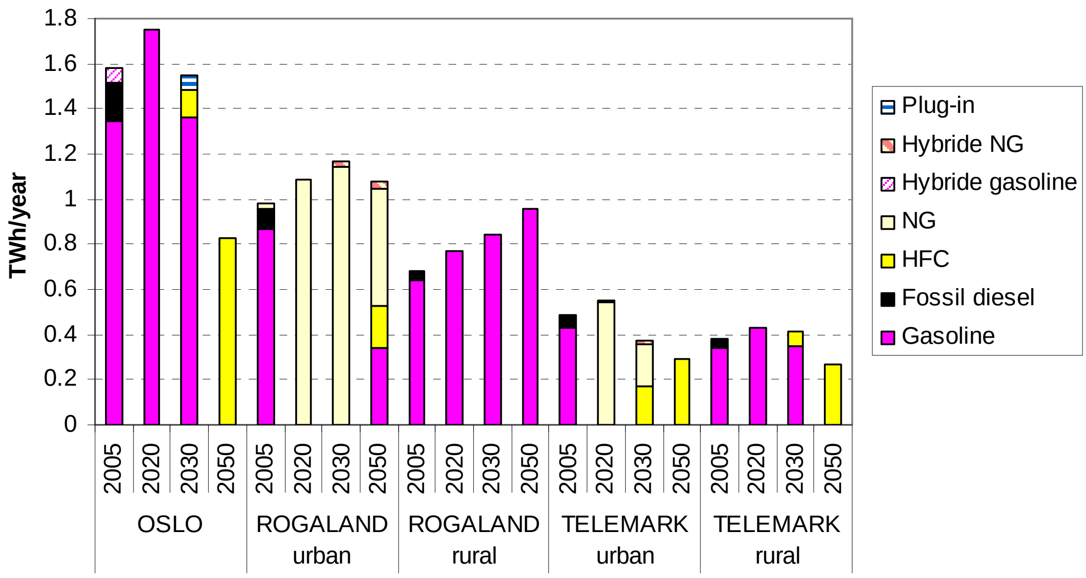

Figure 22 Energy use by car types 2005-2050 in the TAXNO-scenario (TWh/year)

CO2R-scenario

In the CO2R-scenario with limitations on CO_2-emissions more hydrogen cars are used in Oslo than in the HYWAYS-scenario, since the plug-in hybrids also use gasoline and the emissions will then decrease if hydrogen produced from biomass is used instead as in Oslo in 2050.

In rural areas of Rogaland, ethanol cars are introduced in 2020 and are still in use in 2030. In rural areas of Telemark, hydrogen combustion engines come in use instead in 2020-2030. In urban Telemark and in Oslo, the share of fuel cell cars is higher in 2020 and 2030 than in the HYWAYS-scenario, while it is the same in urban areas of Rogaland. In urban areas of Telemark, hydrogen combustion engines are also used in 2020-2030.

With limitations on CO_2-emissions hydrogen cars are used earlier and to a higher extent.

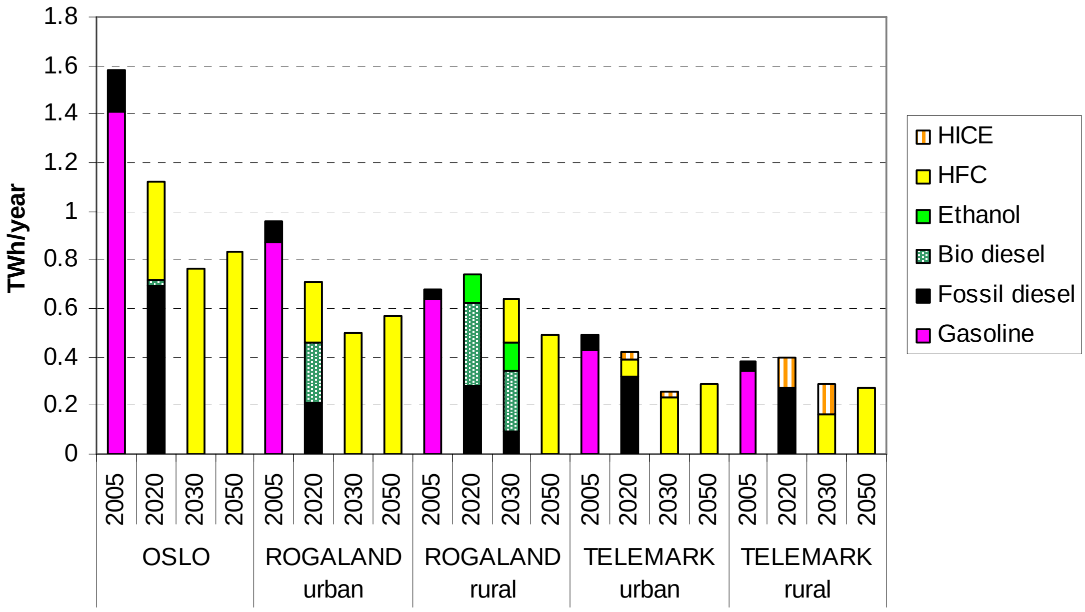

Figure 23 Energy use by car types 2005-2050 in the CO2R-scenario (TWh/year)

7.1.2 Sensitivity analyses

The following sensitivity analyses are all performed based on the HYWAYS-scenario. The different assumptions of the sensitivity analyses are described in more detail in chapter 6.

Higher oil and gas prices

When the oil and gas prices are increased, the share of bio-diesel increases in all regions and time periods. Biodiesel is further described in chapter 7.2. Ethanol is used in 2020 instead of diesel in Telemark and in rural Rogaland in the OIL200-NG163-scenario. The use of hydrogen is decreased in 2020 in all areas but urban Telemark and Oslo. In 2030 the use of hydrogen decreased in urban areas of Rogaland. In rural areas of Rogaland and in Telemark in 2030 there are no changes compared to the basic assumptions, except that hydrogen fuel combustion cars are replaced by fuel cell cars. In the HYWAYS-scenario hydrogen is produced by central SMR and the price increases with increased gas price. In 2050 the consumption is as in the basic assumptions of the HYWAYS-scenario in Rogaland and Telemark, while the plug-in hybrids in Oslo is replaced by fuel cell cars, since the plug-in cars also use gasoline that increases in price with increasing oil prices. Hydrogen in Oslo in 2050 is produced in a bio-gasification plant.

Higher oil and gas prices decrease the use of hydrogen in 2020 and 2030 due to more expensive hydrogen production (electrolysis instead of SMR). Plug-in hybrids in Oslo using both electricity and gasoline are replaced by hydrogen from biomass gasification.

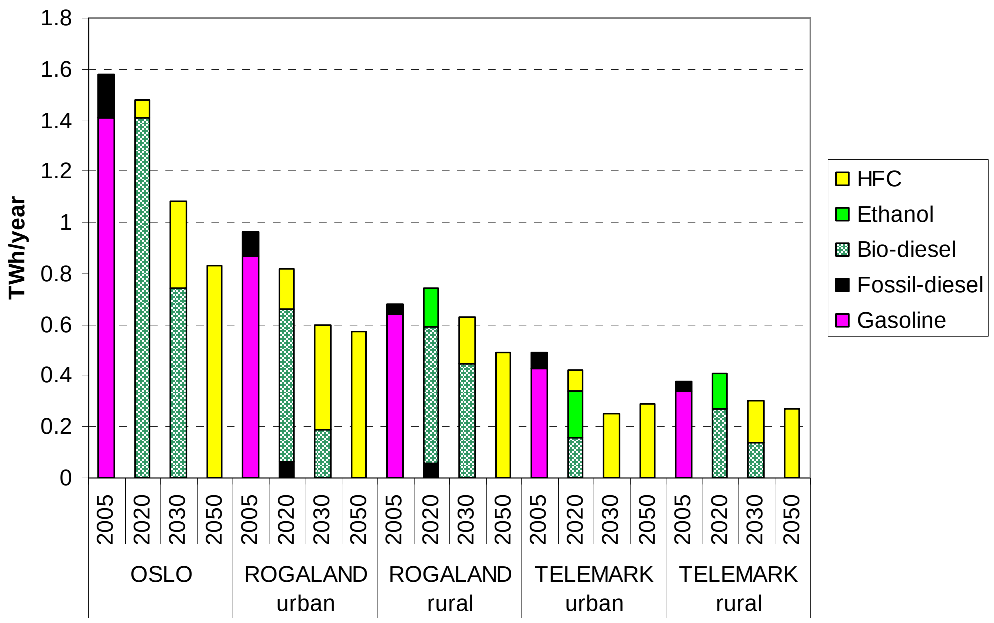

Figure 24 Energy use by car types 2005-2050 in the OIL200-NG163-scenario (TWh/year)

Car parameters

In the CARSENS-scenario in Oslo, electric cars will be used instead of diesel cars and plug-in hybrids. There is no restriction in the model of the share of electric cars, and therefore they are allowed to cover the entire demand.

In the CARSENS-scenario of Rogaland, the use of hydrogen in urban areas in 2050 is by hydrogen hybrids, and in rural areas it is plug-in and fuel cell cars. Before 2050 there is no use of hydrogen in Rogaland. Plug-in hybrids are used instead, both in urban and rural areas. The hydrogen hybrid fuel cell is used instead of "normal" fuel cell cars due to less increase in investment cost and reduction in efficiency as described in chapter 6.5.

In Telemark the use of hydrogen in the CARSENS-scenario will decrease in 2020-2030 but in 2050 it is unchanged, see Figure 25. The hybrid hydrogen fuel call cars will also be used here in 2050.

As in the HYWAYS-scenario, hydrogen is more expensive in Oslo and hence electric cars are used instead of hydrogen cars in Oslo in 2050, while the other regions used hydrogen.

If the investment costs of battery electric vehicles and plug-in hybrids are reduced and the costs of hydrogen FC and ICE cars are increased, less hydrogen will be used for transportation and the introduction of hydrogen will be delayed.

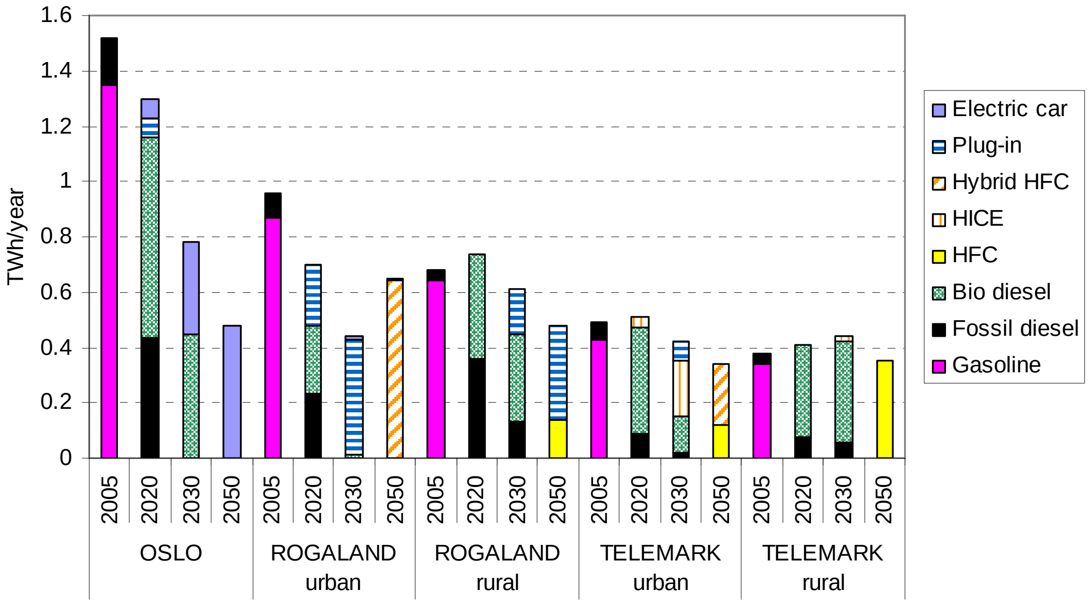

Figure 25 Consumption of energy by car types in the CARSENS-scenario (TWh/year)

Plug-in hybrids will be used in all the regions in 2025-2040 if the investment costs are reduced by approx. 20 % (the CARPLUG scenario). In 2050, plug-in hybrids will be the preferred car in Oslo and Rogaland, while both plug-in and fuel cell cars will be used in both rural and urban Telemark.

Hydrogen production costs and availability

If the production costs of biomass gasification is considerable reduced (see chapter 7.3.2 for a detailed description) there are almost no effect on the hydrogen use in any of the regions. Reduced investment costs of central electrolysis plants generate more hydrogen in Oslo, but no changes in Rogaland and Telemark.

When there is more available by-product hydrogen in Telemark, hydrogen combustion engines are used in 2020 and 2030 both in rural and urban areas. In the HYWAYS-scenario, only urban areas have hydrogen combustion cars, and there are fewer of them.

7.1.3 Summary of car technologies

To illustrate the difference between the car technologies of today and the modelling results of the future, a reference scenario is included in some of the figures. This reference scenario is based on the same car technologies as today with the expected development in demand. It is questionable if such a scenario is realistic in the long term due to limitations on the cumulative petroleum resources, however synthetic oil products could be produced from both biomass and coal. The main reason for introducing this reference scenario is to show the difference between the present situation and all the analysed future possibilities.

Figure 26 and Figure 27 presents the results in 2030 and 2050 for some of the scenarios. In most of the scenarios the energy use is substantially reduced in 2050 compared with the technologies of today, the exception is the TAXNO-scenario in rural Rogaland. In 2030 the picture is more complex. The increased overall efficiency is less in rural areas than in urban areas. In general the scenarios HYWAYS, CO2R and high oil and gas prices give rather similar results and the differences increase with the CARSENS and TAXNO scenarios.

In 2050 the three scenarios HYWAYS, CO2R and high oil and gas prices results in the same use of technologies and energy in Rogaland and Telemark. This is the case also for the TAXNO-scenario Telemark, but in Rogaland this scenario uses gasoline and natural gas due to much lower prices without taxes. In the CARSENS-scenario electric cars are used in Oslo, hybrid hydrogen cars in urban areas of Rogaland and Telemark, plug-in hybrids in rural areas of Rogaland and fuel cells in rural areas of Telemark.

Some conclusions are:

- The relative development of investment costs and efficiencies of different cars and the relative level of energy taxes are more important than limitations on emissions or price level of oil and gas on the use of car types.

- If the investment cost of hydrogen cars are reduced as described in the HYWAYS-scenario (is at the same level as gasoline cars and cheaper then diesel cars in 2025-2050), then hydrogen cars are used if hydrogen can be produced at a reasonable cost.

- If the cost of plug-in hybrids is reduced by 20% more than assumed in the HYWAYS-scenario, these cars are used instead of hydrogen cars as long as no cheap by-product hydrogen is available.
- If the investment costs of battery electric vehicles and plug-in hybrids are reduced and the costs of hydrogen FC and ICE cars are increased, less hydrogen will be used for transportation and it will be introduced later.
- The difference in energy costs due to tax differentiations are important for an early introduction of hydrogen
- With limitations on CO_2-emissions hydrogen cars are used earlier and to a higher extent.
- Higher oil and gas prices increases the hydrogen cost and delay the introduction of hydrogen cars (instead more bio diesel is used).

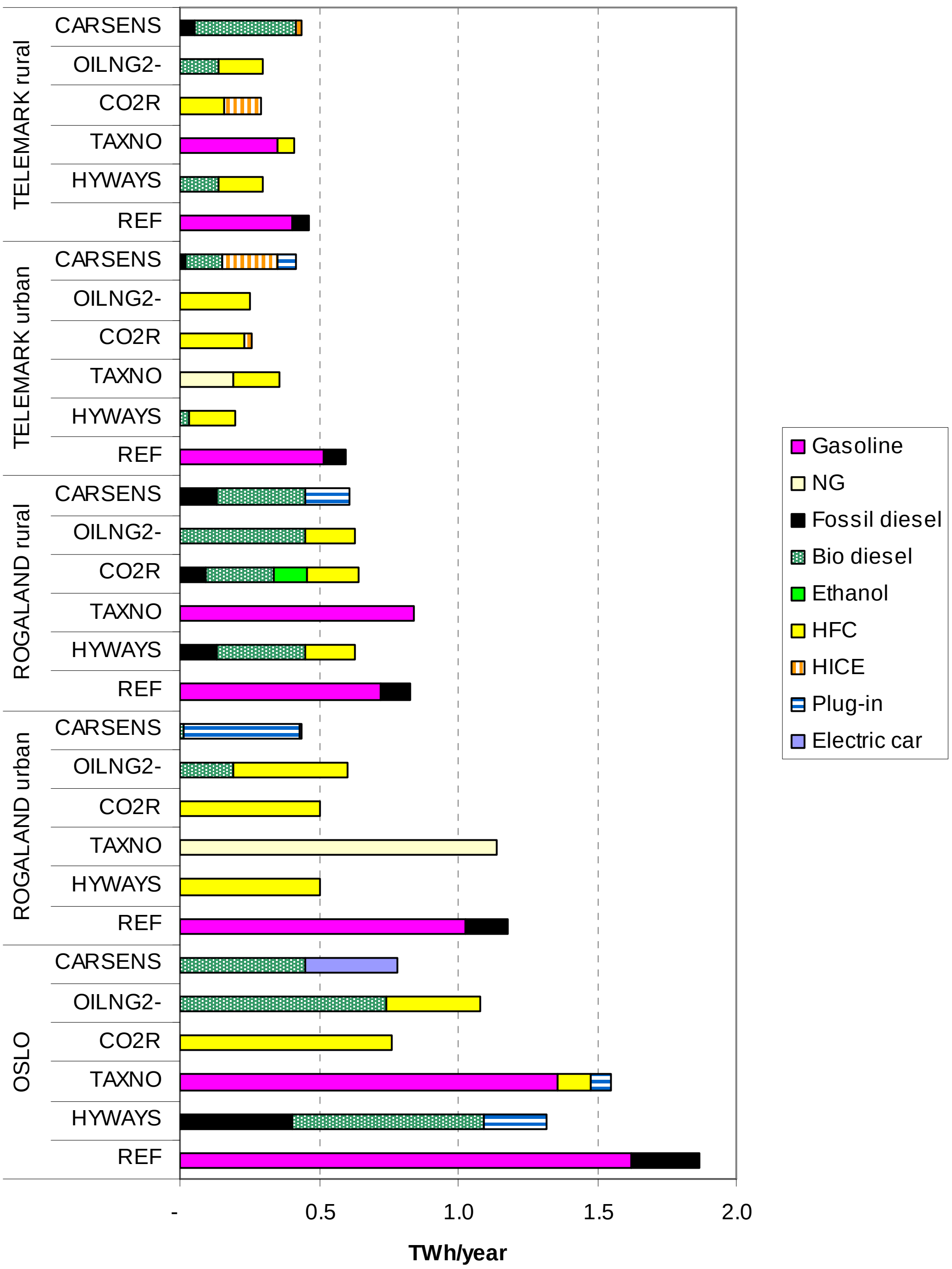

Figure 26 Comparison of energy use by car type in 2030 in some scenarios (TWh/year)

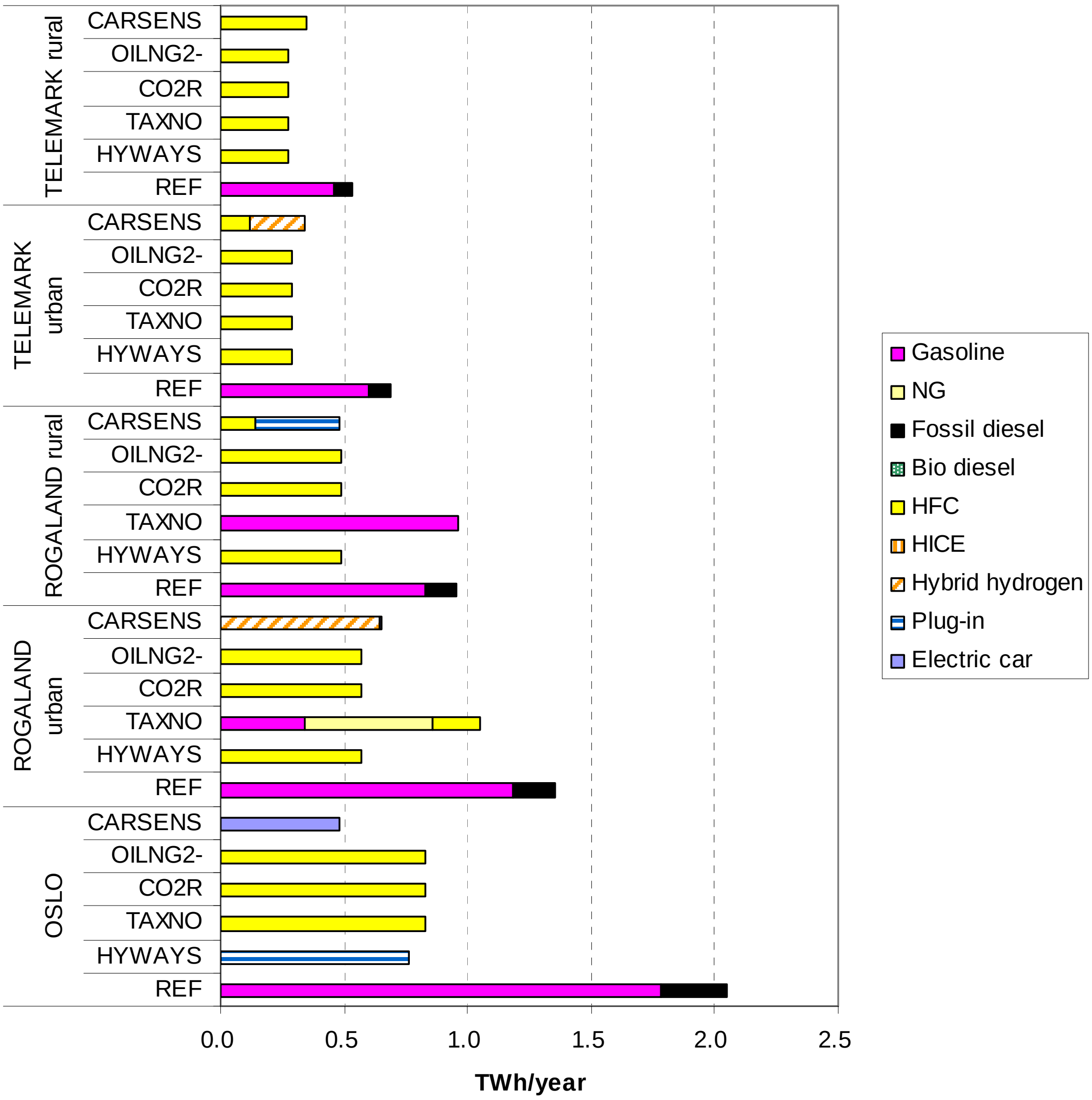

Figure 27 Comparison of energy use by car type in 2050 in some scenarios (TWh/year)

7.2 Total transportation

The transportation sector of the models includes road transport (cars, buses and trucks), railway, ship and machinery. Today, approximately half of the energy consumption in the total transport sector is used by cars. The second largest consumer group is trucks, with approx. 25 %. The cars are modelled in detail, while trucks are not, they can only choose between fossil and biodiesel. Since the cars are described in detail in the previous chapter, the focus here will be on biodiesel and total CO_2-emissions.

Biodiesel

Bio-diesel is used in all regions with the basic assumptions of the HYWAYS scenario in 2020 and 2030, but in 2050 biodiesel is only used in Telemark. The models do not distinguish between biodiesel used by buses, cars or trucks and therefore it is assumed that the bio-diesel share is the same in all type of road traffic. The share of bio diesel is highest in Telemark, see Figure 28.

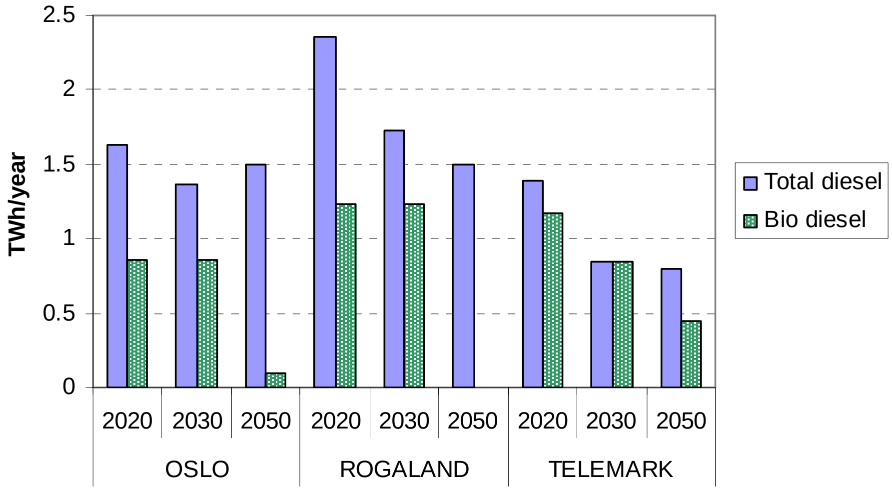

Figure 28 Consumption of diesel made from biomass and petroleum by buses, cars and trucks in the three regions in 2020, 2030 and 2050 in the HYWAYS scenario (TWh/year)

The consumption of bio-diesel increases in all regions in 2050 in the CO2R-scenario, see Figure 29.

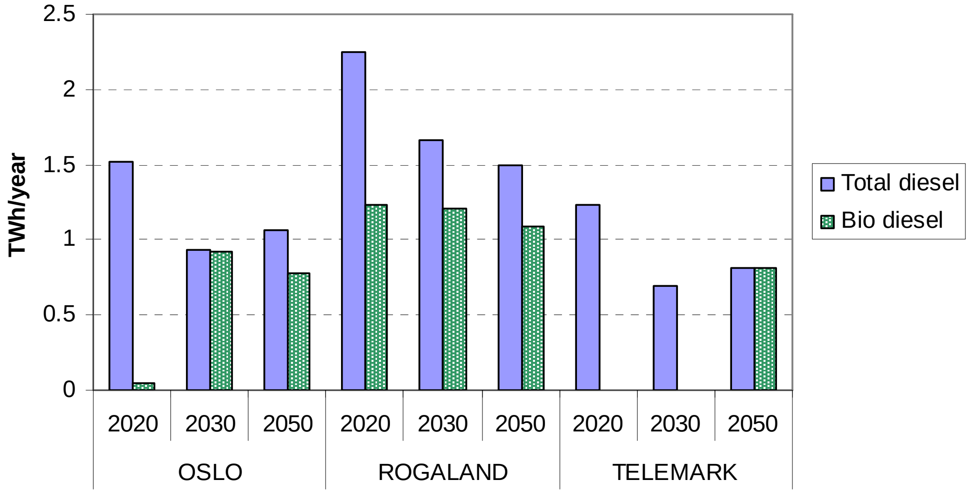

Figure 29 Consumption of diesel made from biomass and petroleum by buses, cars and trucks in the three regions in 2020, 2030 and 2050 in the CO2R scenario (TWh/year)

With increased oil and gas prices the production of bio-diesel will increase and almost all used diesel will be bio diesel, see Figure 30. In the TAXNO scenario no bio-diesel will be produced.

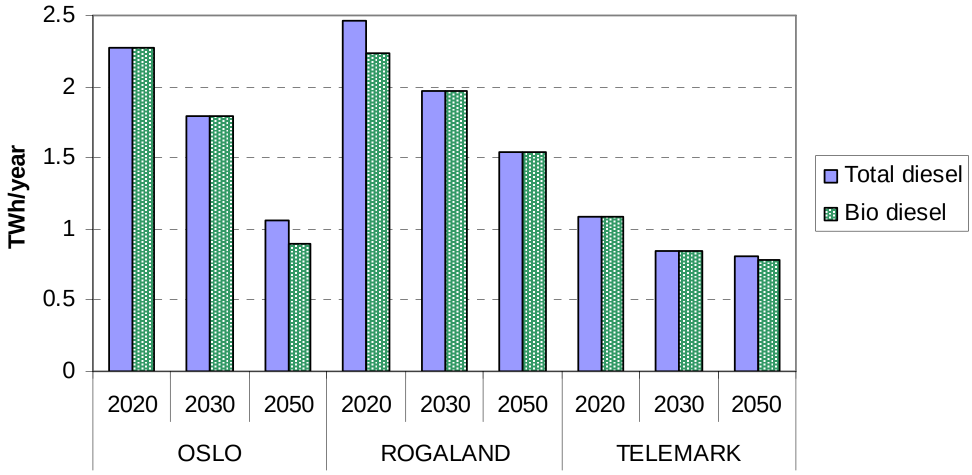

Figure 30 Consumption of diesel made from biomass and petroleum by buses, cars and trucks in the three regions in 2020, 2030 and 2050 in the OIL200-NG163 scenario (TWh/year)

The sensitivity analysis of the effect of decreased investment costs gives little effect on the production volume. The investment costs may increase by 50 % in Telemark without any effects on the production volume. In the other regions the investments cost can not increase by more than 5-15 % without having any effect.

High oil and gas prices are the most important factor for a high share of biodiesel in the transportation sector.

Total energy consumption

Figure 31 presents the energy consumption in total for the transportation sector in the HYWAYS-scenario. The gasoline in Oslo in 2030-2050 is used by plug-in hybrids, that are modelled as 1/3 gasoline and 2/3 electricity.

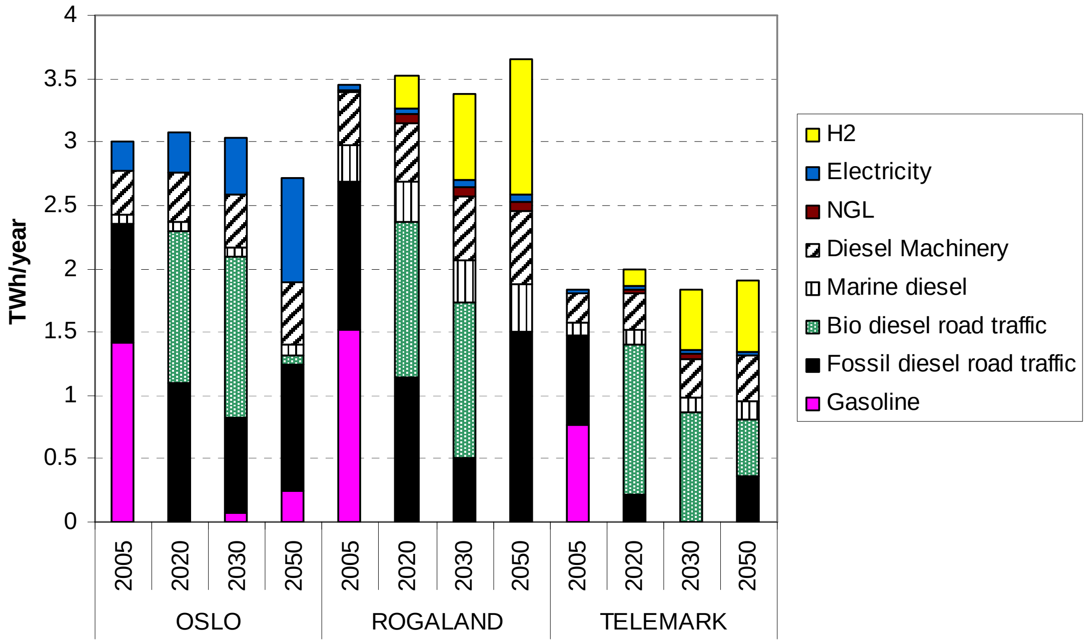

Figure 31 Energy consumption of total transport in the HYWAYS-scenario (TWh/year)

The total CO_2-emissions from the transportation sector in the three analysed regions in 2005, 2020, 2030 and 2050 for the scenarios REF, HYWAYS, TAXNO and CO2R are shown in Figure 32. The emission includes both CO_2-emissions of production of the fuel and emissions from fuel use. In average the reduction in CO_2-emissions compared to the REF-scenario are 48 % in 2050 in the HYWAYS-scenario, 29 % in the TAXNO-scenario and 82 % in the CO2R-scenario.

To achieve considerable reductions of CO_2-emissions, limitations on emissions seems to be necessary.

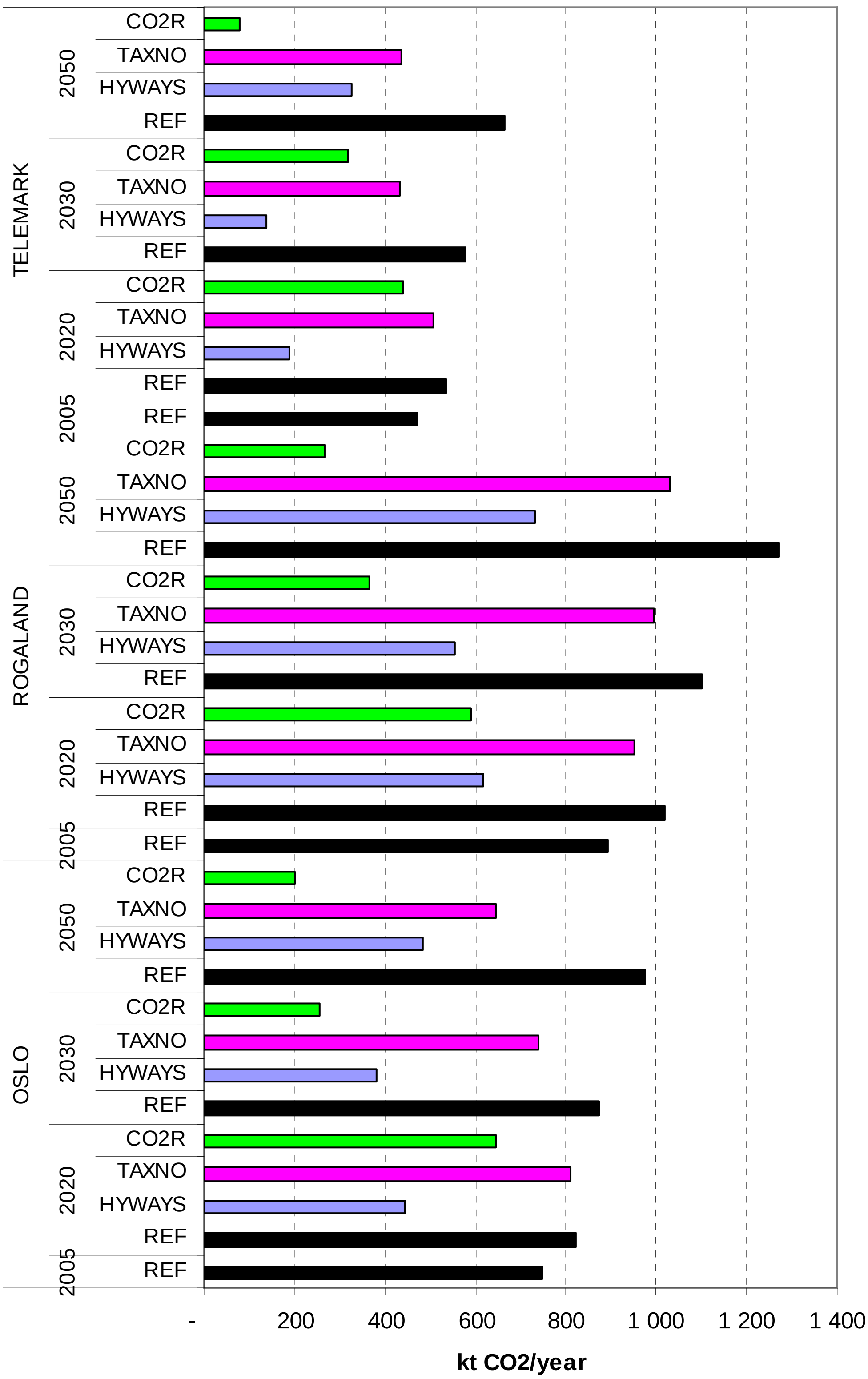

Figure 32 Total CO_2-emissions from the transportation sector (fuel production and use) in the three analysed regions in 2005, 2020, 2030 and 2050 for the scenarios REF, HYWAYS, TAXNO and CO2R (kt CO_2-emissions per year)

7.3 Hydrogen production and transportation

7.3.1 Scenario analyses

HYWAYS-scenario (basic assumptions)

The technologies used for hydrogen production in the three regions with the basic assumptions of the HYWAYS-scenario are presented in Figure 34. Central SMR is the dominating technology in general, especially in 2020 and 2030. In addition by-product hydrogen is used in Telemark. In 2050 central electrolysis is dominating in Rogaland.

In Oslo there is no hydrogen production at all due to higher production costs. Oslo has no electricity production within the region and therefore the electricity price is higher than in the other regions. Since all regions are modelled without any restrictions within the region and there are limitations on exports of electricity out of the region, Rogaland has a surplus of electricity according to the model. The electricity price is then low enough to use central electrolysis for hydrogen production, so when the gas price increases central electrolysis becomes the most economic hydrogen production alternative. The electricity price (high voltage) available for central hydrogen production is shown in Figure 33.

Central electrolysis is assumed to be connected to the high-voltage grid as an industrial plant, while local electrolysis is connected to the low-voltage grid as a non-industrial plant, with its own grid tariffs and energy taxes.

Natural gas is much more expensive in Oslo, than in the other regions, since there are no big consumers of natural gas as the industry in Rogaland and Telemark, and hence the hydrogen production plant would have to take all the transport cost by its own.

If electricity is available at a low price, central electrolysis will be used. If both electricity and natural gas are expensive, other alternatives than hydrogen cars are used.

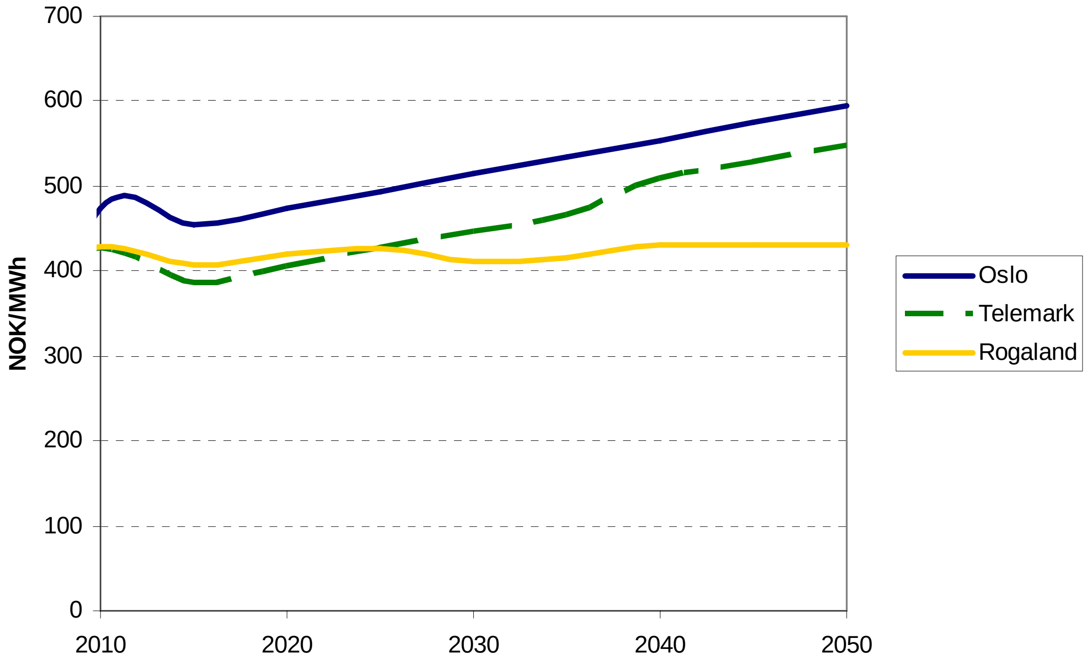

Figure 33 Electricity price (high voltage) including grid tariff and taxes in the HYWAYS-scenario of Oslo, Telemark and Rogaland (NOK/MWh)

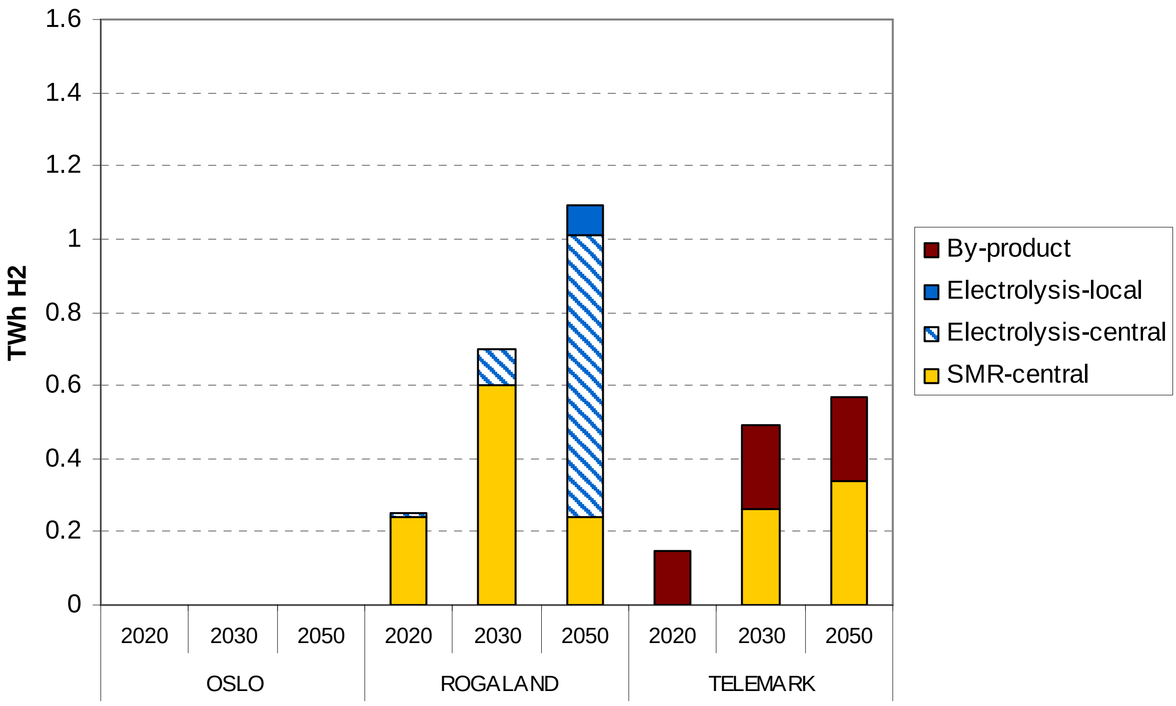

Figure 34 Hydrogen production with different technologies in the HYWAYS- scenario (TWh/year)

Tax neutral scenario (TAXNO)

If all taxes are deleted from the model, the effect on the production of hydrogen is quite different in the three regions.

There are no changes in production technologies in Telemark, but they produce less hydrogen than in the HYWAYS-scenario. The use of hydrogen is almost the same as in the HYWAYS-scenario in 2050, but it is reduced in 2020 and 2030, since gasoline becomes so cheap that it is not profitable to invest in hydrogen cars in this period. In 2050 the investment cost of hydrogen cars is reduced so much that it becomes the cheapest alternative.

In Oslo hydrogen is produced by central SMR in 2050 and to a small extent by local electrolysis in 2030 and 2050, while there was no production in the HYWAYS-scenario. Without taxes natural gas for SMR-plants becomes much cheaper and then the lower investment costs of fuel cell cars compared to plug-in hybrids make fuel cell cars the most profitable in Oslo.

In Rogaland the production is considerably reduced. Central electrolysis is used instead in 2050 and in 2030 local SMR is used instead of central SMR (smaller production unit). Instead of hydrogen cars, natural gas cars are more profitable without energy taxes.

Due to cheaper gasoline and natural gas less hydrogen cars are used in the TAXNO-scenario, but cheaper natural gas for steam reforming also makes hydrogen more profitable than plug-in cars (with gasoline) in Oslo.

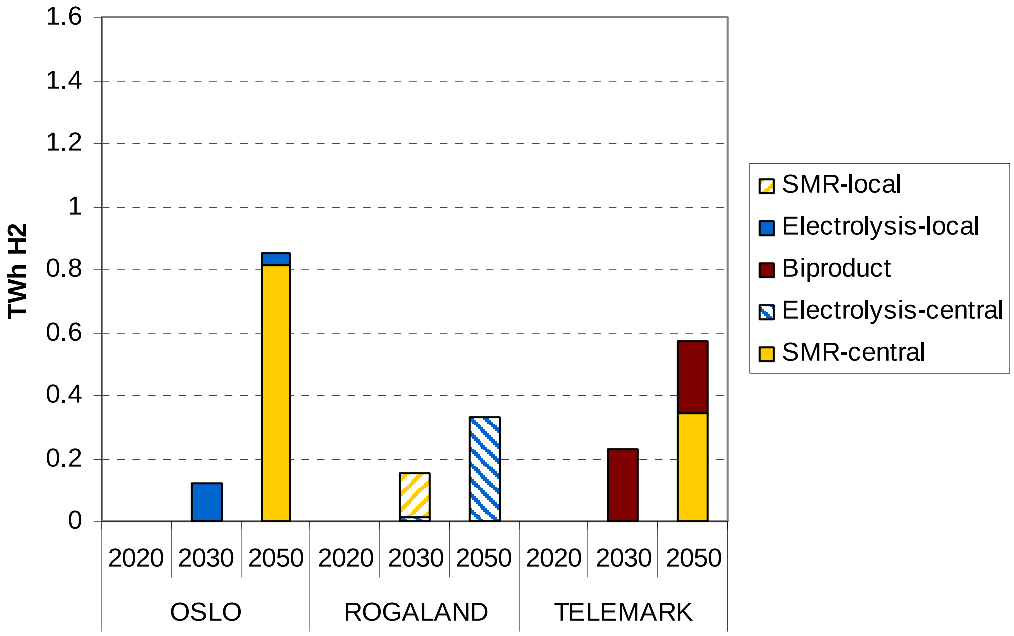

Figure 35 Hydrogen production with different technologies in the TAXNO- scenario with a "tax neutral" system (TWh/year)

CO2R-scenario

Hydrogen production from biomass will be used in Oslo in the scenario with limitations in CO_2-emissions. In 2050 gasification of biomass is the only hydrogen production technology in Oslo, while central and local electrolysis are used in Rogaland, see Figure 36. In Telemark central SMR with CCS will be used from 2030, together with industrial by-product and some central electrolysis. There will also be CCS from several industrial plants, e.g. Yara and Norcem, and it will be invested in a pipeline for transportation of CO_2.

The hydrogen production volume is higher in Oslo and Rogaland in 2050 compared to the HYWAYS scenario.

With limitations on CO_2-emissions more hydrogen is produced and with more renewable energy or SMR with CCS.

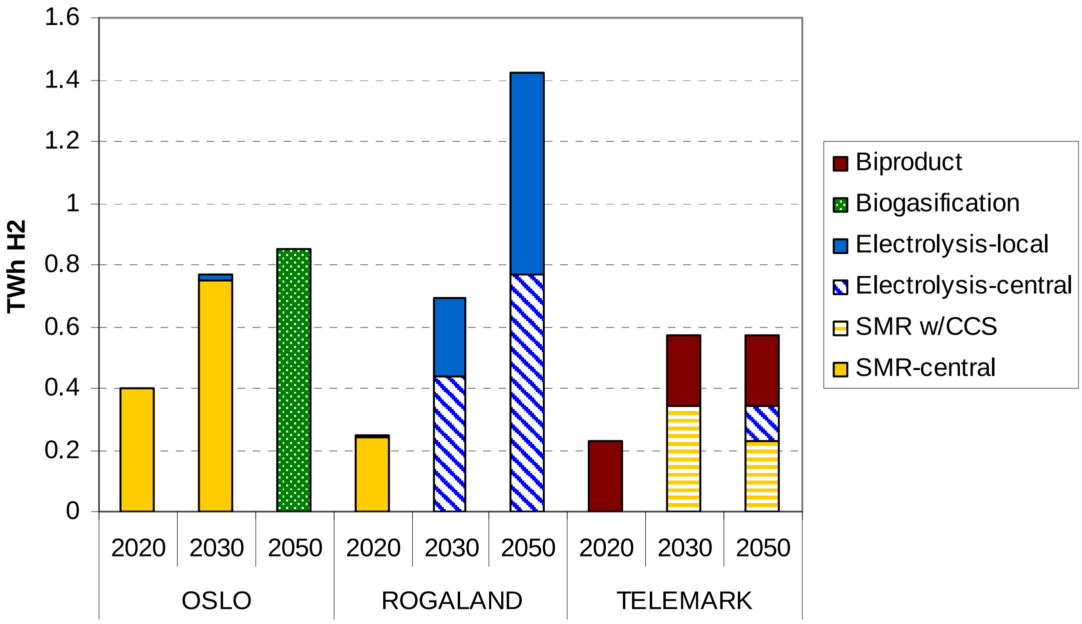

Figure 36 Hydrogen production with different technologies in the CO2R- scenario with limitations on CO_2-emissions (TWh/year)

7.3.2 Sensitivity analyses

The following sensitivity analyses are all performed based on the HYWAYS-scenario. The different assumptions of the sensitivity analyses are described in more detail in chapter 6.

Higher oil and gas prices

When only the oil prices are increased and the gas prices are unchanged from the basis assumptions, there are almost no changes in the production of hydrogen. Increasing the gas prices as well, results in more hydrogen production in Oslo. In Rogaland and Telemark, the volume is about the same, but SMR is replaced by central electrolysis.

In Figure 37 the results of the analysis of high oil and gas prices from 2015 (OIL200-NG163-scenario) is presented.

With higher gas prices no hydrogen will be produced in SMR-plants, instead electrolysis is the main hydrogen production technology.

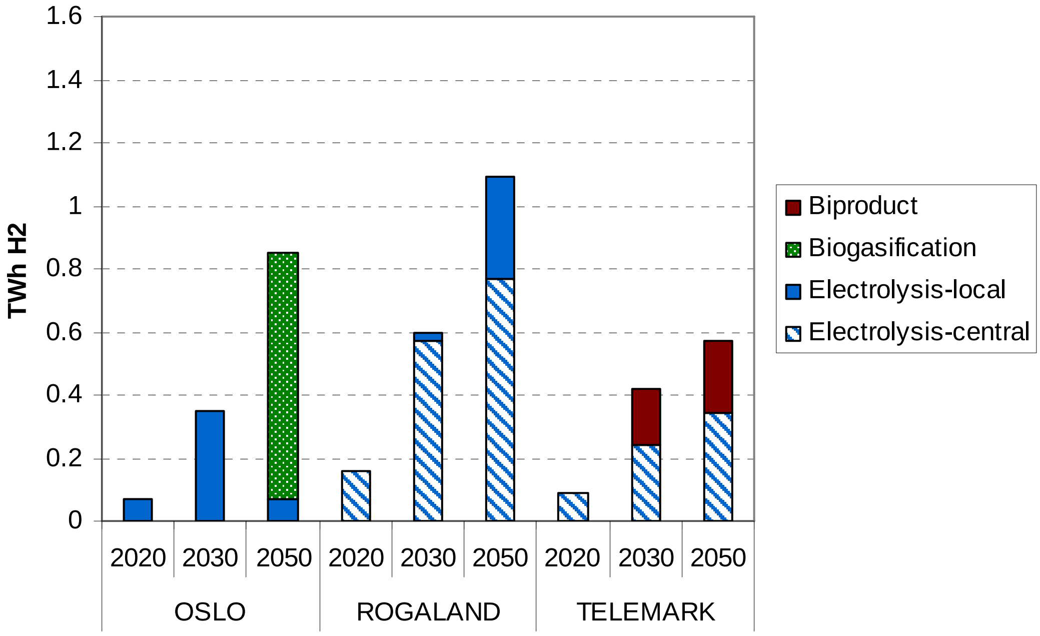

Figure 37 Hydrogen production with different technologies in the OIL200-NG163-scenario with high oil and gas prices from 2015 (TWh/year)

Biomass gasification

The cost and efficiency of gasification of biomass needs huge improvements in order to be competitive. The technology is more interesting in combination with restrictions of CO_2-emissions and when the gas prices increases. In the CO2R-scenario biomass gasification is used in Oslo and it covers all the hydrogen production.

Central electrolysers

Central electrolysis is in use in the HYWAYS scenario of Rogaland together with central SMR. The production increases in 2020 and 2030 if the investment costs are reduced, the efficiency is increased, in the CO2R scenario and if the oil and gas prices increases. If the electricity export capacity is increased, more electricity will be exported out of the region and SMR will be used for hydrogen production instead.

In Telemark, central electrolysis is used if the oil and gas prices increases, there are limitations of CO_2 emissions or if the efficiency is increased. Decreased investment cost has low effect.

Central electrolysis is only a preferred choice in Oslo if the investment costs are very much decreased. If the electricity price is decreased and the investment costs are unchanged, no central electrolysis is used.

By-product hydrogen

In the HYWAYS scenario, the available hydrogen as by-product from industry is based on figures from Hydro Rafnes of 9650 Nm^3/hr (approx. 230 GWh/year). In addition it might be possible to use hydrogen from Borealis, in total 44000 Nm^3/hr (approx. 1000 GWh/year) and this is included in this scenario in the Telemark model. There are no known resources of by-product hydrogen in Rogaland or Oslo. The additional by-product is only available to the transport sector.

More available by-product replaces hydrogen production in central SMR plants in the HYWAYS scenario. The volume is increased in 2020 and 2030, but there is no significant increase in 2050 in the use of hydrogen since even with the basic assumptions, all cars use hydrogen in 2050.

7.3.3 Summary of hydrogen production technologies

Central or local production of hydrogen

All hydrogen in Telemark is centrally produced in all the analysed cases.

In the HYWAYS-scenario of Rogaland hydrogen is only locally produced in 2050 and only a small volume. With higher gas prices more hydrogen is locally produced in 2050, mainly in rural areas. Limitations on CO_2 emissions also result in more local production in Rogaland, both in rural and urban areas (both in 2030 and in 2050). In the TAXNO-scenario, local SMR is used in 2030.

With the basic assumption of the HYWAYS-scenario in Oslo, no hydrogen is produced. With limitations on CO_2 emissions, there is a small local production in 2030 in Oslo. In the TAXNO-scenario the local production is 100 % in 2030 and 5 % in 2050. With higher oil and gas prices, the local production increases.

One should keep in mind that the regions are modelled separately and hydrogen is not transported between regions, thus making large production units less economic than the case would be if a unit could produce hydrogen for several neighbouring regions.

With higher oil and gas prices, the local production of hydrogen increases (if no cheap by-product hydrogen is available).

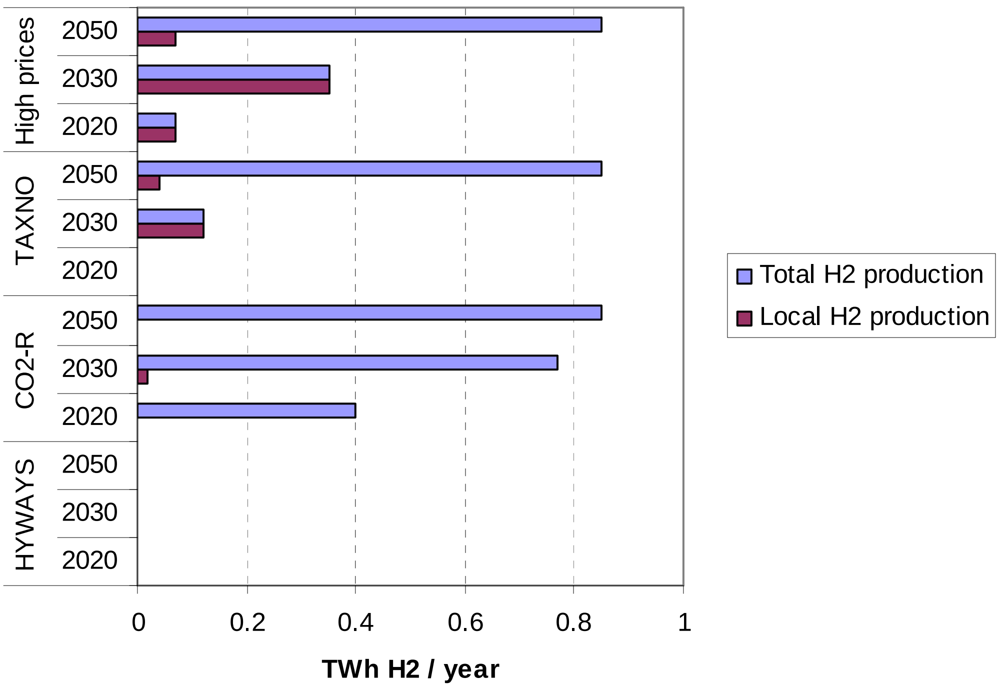

Figure 38 Local and total production of hydrogen in Oslo in the three scenarios (TWh H_2/year)

Transport of hydrogen

As a result of the interaction process with the Infrastructure model, there are restrictions on the share of hydrogen used in urban areas that can be transported by pipeline. In Telemark and Rogaland at least 50 % has to be locally produced or transported by trailer and in Oslo this figure is 5 %.

In Rogaland, the transport by pipelines is 50 % in urban areas in 2030 and 2050, in line with the restriction from the Infrastructure model. The transport of hydrogen by trailer in 2050 is higher in Telemark, than it has to be according to the limitations of the Infrastructure model, see Figure 39.

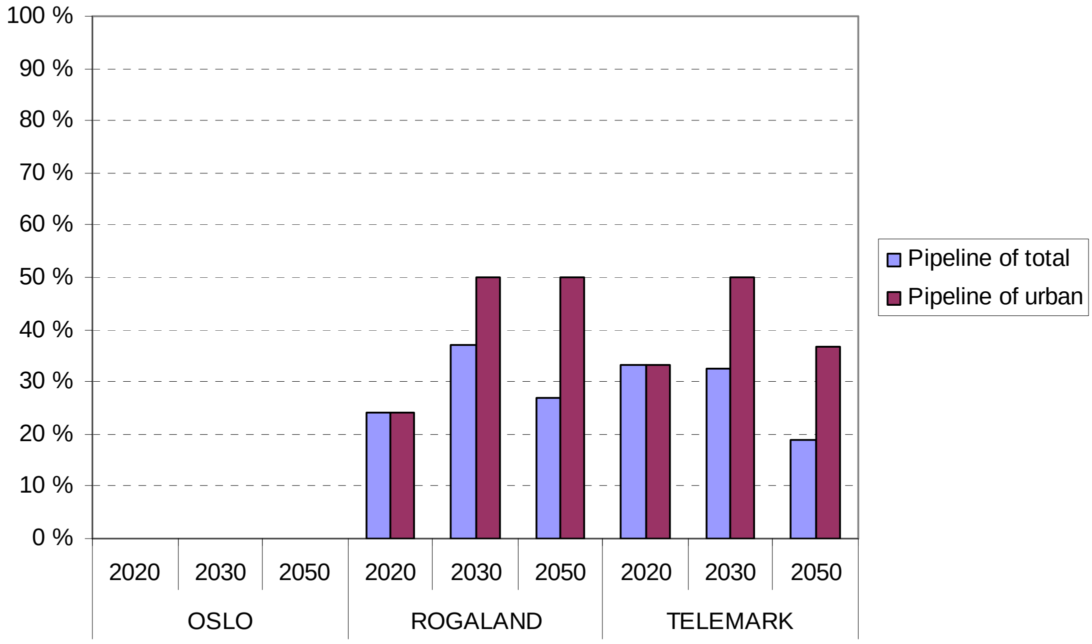

Figure 39 Share of hydrogen transport by pipeline of all central produced hydrogen

Production technologies

Energy prices have a much stronger influence on the production technology than investment costs, since most of the hydrogen price is directly connected to the energy used in the hydrogen production.

Some conclusions of the analysed production technologies are:

- If electricity is available at a low price, central electrolysis will be used.
- With higher natural gas prices no hydrogen will be produced in SMR-plants, instead electrolysis is the main hydrogen production technology.
- If both electricity and natural gas are expensive, other alternatives than hydrogen cars are used, unless there are restrictions on CO_2-emissions; then hydrogen is produced by biomass gasification.
- Due to cheaper gasoline and natural gas less hydrogen cars are used in the TAXNO-scenario, but cheaper natural gas for steam reforming also makes hydrogen more profitable than plug-in cars (with gasoline) in Oslo.
- With limitations on CO_2-emissions more hydrogen is produced and with more renewable energy or SMR with CCS.
- With higher oil and gas prices, the local production of hydrogen increases (if no cheap by-product hydrogen is available).
- As much hydrogen is transported by pipeline as the models allows in most cases.

7.4 Use of biomass

The use of biomass in some end-use sectors in the HYWAYS-scenario in Telemark, Rogaland and Oslo are presented in Figure 40. The use of biomass for the transport sector greatly increases and if this is extrapolated to the rest of the country, there will probably not be enough biomass resources in Norway for this production with the present resources. But if less timber is used for production of pulp and paper, the available resources will increase and the result of the analyses is not that unrealistic.

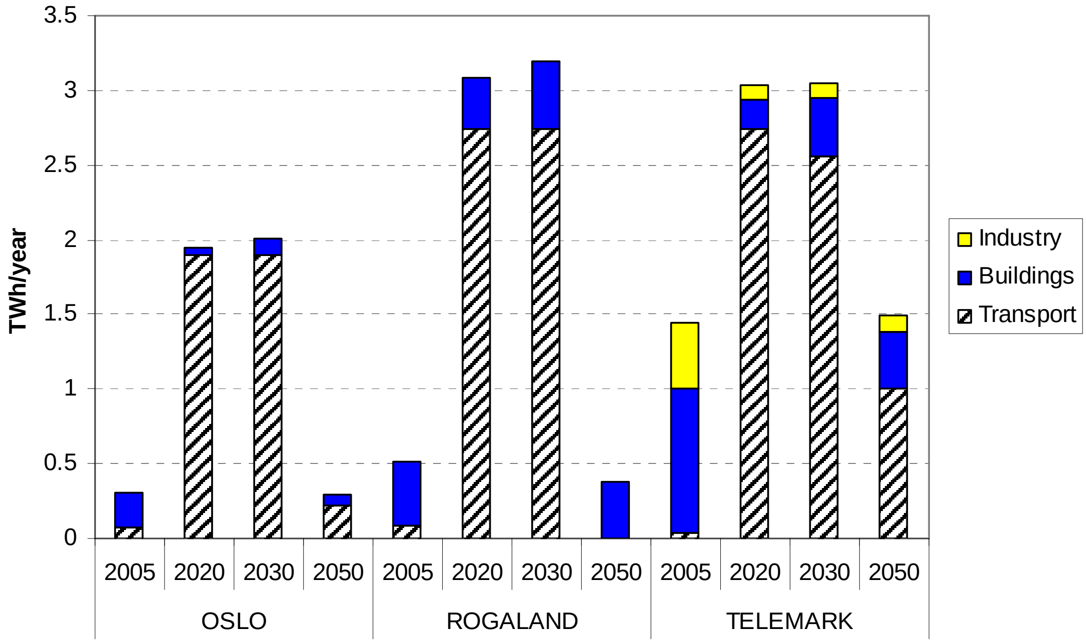

Figure 40 Use of biomass in different sectors in the HYWAYS-scenario (TWh/year)

Bio-diesel is used in all regions with the basic assumptions of the HYWAYS scenario. The models do not distinguish between bio-diesel used by buses, cars or trucks and therefore it is assumed that the bio-diesel share is the same in all type of road traffic. No biomass is used for hydrogen production in the basic assumptions of the HYWAYS-scenario.

In the NOTAX scenario the use of biofuels in the transport sector is reduced in all regions. With restrictions on CO_2-emissions the use of biomass directly as biofuels decreases in Oslo and Telemark in 2020 and 2030, while it increases in 2050 in Telemark and Rogaland. In Oslo biomass is used as raw material for hydrogen production in 2050. Increasing oil and gas prices result in an increased use of biofuels and in Oslo also an increased use of hydrogen produced from biomass.

7.5 Electricity production and use

Figure 41 presents the production of electricity in the three regions with the basic assumptions in the HYWAYS-scenario.

Oslo has almost no electricity production within the city and has to import it from other regions. At present there is a small hydro power production as well as some electricity production from waste incineration in a district heat plant.

In Rogaland there is a large hydro power production as well as a large export of electricity to other regions. The model has a restriction of 1 TWh power export in all time segments, and this is reached in all day-time segments. The wind power production is increasing in all scenarios to approx. 3.5 TWh in 2050. There is a small electricity production from waste in district heat plants in all periods and scenarios.

In Telemark there is a large hydro power production and a large export of electricity to other regions. The model has a restriction of 1 TWh power export in all time segments, and this is reached in all day-time segments. There is no wind power or gas power, but a small contribution from waste and CHP.

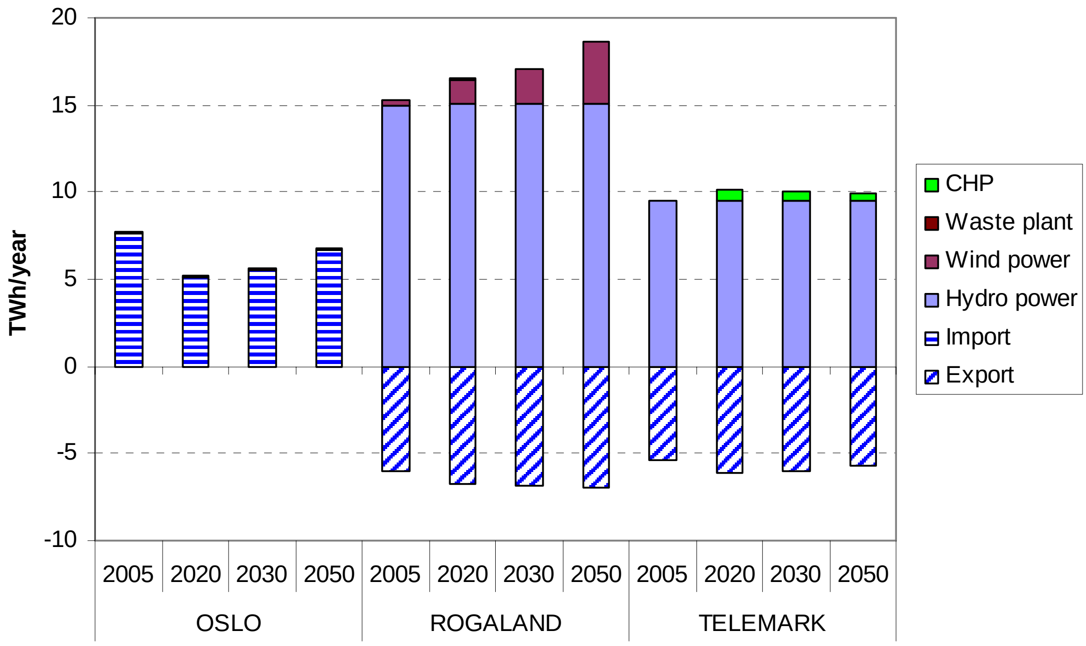

Figure 41 Electricity production technologies and import/export of electricity with basic assumptions in the HYWAYS-scenario in Telemark, Rogaland and Oslo (TWh/year)

Figure 42 presents the electricity use in the HYWAYS-scenario in the three regions for different end use sectors. In most of the scenarios the changes in electricity use are very small. The exception is the scenarios with more electric cars (CARSENS, CARPLUG) where the electricity directly to the transport sector increase and the electricity for hydrogen production decrease in Rogaland.

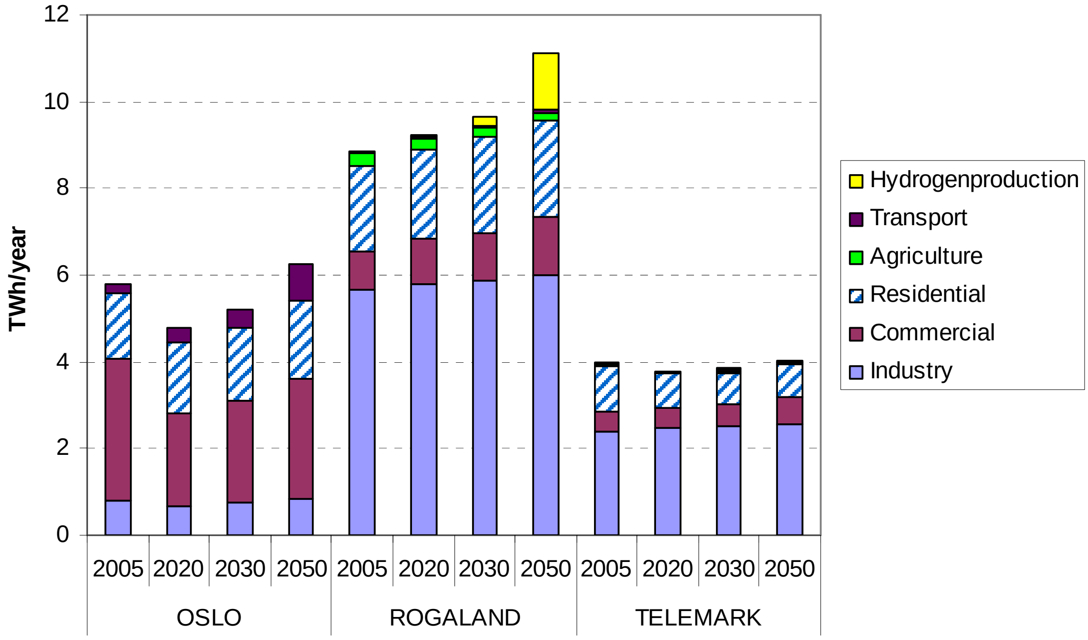

Figure 42 Use of electricity in the HYWAYS-scenario in Telemark, Rogaland and Oslo (TWh/year)

8 Conclusions

The MARKAL analyses are made in order to analyse the entire energy system and compare hydrogen technologies to other possibilities. The main focus has been on the transport sector, especially cars, and what circumstances that is important to make a transition to hydrogen cars profitable.

The NorWays-project is based on technology costs and efficiencies etc. from the HyWays-project and this results in use of hydrogen cars under most circumstances in 2050 and often also already from 2020. The basic assumptions of the analyses include substantial reduction of technology costs and these reductions will not be able without considerable efforts.

We have chosen not to control the introduction of new technologies to a certain level, and this result in a rather fast implementation of new technologies once they have become profitable. Therefore the normal slowness in introduction is not reflected in the analysis results of the models and it seems like it goes very fast to change the car fleet. This is not the case in reality and one should keep that in mind when analysing the modelling results.

The overall efficiency is greatly improved when comparing the HYWAYS-scenario of 2050 with the technologies used today. In average the energy use in 2050 is less than half of that of gasoline and diesel cars and in 2030 the efficiency increase results in 40 % less energy use.

The detailed descriptions of the results are presented in the previous chapter and the main conclusions are:

The effects of changes in relative ***energy prices*** compared to the basic assumptions are:

- Lower electricity price: hydrogen is produced by central electrolysis (Rogaland)
- Higher electricity price & high hydrogen price: Plug-in hybrids (Oslo)
- Higher electricity price & high gas price: delayed introduction of hydrogen (more bio diesel)
- Higher gas prices (“normal” electricity price): delayed introduction of hydrogen cars, less SMR and more central electrolysis, more local production
- No energy taxes: delayed introduction of hydrogen cars (more gasoline and natural gas cars before 2050)

The effects of ***limitations on CO_2-emissions*** are:

- More important for type of hydrogen production technology than for type of car
- Renewable energy is used for hydrogen production (electrolysis or bio gasification)

- Earlier introduction of hydrogen cars

The effects of changes in ***investment costs*** are:

- More important for type of car than for type of hydrogen production technology
- When the investment cost of hydrogen cars are reduced as described in the HYWAYS-scenario (is at the same level as gasoline cars and cheaper then diesel cars in 2025-2050), then hydrogen cars are used if hydrogen can be produced at a reasonable cost.
- When the cost of plug-in hybrids is reduced by 20% more than assumed in the HYWAYS-scenario, these cars are used instead of hydrogen cars as long as no cheap by-product hydrogen is available.
- When the investment costs of battery electric vehicles and plug-in hybrids are reduced and the costs of hydrogen FC and ICE cars are increased, less hydrogen will be used for transportation and it will be introduced later.

The ***different regions*** analysed are examples of the importance of:

- Available hydrogen by-product, which gives earlier introduction of hydrogen cars and use of cheaper, though less efficient hydrogen combustion cars
- Surplus of electricity, which makes central electrolysis profitable
- Basic chemical industry, which finances the infrastructure of pipelines of natural gas, hydrogen and under certain circumstances CCS
- No available cheap energy, which is in favour for the more energy efficient electric battery cars and plug-in hybrids

It is important to keep in mind that all the three models are used as independent models without any possibilities to produce hydrogen for several regions or to import hydrogen from another region. This limits the volumes and economics of large hydrogen production plants and this favours smaller plants and/or other technologies that not are dependent on the benefits of large volumes.

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Appendix 1 Selection of geographical regions

The intention of choosing different regions for the analysis is to assess how the resource availability and energy end use demand in different regions will influence the introduction of hydrogen in the energy system, both with respect to production and use of hydrogen.

Identification of key criteria

The aim of identifying key criteria is to be able to select suitable regions for early introduction of hydrogen in Norway. The Norwegian energy system is characterized by high dependence on electricity, mainly from hydropower. However, over the last decades Norway has become a large exporter of oil and natural gas. Future development of the energy system must take into account the local energy resources, the demographic structure, environmental aspects and the future requirement for security of supply.

We have defined the following key criteria with sub criteria:

- Energy demand
  - Industry
  - Service sector
  - Households
  - Transport

- Electricity and heat production
  - Hydro power
  - Wind power
  - District heating
  - Other – thermal power plant

- Untapped resources
  - Water resources / hydropower
  - Wind resources
  - Biomass
  - H_2 as by-product from industry

- Infrastructure
  - Electricity grid capacity (limitations)
  - District heat grid capacity
  - Natural gas – grid/landing
  - CO_2 (with respect to storage and handling)

- Geographic
  - Coastline
  - Remote islands/areas
  - Population
  - Population density
  - Large cities
  - Local pollution

- Density of cars

- Miscellaneous
  - Purchasing power
  - Population change
  - Local involvement
  - Local political commitment
  - Local energy and H_2 experts/institutions
  - Potential for demonstration project (cars)
  - Restricted areas (national parks)/tourist areas

The selection process, including the weighting of the criteria, is summarized in section 2. Appendix 2 provides information and data on the selected criteria, believed to be the most crucial for an early introduction of hydrogen, divided on each region/county.

Energy demand

Energy demand in a region can be divided in stationary energy demand (households, industry and service sector) and transportation energy demand. The various available energy sources meet the demand for the various energy services. Energy demand in the transportation sector is today mainly covered by use of fossil fuels; gasoline and diesel. In a short-term perspective these fuels can be substituted by bio fuels and in a long-term perspective by hydrogen fuelled vehicles or plug-in hybrids.

The counties with the highest energy demand in households and service sector are Oslo, Akerhus, Hordaland and Rogaland. The counties with the highest total energy demand are Rogaland, Hordaland, Akerhus, Nordland, Møre og Romsdal, Telemark and Oslo, with an annual energy consumption in 2004 ranging from 13 TWh to 21 TWh.

Electricity and heat production

Electricity production

The total average electricity production is approximately 120 TWh/year, and approximately 99 % of the electricity is produced by hydro power. The regions with the largest hydro power production are Nordland, Hordaland, Sogn og Fjordane, Telemark, Buskerud, Vest-Agder and Rogaland with a production ranging from 14 TWh/year to 7 TWh/year.

Wind power plants are mainly located in Møre og Romsdal, Sør-Trøndelag and Finnmark, however the production capacity is still low. The annual production in 2005 in Møre og Romsdal was 0.4 TWh and in Sør-Trøndelag and Finnmark 0.1 TWh.

District heat production

In 2006 a total of 2.6 TWh of district heat was used in Norway. Of this 0.5 TWh was used in the residential sector, 0.3 TWh in industry and the rest in the service sector. In 2005 0.93 TWh was used for district heat production in Oslo, no district heat was produced in Telemark and in Rogaland only 0.017 TWh was used.

Untapped resources

There is a potential for increased electricity production in Norway, mainly from new hydro power and wind power. It is therefore assumed that at an early stage, hydrogen may be produced by electrolysis at all locations where there are no limitations in the grid. Wind resources are huge, but are partly found at locations with no or limited grid connections. Planned installations in 2006 amounted to around 26 TWh. It is further assumed, that new hydro power installations, including small scale turbines amount to around 20 TWh [NVE 2006]. There is a large potential for utilisation of biomass, basically from forest. Biomass, such as pellets, chips, wood, can be used for heating purposes, for production of bio fuel, and for combined heat and power generation. The excess biomass available for energy utilization is estimated to around 24 TWh annually [Bioroadmap 2007].

Today a large amount of electricity is used for heating purposes in households and buildings. There is a potential for substitution of this electricity by other fuels, such as biomass. Utilization of waste for heating purposes is estimated to have a potential of 4-5 TWh [Enova 2006]. Such substitutions could release electricity for hydrogen production by electrolysis.

By-product hydrogen from industrial processes is available at several locations, in particular in Grenland.

Infrastructure

Electricity
There is strong grid capacity limitations in Finnmark, and limitations also in Troms, Nordland, Sør Trøndelag, Nord Trøndelag and Møre og Romsdal. This puts limitations also on the utilization of wind resources in these areas. For the other regions of the country, it is assumed that hydrogen can be produced by electrolysis in moderate amounts, i.e. early introduction phase.

Natural gas
Natural gas pipelines from the North Sea are located in Rogaland, Hordaland, Møre og Romsdal and in Finmark.

A local natural gas grid has been built in the Stavanger area; with a pipeline of 48 km and capacity of 70 M Nm^3 [Lyse].

CO_2 can be deposited in several fields in the North Sea. If transported by pipelines, these could be built from the terminals of natural gas. At present, CO_2 from Sleipner are deposited in the Utsira formation.

Geographic

Norway has a long coastline, a huge number of remote islands/areas and has a low population density compared to Western Europe. Only two counties have no coastline, Hedmark and Oppland.

Oslo is the only large city in Norway, with a population a little above 500.000, and a population density of 1243 per km^2, which is much higher than the next dense populated regions; Akershus and Vestfold, which have a population density of about 100 per km^2. Finnmark has the lowest population density; approximately 2 capita/km^2.

When density of cars is measured as cars/km^2 the highest density will be in Oslo; with 452 cars/km^3, followed by Akershus and Vestfold with a density about 50 cars/km^2. However if density is measured as cars/person it is lowest in Oslo (0.369) and highest in Akershus (0.489).

Local pollution is mainly a problem in large cities and in connection with large-scale industrial production. The following areas are the most relevant regarding local pollution: Oslo, Grenland (Telemark), Bergen (Hordaland), Sunndalsøra (Møre og Romsdal), Trondheim (Sør-Trøndelag) and Mo I Rana (Nordland).

Miscellaneous

Purchasing power as well as estimated population growth are not very dependent on region, and are therefore not considered important in the selection of regions.

Estimated growth in population for Norway is in total 0.30-0.77 % per year, depending on economic growth rates and immigration. However, variations are large on the county level [SSB]. The largest population growth is in Oslo, within the range of 0.41 – 1.09 % per year dependent on the future development of the economy and mobility.

Local involvement from industry, authorities, energy sector, and traffic companies and availability of experts, is considered important for early introduction of hydrogen. The largest cities are most suitable for demonstration projects in the transportations sector. [Stiller et.al 2008a] Restricted areas/tourist areas have not been considered here, but could potentially represent an early niche market.

Examples of communities; which have demonstrated a strong engagement with respect to introduction of hydrogen as an energy carrier are the following:

- Hynor – in particular the nodes where local authorities as well as industry is involved:
  - Stavanger, strong involvement of county authorities and industry
  - Grenland, mainly involvement by industry, R&D institutions, environmental organisation.
  - Drammen, with involvment from Lindum Ressurs og Gjenvinning, Vardar AS, Rådet for Drammensregionen, Buskerud County and Drammen municipality
  - Oslo, local and national authorities, industry, traffic sector. Stor-Oslo lokaltrafikk was one of the initiators for the HyNor project. Demonstration of hydrogen bus in 1999.
- Røst – Remote island with challenges related to power supply.
- Ålesund – Local actors have shown an interest in wind-hydrogen systems.
- HyTrec – Hydrogen filling station was planned in Trondheim (Statoil, Statkraft and DnV) *(cancelled)*
- Utsira – Remote island with wind-hydrogen system.

Selection of regions

In the selection of regions, variations in characteristic regarding local energy resources and energy end use demand were emphasised, in order evaluate how these variations influence on the analysis results. For instance, regions with a large potential of wind power, will be able to produce zero-emission hydrogen based on electricity from wind power, while areas with landing of natural gas, as well as possibilities for CO_2 handling and storage, can produce hydrogen from natural gas. In some regions hydrogen is also available as by-product from industrial processes.

Energy end-use and population density are important when deciding on regions for detailed modelling and analysis. Regions with high population density, high density of cars and large fleets of vehicles (busses, taxis etc) are likely to become regions for early introduction of H_2.

Based on the available information about the different regions and discussion of the most important factors in workshops, we concluded with the following three regions, Rogaland, Telemark and Oslo. The most important reasons for choosing Rogaland, Telemark and Oslo are listed in the following.

Telemark is one of the selected regions, due to:

- Telemark has a large industrial production area in Grenland, with a high energy demand
- Good electricity grid capacity
- Hydrogen available as by-product (54.000 Nm^3/hr) from industry
- Local knowledge, involvement and commitment. Grenland is part of HyNor with hydrogen fuelling station in operation from 2007.
- Dense population in the Skien/Porsgrunn area, more than half of the inhabitants in Telemark live in Skien/Porsgrunn
- Area with increasing interest in natural gas. Natural gas grid in Grenland is an option in the future
- Differences with respect to energy demand, energy resources and population density within the county (rural and urban areas)

Oslo is selected due to the following reasons:

- Highest density of cars (452 $cars/km^2$)
- High population density (1243 $inhabitants/km^2$), and thus expected high density of fleet vehicles
- High energy demand in household and service sector
- Local pollution, especially NO_X and particulate matter
- Potential for district heating – diversity in energy supply
- Local knowledge, involvement and commitment. Oslo is part of HyNor project

Rogaland is selected, due to the following:

- Landing of natural gas –possibility of producing hydrogen by steam methane reforming (SMR), and corresponding deposition of CO_2 in oil or gas fields
- Highest industrial energy demand, and also high energy demand in households/service sector and transportation sector
- Relatively high population density
- The only local distribution grid for natural gas in Norway
- Large potential for offshore wind power. Largest capacity of installed wind-power at present.
- Local knowledge, involvement and commitment. Stavanger is part of HyNor with H_2 fuelling station in operation from August 2006
- Good electricity grid capacity
- Marine transportation

Hordaland, Møre and Romsdal and Finnmark were considered, however not selected for analysis in this project. These counties are however of interest and could be selected for a later study.

Hordaland is relevant due to a high energy demand of transportation sector and households/service sector, reasonable population and car density, local knowledge, involvement and commitment, the potential for wind power and marine transportation sector.

Møre og Romsdal is interesting due to strong increase in industrial energy demand, especially as a result of increasing production capacity at Hydro, Sunndalsøra and the new natural gas land installation in Aukra, Ormen Lange. Other important factors are local pollution (e.g. Geirangerfjorden), grid limitations for electricity, which could lead to alternative energy carriers, large potential for both onshore, and offshore wind power, local knowledge, involvement and commitment and the marine transportation sector.

Finnmark is unique due to the large potential for both onshore and offshore wind power combined with strong grid limitations for electricity. Thus, the huge potential for onshore and offshore wind power will be difficult to utilize. Furthermore, there are large resources, as well as a landing site, for natural gas, with correspondning potential for CO_2 storage (long-term). Finnmark has therefore a potential for large-scale production sites for hydrogen, but the possibilities for local/regional utilisation are scarce, due to very low population density and limited infrastructure. A case study on hydrogen production for export, than to make a regional analysis of Finnmark has been carried out as part of the NorWays project [Stiller et.al, 2008b].

Appendix 2 Criteria for selection of regions

Criteria for selection of regions

		Demographic data					Energy data										Other indicators						
		Population	Population density (inh./km2)	Density of cars (pr. km^2)	Cars per household	Large cities	Productive forest (km^2)	El. grid limitations	Natural gas pipeline	CO_2 storage	Energy demand (GWh)	Local biomass	Wind resources	Water resources (hydro powe	H_2 as byproduct	Other energy resources	Local involvement	Availability of experts	Local pollution	Remote areas	Other:	Other:	**Selected regions**
NO011	Oslo	521,886	1243	452	0.80	y	3,248	n	n	n	13,192		n		n		y	y	y	n			
NO012	Akershus	488,618	108	52	1.01	n	13,040	n	n	n	14,243	y	n		n		y	y	n	n			
NO021	Hedmark	188,326	7	4	1.03	n	6,802	n	n	n	6,993	y	n		n			n	n	n			
NO022	Oppland	183,690	8	4	1.03	n	2,292	n	n	n	7,138		n		n			n	n	n			
NO031	Østfold	256,668	67	30	0.98	n	5,465	n	n	n	11,858	y	n		y			n	n	n			
NO032	Buskerud	242,331	18	8	1.02	n	1,214	n	n	n	12,333		n		n			n	n	n			
NO033	Vestfold	219,480	103	47	0.98	n	4,996	n	n	n	8,830	y	n		y			n	n	n			
NO034	Telemark	166,124	12	5	0.98	n	3,362	n	n (possible)	n	13,877	y	n		y		y	y	n	n			X
NO041	Aust-Agder	103,374	12	5	0.96	n	2,470	n	n	n	3,584		n		n			y	n	n			
NO042	Vest-Agder	160,127	24	10	1.00	n	1,205	n	n	n	8,545		n		n			y	n	n			
NO043	Rogaland	388,848	46	19	1.04	y	2,426	n	Kårstø	y	21,398		y		n			y	n	y			
NO051	Hordaland	445,059	31	12	0.93	y	2,548	n	Kollsnes	y	20,390		y		y			y	n	y			
NO052	Sogn og Fj	107,222	6	3	0.98	n	2,768	n	n	n	9,362		y		n			n	n	y			
NO053	Møre og Ro.	244,570	17	7	0.98	n	4,140	y	Aukra+Tj.bergodd.	y	13,883	y	y		y		y	n	n	y			
NO061	Sør-Trøndelag	270,266	15	6	0.98	y	5,828	y	n (possible)	y	8,423	y	y		n		y	y	n	y			
NO062	Nord-Trøndelag	127,973	6	3	0.98	n	4,611	y	n (possible)	n	6,803	y	y		n			n	n	y			
NO071	Nordland	237,057	7	3	0.86	n	3,116	y	n	n	13,995		y		y			n	n	y			
NO072	Troms	152,628	6	3	0.90	n	832	y	n	n	5,458		y		n			n	n	y			
NO073	Finnmark	73,210	2	1	0.86	n		y	Melkøya	y	2,551		y		n			n	n	y			
	part of Oslo+Akersh	794,356	2877			y			n										y				
	Bergen	211,326	2393			y			possible										y				
	Stavanger/Sandnes	169,455	2337			y			possible										y				
	Trondheim	144,434	2432			y			y										y				
	Grenland	84,657	1876			n			possible										y				

Institute for Energy Technology

Institute for Energy Technology
P.O. Box 40
NO-2027 Kjeller
Norway
Tlf 0047 63 80 60 00
Telefax 0047 63 81 63 56
www.ife.no