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Production and use of Hydrogen – Regional Energy Systems Analysis of Oslo, Telemark and Rogaland

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Abstract

The transportation sector in Norway represents approximately 30 % of the CO_2-emissions. In order to significantly reduce CO_2-emissions, measures towards the transportation sector have to be addressed. This includes both efficiency and new vehicle fuels. The NorWays project has been aiming at providing decision support for introduction of hydrogen as an energy carrier in the Norwegian energy system. Important objectives have been to analyze and evaluate scenarios, market segments as well as geographical regions for introduction of hydrogen. Regional MARKAL models were developed for the counties Oslo, Telemark and Rogaland. The MARKAL models have been used in order to analyze the entire energy system and compare hydrogen technologies to other possibilities, such as bio fuels, plug-in hybrids etc. The analysis focuses on how taxes, restrictions and energy prices have an impact on the production and use of hydrogen towards 2050. The main scenarios analyzed have been a scenario based on assumptions from the EU hydrogen roadmap project HyWays, a scenario with no taxes on transport energy and a scenario with 75 % reduction in CO_2-emissions by 2050. In the HyWays scenario all cars in Rogaland and Telemark use hydrogen in 2050. In Oslo, there are no hydrogen cars in this 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.

Keywords: hydrogen, energy source, infrastructure, costs, emissions

1 Introduction

The overall aim of the analysis in the NorWays project has been to provide decision support for the introduction of hydrogen as an energy carrier in the Norwegian energy system, and important objectives have been to carry out analysis and evaluation of scenarios, market segments as well as geographical regions for introduction of hydrogen.

The work has been funded by the Research Council of Norway with industrial co-financing from Statoil, Hydro, Statkraft and Hexagon. Active participation of stakeholders has been an important working methodology of the project.

The main goals of the 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 bio fuels. The project includes modeling at national, regional and local level, by using energy system modeling, which is presented here, but also well to wheel-studies and infrastructure analysis.

The work has been carried out in close cooperation with the EU hydrogen roadmap project HyWays [1]. Hydrogen technology parameters are mainly from the E3 database [2].

2 Assumptions

The basic assumptions described in this report are based on the results from the HyWays project [1]. An important input has been 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 energy prices used in the basis scenario are presented and in Fig.1 and Fig.2.

The models allow import and export of electricity and bio energy, however there is no possibility to import or export hydrogen out of/into a region or between regions.

The price of imported and exported electricity is based on a quota price of 25 €/ton CO_2. 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.

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.

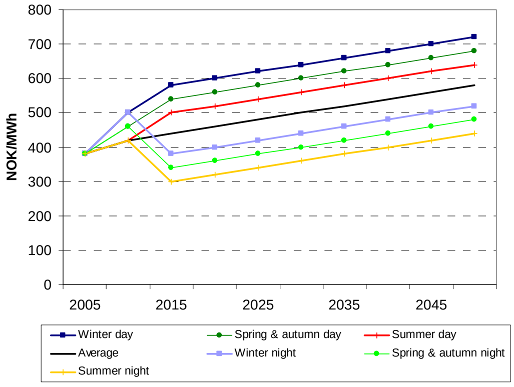

Figure 1 Electricity price 2005-2050 (NOK/MWh)

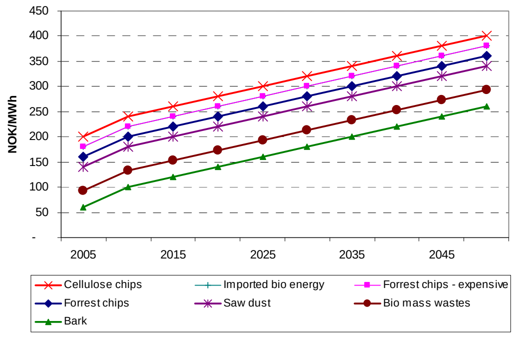

Figure 2 Biomass prices 2005-2050 (NOK/MWh)

The import price of natural gas is predicted as natural gas in WETO-H2 [3], 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 foresight of energy demand is based on the work done in [4]. 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 growth from 2005 to 2050 in the transportation sector is in average about 40%.

3 Regional MARKAL models

3.1 Model structure

A generic regional MARKAL [5] (MARKet ALocation) model was developed, constructed to represent a general region, neither adapted to special local conditions nor to a specific situation [6]. Based on the generic regional model, regional models were developed for Oslo, Telemark and Rogaland. The regions Telemark and Rogaland are divided in two areas (urban and rural), while Oslo is modeled as one area (urban). The MARKAL models have been used in order to analyze 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.

The MARKAL 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 modeling 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 analyze 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 Fig.3. Hydrogen is modeled as an energy carrier with day-night and seasonal storage adapted from the HyWays-project.

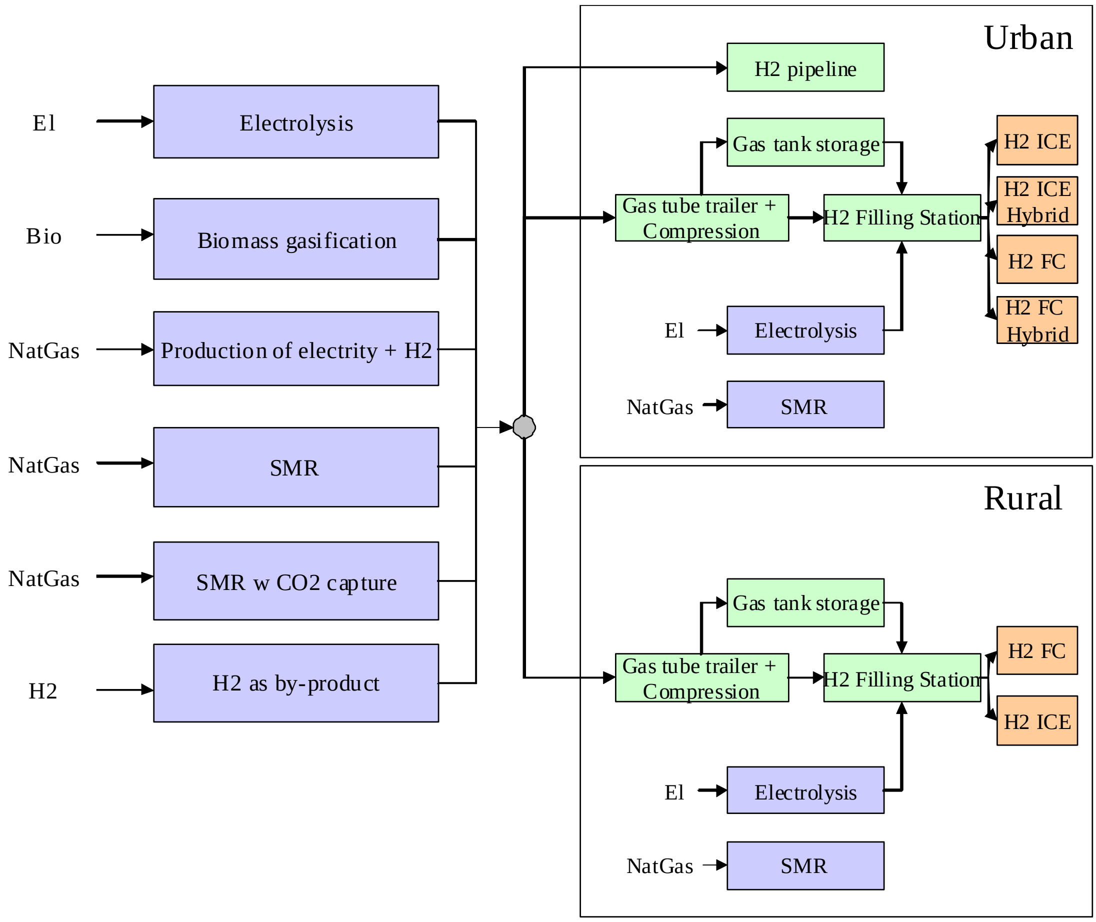

Figure 3 Modeling of hydrogen infrastructure in the regional MARKAL models

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.

The three regional 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 favors smaller plants and/or other technologies that not are dependent on the benefits of large volumes.

3.2 Interaction with the Infrastructure model

The infrastructure model H2INVEST [7] developed within the NorWays project optimizes the build-up of a hydrogen supply infrastructure for a given demand development. The Infrastructure model is useful for the screening and analysis of the transportation segment. An iteration routine between the infrastructure model and MARKAL was performed to validate and calibrate the MARKAL assumptions on hydrogen distribution.

The infrastructure model gave transport costs and distances to MARKAL and MARKAL gave hydrogen demand for rural and urban areas to the infrastructure model.

4 Analysis

4.1 Scenario analysis

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 and identify the parameters and conditions that are important to make a profitable transition to hydrogen cars.

The main scenarios in the project have been:

- HyWays: Basic assumptions with technology costs (H2) based on results from the HyWays project
- No-tax: No taxes on transport energy ("revenue neutral")
- CO2-R: Reduced CO_2-emissions by 75% in 2050

These scenarios have been compared with a reference scenario based on the assumptions of World Energy Outlook [8] with no new transport technologies. This is included in order to compare the results with the situation of today. The baseline of WEO uses 3 % bio fuels, 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.

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 is included.

A simple way of analyzing the effects of taxes on transport energy is to delete all taxes in the model, as done in the No-tax scenario. 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.

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 on emissions in the period 2005-2020.

4.2 Sensitivity analysis

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

The sensitivity of higher prices of oil and natural gas is analyzed in four different combinations. It is the relative changes in prices that are most important in these analyses, not the absolute price of each energy carrier. In the sensitivity analyses of increased petroleum prices the maximum price of crude oil is 200 $/barrel, and the maximum price of natural gas is 163 $/boe. 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 these analyses the electricity price and the prices of biomass are kept the same as in the basic assumptions.

There are also large uncertainties about when new car technologies will be available at a reasonable cost, and the sensitivity of change in car parameters has been analyzed as follows:

- Delayed cost reduction for H2 cars by 10 years
- Sensitivity for investment costs of plug-in hybrids

- Sensitivity for investment costs, operation and maintenance costs and efficiencies of cars (CarSens)

5 Analysis results

The main focus of the analysis has been on car types and hydrogen production technologies. “Cars” includes both private and fleet vehicles. Private cars are divided into use in urban and rural areas in the analyzed regions, except for Oslo which is modeled as one urban area.

The type of cars in the three scenarios HyWays, No-tax and CO2-R are described first, followed by a sensitivity analysis of energy prices, technology costs and car efficiencies. Finally, the hydrogen production is presented, as well as the effect on CO_2-emissions.

5.1 HyWays-scenario (basic assumptions)

Hydrogen cars are introduced in 2020 in the counties Rogaland and Telemark but not in Oslo, with the basic assumptions. The gasoline cars of today will first be replaced by diesel cars with a high share of biodiesel in all regions, as there are no import restrictions of import of biodiesel. 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 no hydrogen cars will be used in Oslo with the basic assumptions from HyWays. 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 Rogaland and Telemark are fuel cell cars, see Fig.4.

Even if the demand for transport is increased by about 40 % in the analyzing period, the energy consumption is reduced due to more efficient hydrogen fuel cell cars and plug-in hybrids in the future compared to present combustion engines.

Biodiesel is used in all regions with the basic assumptions.

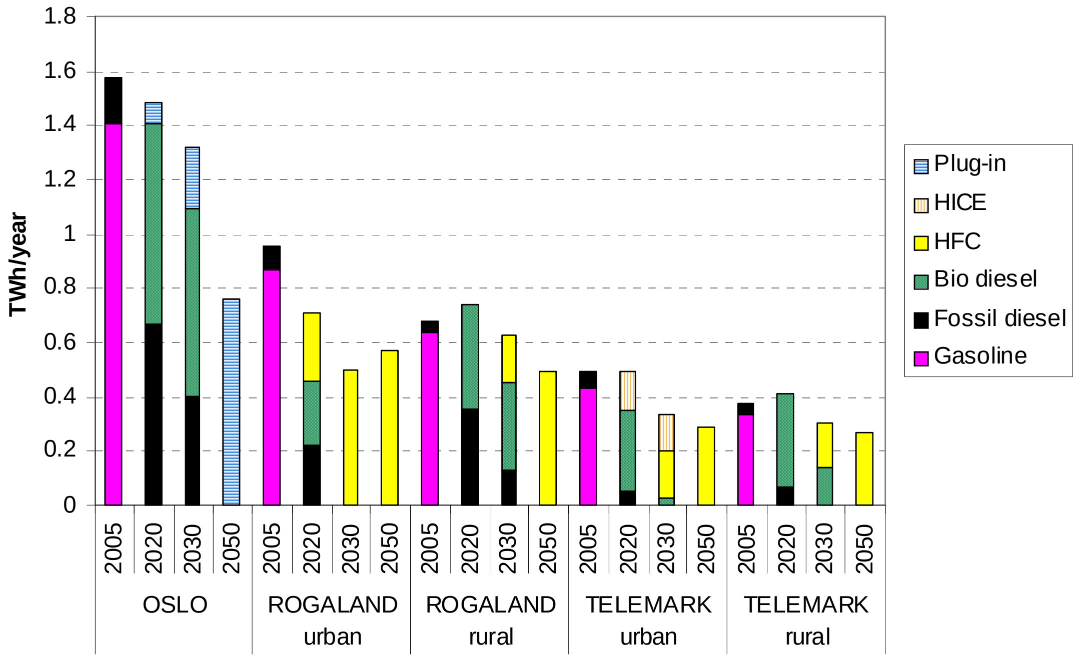

Figure 4 Energy use by car types 2005-2050 in the HyWays-scenario (TWh/year)

5.2 Tax neutral scenario (No-tax)

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.

The energy prices are lower when taxes are eliminated, and then the more expensive cars will not be profitable in the mid-term of the analyses period.

Biodiesel will not be used in any of the regions in the No-tax 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 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 No-tax 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 No-tax scenario but not in the HyWays scenario, due to cheaper natural gas for hydrogen production in a central SMR-plant.

This indicates that new car technologies only are competitive in mid-term of the analysis period if there are differences in taxes between fossil fuels and other fuels, such as electricity, hydrogen and bio-fuels, see Fig.5.

To be able to achieve an introduction of new car technologies, it is crucial to maintain differences in energy prices.

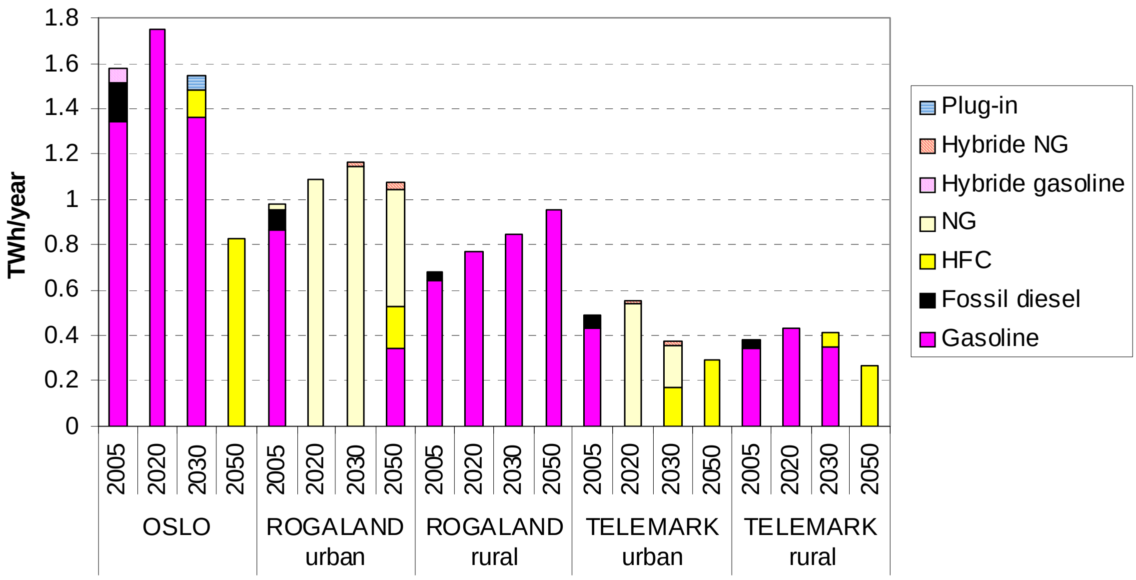

Figure 5 Energy use by car types 2005-2050 in the No-tax-scenario (TWh/year)

5.3 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. The emissions decrease if hydrogen produced from biomass is used instead of plug-in-hybrids 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 are used 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.

This implies that implementation of limitations in CO_2-emission contribute to an earlier introduction of hydrogen cars.

5.4 Sensitivity analyses

Sensitivity analyses have been performed based on the HyWays-scenario.

Sensitivity of oil and gas prices
When the oil and gas prices are increased, the share of bio-diesel increases in all regions and time periods.

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.

Car parameters
In CarSens the sensitivity for investment costs, operation and maintenance costs and efficiencies of cars have been analyzed with alternative development of investment costs of most cars. 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. The operation and maintenance costs of hydrogen fuel cell cars (incl. hybrid) are increased and the efficiency is reduced.

In CarSens in Oslo, electric cars will be used instead of diesel cars and plug-in hybrids. In 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. In Telemark the use of hydrogen in CarSens will decrease in 2020-2030 but in 2050 it is unchanged. The hybrid hydrogen fuel call cars will also be used here in 2050.

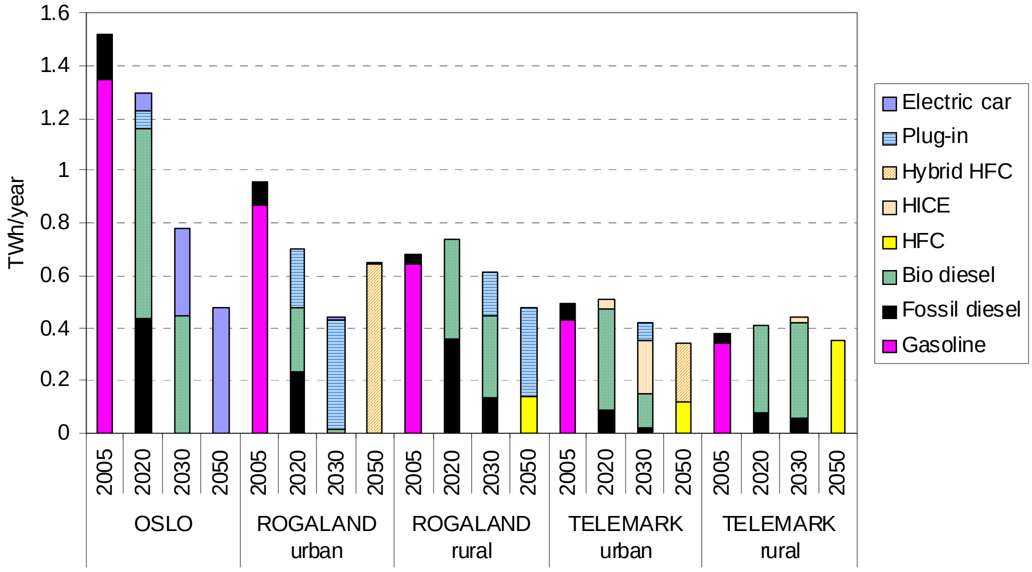

Figure 6 Consumption of energy by car types in the CarSens-scenario (TWh/year)

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.

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 compared to the HyWays assumptions, the introduction of hydrogen will be delayed and less hydrogen will be used for transportation. If the investment costs are reduced by approximately 20 %, plug-in hybrids will be used in all the regions in 2025-2040. In 2050, plug-in hybrids will be the preferred car in Oslo and Rogaland, while both plug-in hybrids and fuel cell cars will be used in Telemark.

5.5 Hydrogen production

The technologies used for hydrogen production in the three regions with the basic assumptions of the HyWays-scenario are presented in Fig.8. 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 modeled 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.

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.

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 for hydrogen production. On the other hand, if both electricity and natural gas are expensive, other alternatives than hydrogen cars are used, and the preferred alternatives are electric cars, plug-in hybrids and bio diesel.

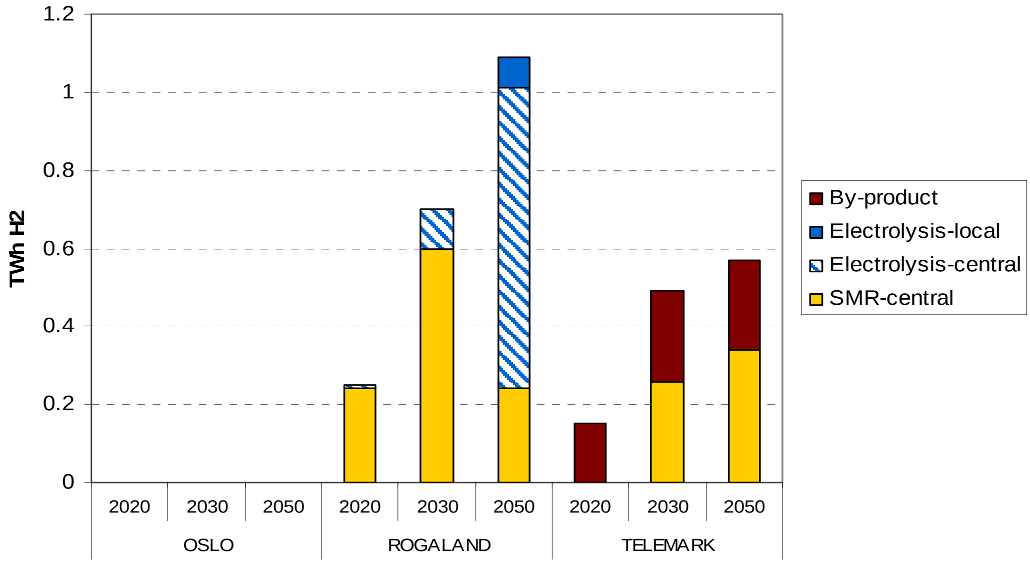

Figure 7 Hydrogen production with different technologies in the HyWays-scenario (TWh/year)

5.6 CO_2-emission

While the pervious figures only presented the results of the cars used, in Fig.8- Fig.10 the CO_2-emissions from the total transportation sector in the analyzed regions are shown for the scenarios REF, HyWays, No-tax and CO2-R. REF is included to be able to compare introduction of new technologies with a continuance of present used technologies. The emission includes both CO_2-emissions from production of the fuel and emissions from fuel use. In average the reduction in CO_2-emissions compared to the REF-scenario are 68 % in 2050 in the HyWays-scenario, 29 % in the No-tax-scenario and 87 % in the CO2-R-scenario.

To achieve considerable reductions of CO_2-emissions from the transportation sector, limitations on emissions is an effective way to ensure the implementation of new technologies.

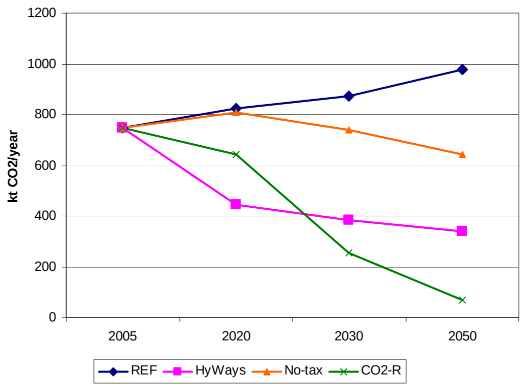

Figure 8 CO_2-emissions in Oslo in the different scenarios (kt CO_2/year)

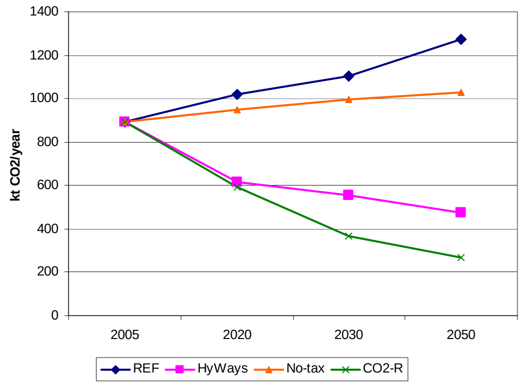

Figure 9 CO_2-emissions in Rogaland in the different scenarios (kt CO_2/year)

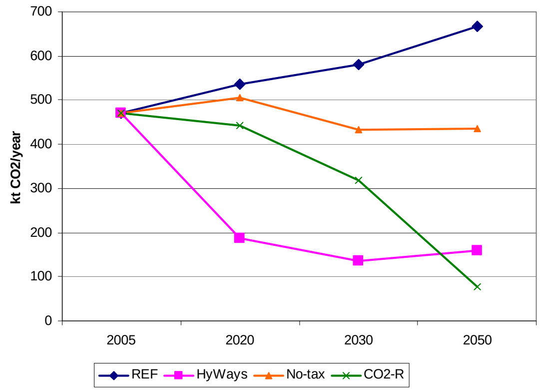

Figure 10 CO_2-emissions in Telemark in the different scenarios (kt CO_2/year)

6 Conclusions

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 CO2-

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 analyzed 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.

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References

[1] HyWays: The European Hydrogen Roadmap and E3 database

[2] E3database, a tool for the evaluation of energy chains, Ludwig-Bölkow-Systemtechnik GmbH, Ottobrunn, Germany, www.e3database.com

[3] World Energy Technology Outlook – WETO H2, ISBN 92-79-01636-9, ISSN 1018-5593, European Communities, 2006

[4] NOU 2006:18, A climate friendly Norway (In Norwegian)

[5] Documentation of the MARKAL Family of Models: Part I – Standard MARKAL, October 2004, available at www.etsap.org

[6] Rosenberg, E. et al., Description of the Generic Regional MARKAL model of the NorWays project, IFE/KR/F-2006/186

[7] Stiller, C., Bünger, U. Description and results of the infrastructure model H2INVEST, http://www.ivt.ntnu.no/docs/norways/Deliverables/D8_H2Invest_Final.pdf

[8] World Energy Outlook 2006, www.worldenergyoutlook.org/2006, http://www.iea.org/textbase/nppdf/free/2006/weo2006.pdf

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