HyWays

FIRST PHASE OF THE PROJECT

REPORT OF THE MACRO-ECONOMIC ANALYSIS

(DELIVERABLE D3.8)

VERSION 2

PROVIDING DETAILS OF THE INTERACTION OF MACRO-ECONOMY WITH THE ENVIRONMENT AND ENERGY SYSTEMS

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30/11/2005

Disclaimer

The results in this report are a reflection of a non-final stage of the HyWays project, with substantial stakeholder consultation still under way. Significant modifications are still due, and consequently none of the results given in this report should in any way be considered as final HyWays results.

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1 Executive Summary

1.1 Objective, model, and data input

The macroeconomic consequences of the introduction of hydrogen in the transport sector are assessed using the PACE-T model as developed at ZEW. PACE-T is a dynamic computable general equilibrium model, i.e. it is a model of the economy that portrays the operation of many different economic agents (households, production sector etc.) simultaneously and numerically solves the path for all endogenous variables over a certain period. Such a framework is suitable to determine the economy-wide repercussion effects of different policies. The analysis in this report thereby focuses on the effects of implementing hydrogen cars on transport demand, real consumption, welfare, GDP and wage rates.

The multi-sectoral PACE-T model features eight regions – six Member States (France, Germany, Greece, Italy, Netherlands, Norway), the rest of the EU, and the rest of the world. It furthermore distinguishes between six different car types. These are small, medium and large cars which are powered by either a conventional technology or hydrogen. Passenger cars are modelled as durable consumption goods where we assume conventional and hydrogen cars to be perfect substitutes. This means that the consumer decision is based only on the price differences between hydrogen and conventional cars. These price differences are based on capital services of the automobile stock present in the respective economy, fuel and expenditures for repair and maintenance.

PACE-T is a hybrid model which integrates top-down and bottom-up data. The top-down data consists of data on production and income generation as well as on revenues and expenditures of the different economic agents which are taken from the GTAP5 database (GTAP 2002). It distinguishes energy inputs, non energy inputs, labour and capital. The different hydrogen production, distribution and storage, and car technologies are specified through the generic cost structure, the import/export shares, the output in the business as usual, and capacity constraints. The trade shares of hydrogen and conventional cars are taken form the sector “Motor vehicles and parts” of the GTAP database. The inclusion of passenger cars which are powered by either a conventional technology or hydrogen demands further input data, the so-called bottom-up data. Data on car and hydrogen production technologies is directly taken from the MARKAL model. This data is mainly related to the capacity and production activity of various technologies and related parameters. Further information on the technical and economical characterisation of the hydrogen infrastructure technologies from the E3Database enters PACE-T via the MARKAL data. Given the output quantities and the cost structure of the different hydrogen technologies the aggregate production data of the industrial sectors is split down to accommodate a consistent bottom-up representation. The input structure of car and hydrogen production technologies is therefore adopted from the ISIS model.

The analysis of the introduction of hydrogen in the transport sector is carried out relative to a baseline without hydrogen technologies. The scenario analysis then assumes hydrogen cars to become competitive via a learning curve approach.

1.2 Macroeconomic effects of introducing hydrogen cars

The main findings of introducing hydrogen in the transport sector are very similar in all scenarios. All Member States (MS) are expected to experience increases in transport demand, real consumption, GDP (gross domestic production) and welfare.

Figure 1: Real consumption in the H2H scenario

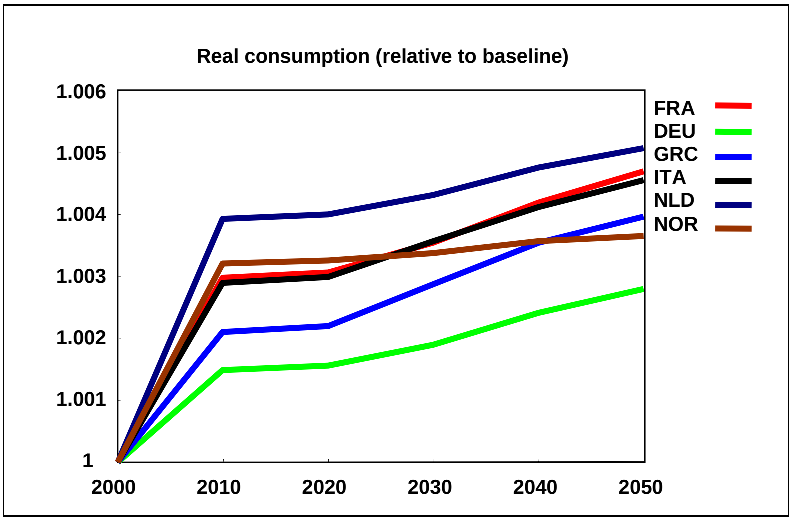
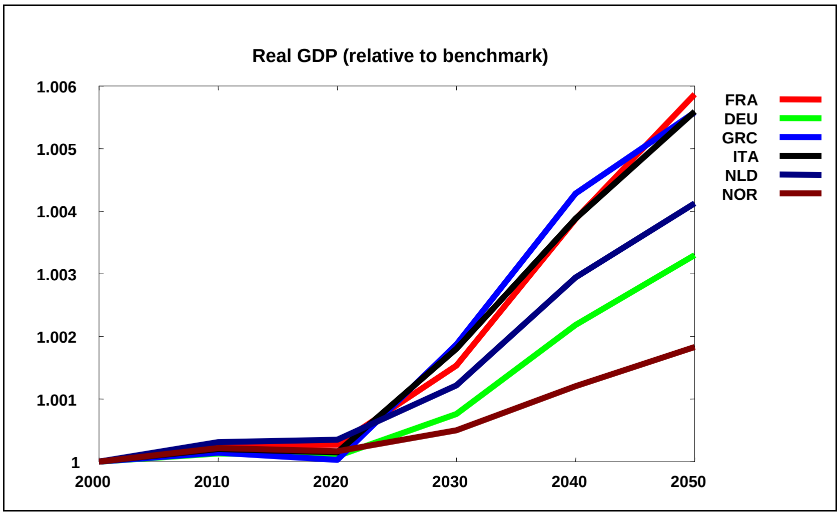


Figure 1 shows the development of real consumption in the six MS assuming high hydrogen penetration rates and a steep learning curve. Obviously, the Netherlands can experience the highest increase in real consumption of 0.5 percent in 2050 compared to the baseline. In contrast, consumption in Germany rises by only 0.2 percent. The other countries range in the middle. These findings are mainly driven by the hydrogen production costs in the six MS, the lifetime costs for hydrogen and conventional cars and the assumed hydrogen penetration rates in the different car classes. Since hydrogen production costs are lowest in the Netherlands, the cost savings potential due to the introduction of hydrogen cars is highest. Consequently, consumption in the Netherlands also increases the largest. The opposite holds true in the case of Germany. Here hydrogen production costs are highest which leads to much smaller cost savings and thus the lowest rise in consumption across the six MS.

The observed increase in real consumption directly translates into welfare gains in all MS. Not surprisingly, welfare increases are largest in the Netherlands, France and Italy where it rises by 0.45 percent, 0.38 percent and 0.37 percent, respectively. More modest improvements in welfare are observed in Norway, Greece and Germany. Here welfare rises by 0.34 percent, 0.30 percent and 0.21 percent, respectively. This result is due to the fact that real consumption in the MS increases since lifetime costs of hydrogen cars are lower than for conventional cars which yields to a higher consumers' budget.

Figure 2: Real GDP in the H2H scenario



The development of real GDP as shown in Figure 2 is slightly different. In the periods before 2020 GDP remains almost unchanged to the baseline since there are only few hydrogen cars in the market. Afterwards, however, GDP starts to rise in all six MS. Thus GDP in 2050 exceeds the respective baseline value by approximately 0.6 percent in France, Italy and Greece, by 0.4 percent in the Netherlands, by 0.3 percent in Germany, and by 0.2 percent in Norway. These differences across the MS mainly stem from the different development of penetration rates and hydrogen production costs. The results in each MS further depend on the assumed paths for future fossil fuel prices and on hydrogen and conventional car production costs.

Of course, assuming high hydrogen penetration rates and a large decrease in hydrogen production costs seems to be a very optimistic scenario. However, the overall findings of the other scenarios are comparable and the principle results point into the same direction but with smaller magnitude. Assume, for example, high penetration rates and a lower rate of cost reduction. Welfare in Italy and the Netherlands now increases by only 0.25 percent and 0.24 percent, respectively, and Germany and France experience welfare gains of 0.10 percent and 0.11 percent respectively. This reflects the smaller cost savings potential which leads to a smaller increase in consumption in all MS. Consequently, GDP in 2050 also rises more modestly by 0.4 percent in Italy and 0.1 percent in Norway with the other countries ranging in between these two extremes.

Additionally assuming lower hydrogen penetration rates leads to even smaller macroeconomic impacts of the introduction of hydrogen in the transport sector. But again, the macroeconomic variables are slightly positive affected.

1.3 Conclusions

Under the assumptions of HyWays the introduction of hydrogen in the transport sector leads to improvements in the macroeconomic variables in all six MS. However, the economic gains depend heavily on the assumed learning curve of hydrogen cars and on the future development of hydrogen infrastructure costs. But also the path of fossil fuel prices affects the extent to which hydrogen cars become competitive in the future. Thus the cost savings potential between the lifetime costs of conventional and hydrogen cars determines the increase in the consumers' budgets which finally drives the increase in consumption, welfare and GDP in the different scenarios.

2 Introduction

The EU "HyWays" project aims at a realistic quantification of the effects of a European hydrogen promotion policy, combining expertise from energy engineering, energy system modelling and economics. Within the project, data on a large array of hydrogen-related technology is collected and processed in different kinds of models in order to investigate the technical, socio-economic and emission challenges and impacts of realistic hydrogen supply paths under consideration of technological and economical needs. The aim of the project is to deliver a validated roadmap for the large-scale introduction of hydrogen as an energy carrier in the transport and power market and as a storage medium for renewable energy.

This report analyzes the macro-economic consequences of a hydrogen promotion policy in the transport sector. For the assessment of economy-wide repercussion effects of an introduction of hydrogen in the transport sector, we use the computable general equilibrium (CGE) model PACE-T. PACE-T is a dynamic, multi-region and multi-sector model based on the GTAP database and additional energy and transport data. The original model was adjusted for the specific needs of the “HyWays” project. It thus features 8 regions – 6 Member States (France, Germany, Greece, Italy, Netherlands, Norway), the rest of the EU (REU) and the rest of the world (ROW). Passenger cars are modelled as a durable consumption good; consumption of passenger transport services uses capital services from the stock of cars, fuel and auxiliary inputs. The model distinguishes between three different car sizes: small, medium and large cars which are powered by either a conventional technology or by hydrogen. In the reference scenario hydrogen technology is assumed to be inactive. It can become active in the considered policy scenarios if lifetime hydrogen car costs are competitive. This is mainly reached by (1) a cost decrease of hydrogen cars by, for example, R&D and/or (2) regulation like, for example, subsidising hydrogen cars (as long as hydrogen car lifetime costs exceed conventional car lifetime costs). In the model this is implemented via a learning curve approach.

The analysis of the possible impact of the introduction of hydrogen on transport demand, real consumption, GDP and welfare considers two scenarios where the hydrogen technology becomes competitive: (1) a high-penetration rate scenario (H2H) and (2) a low-penetration rate scenario (H2L). The penetration rates were directly taken from the MARKAL model (for additional information see deliverable D 3.6). Both scenarios assume a steep learning curve, i.e. there is a relatively high rate of cost decrease for hydrogen fuelled cars. As the results of these two scenarios suggests, the effects of the introduction of hydrogen in the MS are fairly small. Transport demand and real consumption slightly increase compared to the references scenario. This is mostly due to the cost reduction of the cheaper hydrogen technology. As a consequence, all MS will experience small GDP and welfare increases. The differences between the single MS mainly stem from the different hydrogen penetration rates and production costs.

In order to analyze the sensitivity of our simulation results, we additionally consider two more pessimistic scenarios which assume a less steep learning curve. The rate of cost decrease for hydrogen production is thus smaller. Again simulations are carried out for a high penetration rate (L2H) and a low penetration rate (L2L). The results of this sensitivity analysis are very similar to the scenarios with a high cost decrease. Of course, the effects on GDP and welfare are even smaller since hydrogen cars become competitive later, i.e. the positive cost reduction appears later during the considered period.

This report proceeds as follows. The next section briefly reviews the links to the input data from the MARKAL and the ISIS model. Section 4 gives an introduction of the methodological approach of the PACE-T model. Section 5 explains the input data and their treatment in PACE-T in more detail. Section 6 presents the results of the two scenario simulations and the sensitivity analysis. Afterwards the main lessons learnt from the simulation results are summarized and section 9 concludes. Note that the Appendix provides detailed developments of penetration rates and car lifetime costs for all MS in the considered scenarios.

3 Feedbacks and links between models

The parameterization of the PACE-T model requires the reconciliation of top-down data and bottom-up data stemming from different data sources. PACE-T is generally based on the fundamental GTAPinGAMS structure (Rutherford 1998). The top-down data comes in the form of social accounting matrices (SAM) provided by the GTAP5 database (GTAP 2002) to which the model is calibrated.

However, the inclusion of passenger cars which are powered by either a conventional technology or hydrogen demands further input (bottom-up data) which is taken directly from two other models applied in the HyWays project (see deliverables D3.2, D3.6 and D 3.7).

First, data on car technology and hydrogen production technology are taken directly from the MARKAL model (see also deliverable D 3.6 “Energy system modelling of a hydrogen economy”). These data are mainly related to the capacity and activity of various technologies and related parameters. Among these are

- activity level
- costs
- delivery cost
- fuel cost
- fuel input
- installed capacity
- investment cost
- new capacity
- operation and maintenance (O&M costs).

Information on the technical and economical characterisation of the hydrogen technologies from the E3Database is directly adopted in MARKAL. This data thus enters PACE-T via the data input from the MARKAL model. Therefore PACE-T does not require specific information directly from the MS and the industry.

Second, given the output quantities and the cost structure of the different hydrogen technologies the aggregate production data of the IO sectors is split down to accommodate a consistent bottom-up representation. Therefore, the input structure of car and hydrogen production technologies are adopted from the ISIS model (see also deliverable D 3.7 “Report on the lead market approach and the input/output analysis of energy systems on all branches of industry”).

For more details on the interaction of the models in the HyWays project see deliverable D 3.2 “Definition of model data exchange and model interfaces”.

4 Methodological approach

PACE-T belongs to the class of computable general equilibrium models.[1] These models are used for quantifying the impacts of policy changes on economy-wide resource allocations where the behaviour of different actors is founded by microeconomic reaction functions. CGE models are suitable for studying price-dependent interactions between the energy system and the rest of the economy. Due to the general equilibrium property of the models, all income circuits are closed. That means that the origination and the spending of income for all major economic agents like households, firms, the government, and foreign countries are simultaneously explained. Furthermore, these kinds of models allow to analyse efficiency aspects of regulatory interventions.

As already mentioned, PACE-T is based on the fundamental GTAPinGAMS structure (Rutherford 1998). It thus incorporates top-down benchmark data in the form of social accounting matrices (SAM) to which the model is calibrated. In addition to this top-down approach, the model as used in the HyWays project incorporates a bottom-up foundation of the energy and transport sector. Discrete technologies are integrated in these two sectors in order to being able to study the effects of the transition towards the hydrogen economy. That means that the model shows top-down as well as bottom-up features.

The model applied in the project distinguishes between eight regions: The six Member States (MS) are each covered by an own region. The additional two regions are the rest of the EU (including Switzerland and Iceland) and the rest of the world. PACE-T is disaggregated into nine sectors. These are the transport sector, energy intensive production, six energy sectors, and the rest of the production. The model is set up as a fully dynamic model with optimal savings and investment decisions. Period length is chosen to be 10 years with the model horizon extending from 2000 to 2080[2]. International trade (except for passenger cars) is modelled in the Armington fashion (Armington 1969) where goods produced in different countries are treated as imperfect substitutes and their import shares depend on their relative prices.

The transport sector in the model is included in a way that households do not consume cars as such but transport services that are produced with various inputs. The value of these services is mainly composed of capital services of the automobile stock present in the respective economy, fuel and expenditures for repair and maintenance. Passenger cars are modelled as durable

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[1] The general equilibrium structure of these models is based on Arrow and Debreu (1954). An introduction to applied general equilibrium analysis can be found in Shoven and Whalley (1984). Computable general equilibrium models are used in almost all economic fields in order to quantify the impact of policy reforms. For an overview of these studies see e.g. Bhattacharyya (1996), Conrad (2001), Gottfried et al. (1990) or Gunning and Keyzer (1995).

[2] We only report simulation results up to year 2050. The additional period between 2060 and 2080 accounts for the terminal condition of the model.

consumption goods. Car lifetime is assumed to be 12 years for all cars. The model distinguishes between three different size classes for cars. These are small, medium and large cars which are powered by either a conventional technology or by hydrogen.

When consumers make their car purchasing decision they take into account (1) the car consumer price, (2) the price of the fuel as well as the O&M costs, and (3) the depreciation pattern of the car (lifetime). Consumers have to choose between transportation services produced by either a conventional technology or hydrogen. In the model, hydrogen and conventional cars are assumed to be perfect substitutes. As a consequence, households simply choose the cheaper technology. This assumption seems to be relatively unrealistic given the fact that there are further factors affecting car demand like e.g. noise or driving properties. However, due to the lack of detailed empirical data on hydrogen car demand there is no possibility to calibrate a more flexible demand function.

The baseline simulation in the PACE-T model assumes the hydrogen technology to be inactive. In the scenario analysis the hydrogen technology becomes active due to a cost decrease of hydrogen cars or by subsidizing hydrogen cars. Since consumers always choose the cheapest alternative (see the explanation above), the more expensive technology would simply be withdrawn from the market. In order to prevent such a development, both technologies have to be equally expensive. This is reached by either taxing or subsidizing the hydrogen technology. The respective amounts are lump-sum transferred to the consumer.

All scenarios in PACE-T are based on the structural identity assumption. Thus the international input-output structures of hydrogen and conventional cars are the same. This means that if a country is producing and exporting conventional cars at present, the assumption is made that this country will also produce and export hydrogen cars in the future.

In order to solve the model, the following equilibrium conditions have to hold: (i) zero profit conditions for all production sectors (under the assumption of perfect competition), (ii) market clearance on all markets (perfectly adjusting prices) and (iii) exhaustion of the representative consumer’s budget through consumption purchases.

5 Input data and scenario assumptions

5.1 Input data

As already explained in Section3, the parameterisation of PACE-T requires the consideration of top-down and bottom-up data stemming from different data sources.

The top-down data comes in the form of social accounting matrices (SAM) from the GTAP5 database (GTAP 2002). The SAMs summarise the benchmark data to which the model is calibrated. It distinguishes energy inputs, non energy inputs, labour and capital. The different hydrogen production, distribution and storage, and car technologies for the model regions for the 10 year periods up to 2050 are specified through the generic cost structure, the import/export shares, the output in the business as usual, and capacity constraints. The trade shares of hydrogen and conventional cars are taken form the sector “Motor vehicles and parts” of the GTAP database.

Further input data on both the hydrogen production technology and the characteristics of different car types for the bottom-up foundation of PACE-T are taken from the output of the MARKAL model.

Since the consumer’s car purchasing decision is based on consumer car prices, PACE-T requires further input of tax data for the model regions. This data is taken from a recent report of the German Institute for Economic Research (DIW 2002).

Eight regions are integrated in the current version of PACE-T. These are the six MS France, Greece, Italy, The Netherlands, Norway and Germany as well as the rest of the EU (REU) and the rest of the world (ROW).

5.1.1 Hydrogen production costs

Hydrogen production costs are heterogeneous across countries and periods because each country uses a different mix of hydrogen production technologies with different fuel or electricity inputs. In the initial phase of the hydrogen transportation, the by-product hydrogen can account for a significant part of the hydrogen production. When the hydrogen demand increases in the later periods, steam methane reforming becomes the major production technology. There are significant differences across the MS, which are described in detail in the MARKAL report (see deliverable D 3.6 “Energy system modelling of a hydrogen economy”).

Average costs of hydrogen production are calculated by summing costs of investment, fuel inputs and O&M. We assume a linear depreciation of hydrogen production technologies and calculate yearly depreciation rates as the reciprocal of the lifetimes. Average annual cost components (investment, fuel and O&M) for each country are derived by dividing total annual cost positions (given in MARKAL in MEUR (Million Euro)) by total annual hydrogen production (in Petajoule = PJ) in the respective country. The latter is computed by summing the activity levels of all technologies used in this country.

a) Investment costs

Investment costs are the costs of the setup of new generation or distribution facilities. We annualise total investment costs given in MARKAL with the yearly depreciation rate. They are calculated separately for generation and distribution costs.

Generation investment costs are costs directly related to the technologies. Total investment costs (in MEUR) for a specific technology are calculated by multiplying investment costs per hydrogen production (in MEUR/PJ) with installed capacity (in PJ). Finally, average annual generation investment costs (in MEUR/PJ) are generated by multiplying the costs of a particular technology with the sum of interest rate and depreciation rate and weighting with the respective production share. Distribution investment costs are calculated analogously to generation investment costs. Here the weighting is over the distribution technologies. Total average investment costs are the sum of average generation and average distribution investment costs.

b) Fuel costs

Average fuel costs (in MEUR) for a particular country and year are calculated as a weighted average over all technologies with their respective fuel inputs. The oil-price is one of the factors which determine the fuel costs. PACE-T is calibrated such that the oil price equals the MARKAL oil price in each of the periods in the baseline. The scenarios can lead to deviating oil prices.

c) Operation and maintenance costs

O&M costs (in MEUR) are directly taken from the MARKAL output interface, aggregated over all technologies and divided by total hydrogen production activity level (in PJ).

5.1.2 Price differences of hydrogen and conventional cars

For a comparison of the costs of hydrogen and conventional cars it is necessary to consider the costs over a car’s lifetime. We assume a uniform, non-stochastic lifetime of 12 years for each car. Total automobile costs are then calculated as the sum of purchase and utilisation costs for both hydrogen and conventional cars over their lifetime where utilisation costs are further decomposed into fuel costs and other costs (in the MARKAL model other costs are further divided into O&M costs and delivery costs). The derivation of car lifetime costs of conventional and hydrogen cars is explained in the following.

a) Conventional cars

The aggregate car category "conventional cars" encompasses six sub-categories, namely three size categories of diesel cars as well as of gasoline cars from the MARKAL output. The three sizes are "small", "medium" and "large" cars (according to the MARKAL data). The weights of the categories are based on their particular share in total activity level differentiated by year and country.

Investment costs are incurred at the moment of acquisition and thus are not discounted. They are calculated as a weighted average of investment costs.

All costs which are incurred during the usage of the car must be discounted to the year of acquisition. We assume the annual costs to be constant over the whole period of usage, which results in a discount factor of $((1+i)^n-1)/(i*(1+i)^n)$, with interest rate i (=4%) and lifetime n (=12 years). Thus, each annual cost position has to be multiplied by this factor (instead of factor 12 without discounting).

According to MARKAL, net fuel costs are assumed to be equal in all countries. The reason is that the main driving factor for the fuel costs net of taxes is the oil-price. In order to derive the annual fuel expenses in Euro per car, fuel costs per litre are multiplied by average fuel input (in litre) per car per year. Fuel costs are discounted and aggregated over the car's lifetime. Consumer fuel prices consist of net prices plus fuel taxes. Taxes for gasoline and diesel are assumed to be constant over time (in Euro per litre), but are varying across countries. Tables 1 and 2 show the fuel taxes in the year 2002 which are implemented into the model.

Table 1: Gasoline fuel taxes (in Euro per litre)

DEU	FRA	GRC	ITA	NDL	NOR
0.63	0.57	0.33	0.52	0.62	0.60

Source: DIW (2002).

Table 2: Diesel fuel taxes (in Euro per litre)

DEU	FRA	GRC	ITA	NDL	NOR
0.44	0.38	0.28	0.38	0.34	0.49

Source: DIW (2002).

The sum of net fuel costs and weighted fuel taxes makes up the gross fuel costs per litre.

The remaining costs that are incurred during the vehicles' lifetimes are subsumed under "other costs". They consist of O&M costs as well as costs for the delivery of fuel. Expenses per year and car are again calculated as weighted averages and multiplied by the discount factor.

b) Hydrogen cars

The aggregation for the car category "hydrogen cars" is similar to the category "conventional cars". Now we differentiate between "hydrogen fuel cell cars" and "hydrogen internal combustion engine cars". The three size categories "small", "medium" and "large" are maintained as for conventional cars.

Hydrogen production costs have been calculated in Million Euro per PJ. Assuming average cost pricing and no taxes on hydrogen, the production costs can directly be used to generate hydrogen car fuel costs. This is done by multiplying with the average fuel input per car per year (again as a weighted average of the values given in the MARKAL model).

c) Cost difference

The value of the cost difference between conventional and hydrogen cars highly depends on whether taxes for conventional fuel are taken into account or not. Consequently, a cost comparison must distinguish between a net cost and a gross cost analysis.

The net cost difference is important when the welfare implications of introducing hydrogen cars are to be analysed. The comparison of net costs allows to determine when hydrogen cars become competitive. When considering the consumer's car choice, gross car costs have to be taken into account. Gross costs are calculated from the car prices including the fuel taxes in the different countries.

5.2 Scenarios

In the following we analyse two scenarios, namely the high penetration rate scenario (H2H) and the low penetration rate scenario (H2L). While the hydrogen technology is assumed to be inactive in the baseline, hydrogen cars become competitive and thus enter the market in both scenarios. The properties of the hydrogen technologies (e.g. costs) and the hydrogen penetration rates are adopted from the respective MARKAL runs[3]. By implementing the MARKAL results every assumption that influences the corresponding MARKAL results is indirectly adopted by

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[3] Input data for the scenarios with the high learning curve approach were taken from Markal_V6.3.

PACE-T. These assumptions are for example the impacts of the learning curve approach or of the policy framework on technology choice and technology properties. Both scenarios are based on the assumption of a relatively steep learning curve. This means that the rate of cost decrease is relatively high. Except for the introduction of hydrogen technologies there are no additional changes for the two scenarios compared to the baseline.

PACE-T is calibrated such that the share of cars of the three size categories in the different countries in the year 2000 equals the share in the MARKAL model. For later periods, the substitution elasticity between the different size categories is – in contrast to MARKAL – assumed to be zero. The penetration rates are introduced as relative share of new hydrogen cars on all new cars for each of the three size categories, countries, and periods. These rates are directly adopted from the MARKAL results.

In the baseline hydrogen technologies are inactive in both the MS and the other regions. Penetration rates in the scenarios are only applied for the MS while hydrogen technologies remain inactive in the rest of the EU and the rest of the world. This assumption allows to directly analyse the effects of introducing hydrogen cars in the six MS.

Since PACE-T assumes both car types (hydrogen and conventional) to be perfect substitutes, the representative consumer always chooses the cheapest alternative. As a consequence the more expensive technology would simply be withdrawn from the market. Of course this would be highly unrealistic. In order to make both hydrogen and conventional cars to remain in the market in a certain period, a certain size category, and a certain MS, total lifetime costs[4] of both car types (including taxes or subsidies) have to be equal. The difference between the producer price and the consumer price of the hydrogen car determines whether the seller would make a profit or a loss when selling a hydrogen car.

Since we do not analyse any distributional aspects within PACE-T, this difference (profit or loss) is lump-sum transferred to the representative consumer. Consequently, the budget of the representative consumer increases with the purchase of a hydrogen car if the consumer price exceeds the producer price. In the case that the consumer price is below the producer price, the representative consumer’s budget decreases by this difference. You could also think of a different story with the same effects: The seller is taxed or subsidised to the extent of the difference between the hydrogen car producer and consumer price. These tax revenues or subsidy outlays are lump-sum transferred to the representative consumer. Again, the budget of the representative consumer increases with the purchase of a hydrogen car if the producer price is lower than the consumer price and the seller is thus taxed, and vice versa.

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[4] The calculation of lifetime costs for both car types is explained in detail in sections 5.1.1 and 5.1.2.

In addition to the analysis of the high- and low-hydrogen penetration scenario with the steep learning curve approach, we also present the results of two sensitivity runs. Precisely, we again consider either high or low hydrogen penetration rates. But in contrast to the two previous scenarios we now assume a less steep learning curve, i.e. the rate of cost decrease for the hydrogen production is now lower. As before, we adopt the respective results of the MARKAL model[5] in PACE-T. All other assumptions are the same as mentioned above.

The results of the scenario calculations and the sensitivity runs are described in chapter 6.

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[5] The input data for the simulations with the low learning curve approach are taken from Markal_V6.4.

6 Results

The following two sections analyse in detail the two scenarios H2H and H2L with the high learning curve approach and either high or low hydrogen penetration rates. Afterwards, we discuss the two sensitivity scenarios L2H and L2L which assume a lower rate of cost decrease for hydrogen. As already mentioned above, all considered scenarios are based on the structural identity scenario as outlined in the ISIS model (see also the explanation in Section 4).

Since the proceeding is equal for each of the six MS and most of the results are similar across the MS, the results for the different countries are described in parallel in the following. This allows for a better comparison of the macroeconomic effects of the introduction of hydrogen cars in the MS.

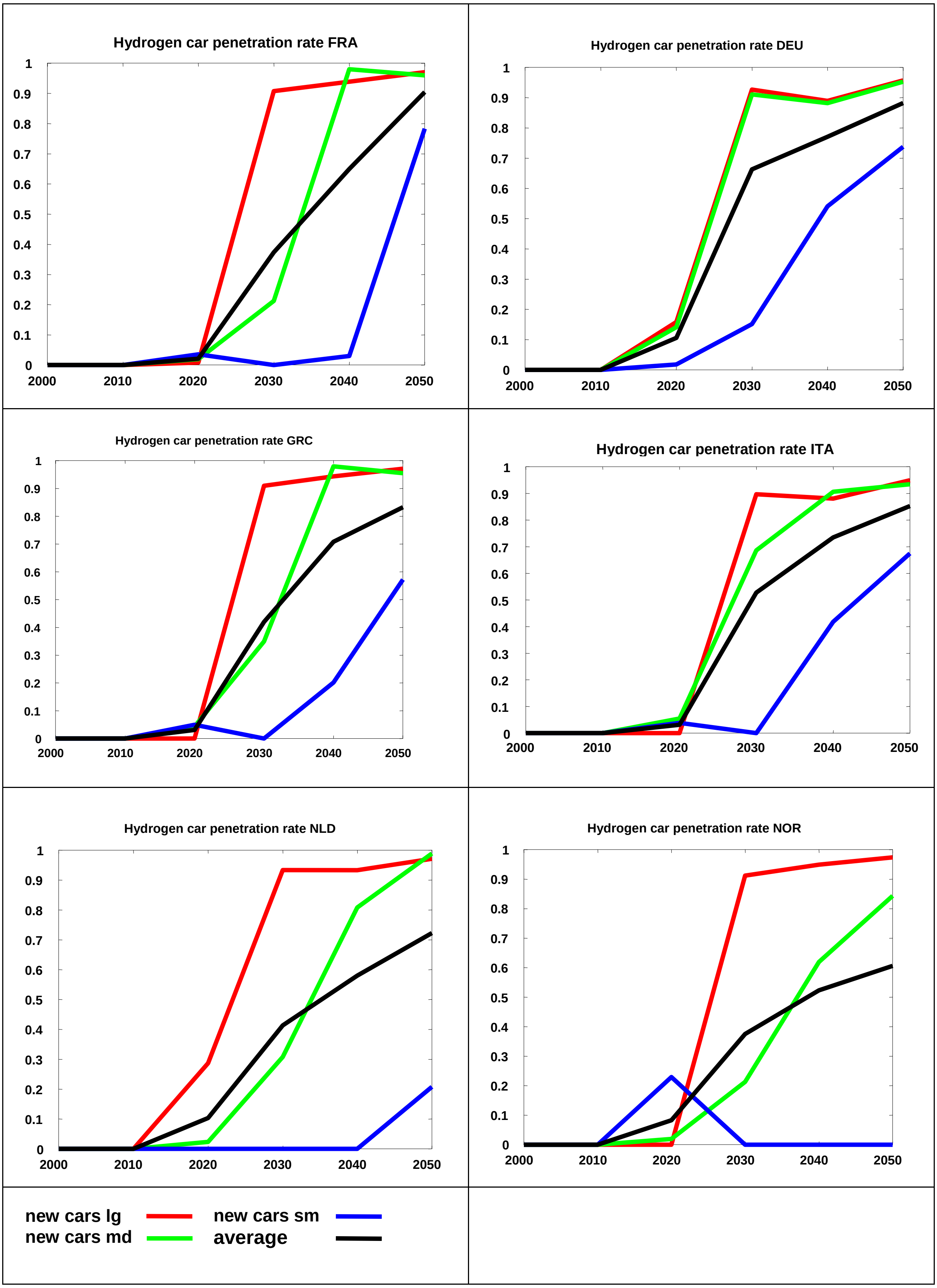
6.1 High hydrogen penetration (H2H)

The first scenario considers the simulation results if the penetration rate for hydrogen is high and the rate of cost decrease is high. We first highlight the development of the penetration rates in the six MS until 2050 and compare the costs of conventional and hydrogen cars in detail. Afterwards we analyse the impact of the introduction of hydrogen cars on transport demand, real consumption, welfare, GDP, and the wage rate in the MS.

6.1.1 Penetration rates

As already mentioned, PACE-T adopts the share of hydrogen cars in each car size category, in each period and in each MS directly from MARKAL. Figure 3 shows the development of the penetration rate of new hydrogen cars as share of overall new cars in the respective size category between the years 2000 and 2050. This development is depicted for each of the six MS countries in a separate diagram. In addition to the penetration rates of the three size categories Figure 3 also presents the average penetration rate for hydrogen cars. The latter is defined as the share of new hydrogen cars in overall new cars in the respective country and the respective period.

Figure 3: Hydrogen penetration rates for new cars in different countries



The penetration rates for new cars in each size category are derived by an optimisation process in the MARKAL model. First the target for the overall penetration rate (all size categories aggregated) is implemented into MARKAL. The model then calculates the cost optimal penetration rates for the different car classes which meet the overall penetration target. This optimisation process applied in the MARKAL model of course affects the development of penetration rates in PACE-T.

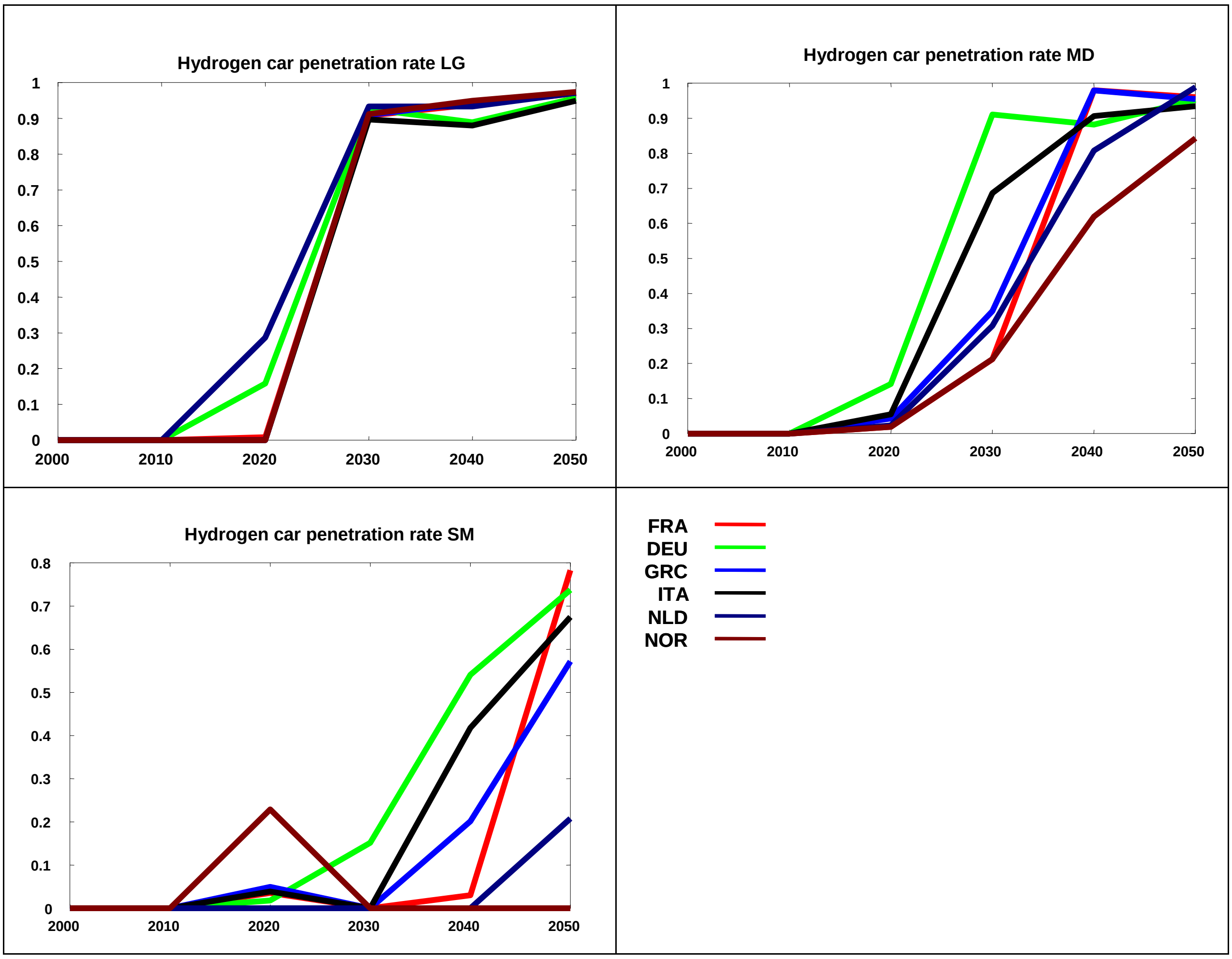
Obviously, the paths for the penetration rates in PACE-T are similar in the six MS. In the early period of the hydrogen introduction (2020) the penetration rates of new small cars (new cars sm) are slightly higher than the rates of new medium sized (new cars md) or new large cars (new cars lg). This holds especially true for France, Greece, Italy, and Norway where in the latter country the penetration rate for small cars even exceeds 20 percent. After 2020 the penetration rates for medium and large cars increase steeply in all MS and reach values between 80 and 100 percent. The penetration rates of medium and large cars clearly dominate the ones of small cars.

These findings are not surprising. Small cars are the cheapest car category and hence the hydrogen technology should be introduced in small cars as long as the hydrogen technology is not cost efficient enough. This is exactly observed until 2020. As soon as the hydrogen technology becomes more cost efficient, the technology should be introduced in large cars. This explains why the penetration rates for small cars are initially relatively high (compared to the other size categories) while they are relatively low in later periods.

Having a look at the average penetration rates, Figure 3 implies a very steep increase in hydrogen penetration in all MS from 2020 onwards. In 2050, the average penetration rate of hydrogen cars will reach almost 90 percent in France, Germany, Greece and Italy whereas it is only 70 percent in the Netherlands and 60 percent in Norway. Note that the average penetration rate for new cars in PACE-T can differ from the respective rate in MARKAL. The reason is that the shares of cars in the different size classes can differ from MARKAL during the model periods.

In order to allow for a better comparison of the development across the MS, Figure 4 shows the penetration rates for all countries in each size class.

Figure 4: Hydrogen penetration rates for new cars in different size classes



It is remarkable that the paths of the penetration rates for new large hydrogen cars are almost identical across the MS. For small and medium sized cars the differences are much larger. Take the medium sized cars. While the level of penetration rates in 2050 is almost identical in all MS, the timing of the increase differs. In Germany and Italy penetration rates are already at a high level in 2030, while in the other countries the largest increase is observed until 2040. In the small car segment, the development of penetration rates is similar in France, Germany, Greece, and Italy reaching levels of about 60-80 percent. Compared to these findings, penetration rates in the Netherlands and Norway are at very low levels. They reach only 20 percent in the Netherlands and are even zero in Norway in 2050.

The industry partners and modellers of the HyWays project agreed to assume a lifetime of 12 years for all cars in MARKAL, ISIS and PACE-T. Since one period in the PACE-T model covers 10 years, the stock of car fleet in one period is composed of a share (one sixth) of the stock of the previous period and the stock of new cars introduced in the actual period. As a consequence, the share of hydrogen cars in the car stock differs from the share in new cars. Figures 27 and 28 in Annex 10.1 again provide the development of penetration rates similar to Figures 3 and 4 but report on the hydrogen share of cars **in the stock** rather than on the hydrogen share of new cars (as shown in Figures 3 and 4). As these figures indicate, the differences between the shares of hydrogen cars in the stock and the share of hydrogen cars in new cars are fairly small due to the fact that the assumed car lifetime exceeds the model period by only one sixth which makes hardly any difference to the path of penetration rates.

6.1.2 Cost Comparison

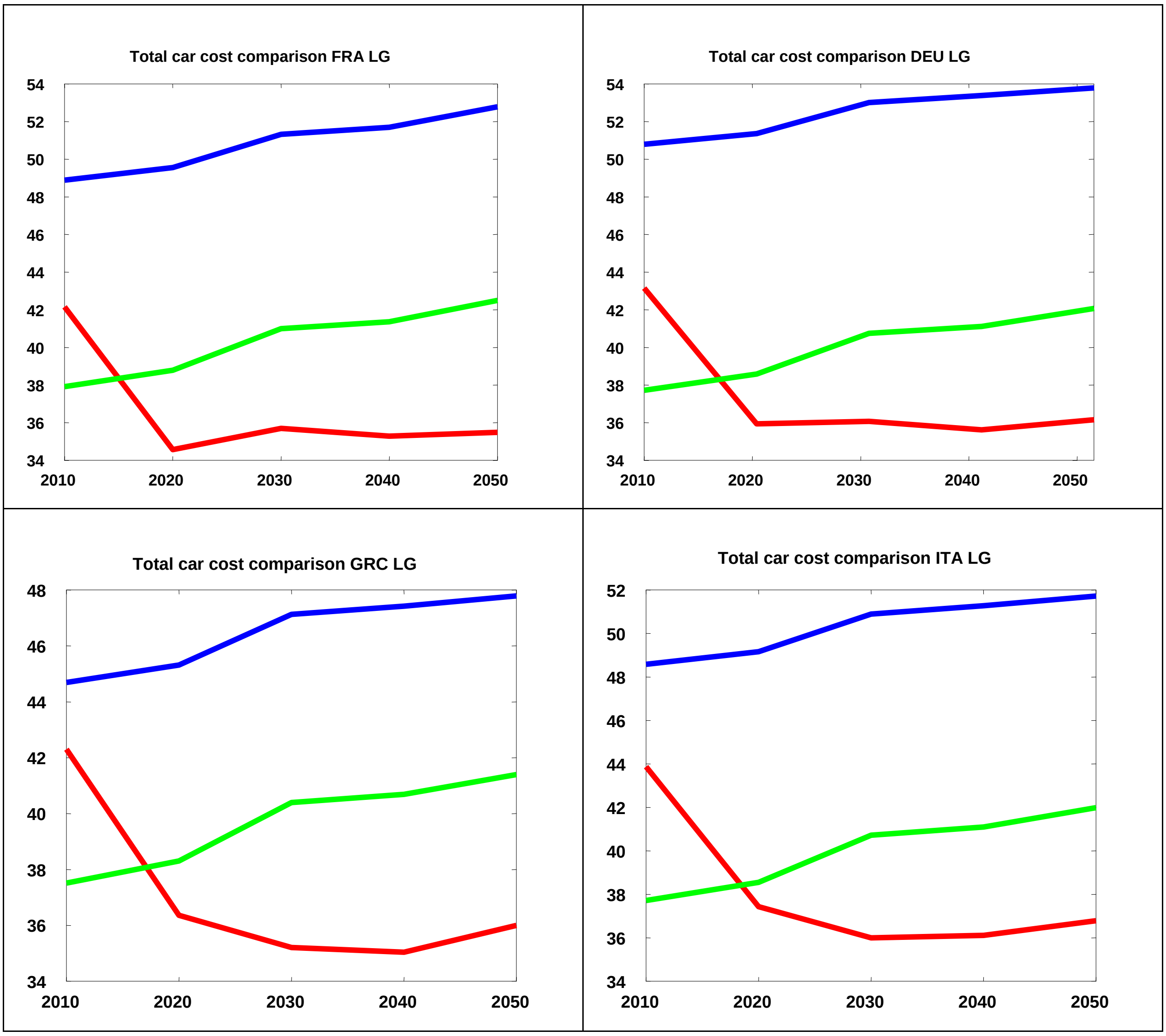
The breakdown of the MARKAL output into car costs, fuel costs and O&M costs in PACE-T was already explained in Section 5. However, few values that are needed for a cost comparison could not be taken directly from the MARKAL results. This holds for some O&M costs if the respective technologies become active later than in 2010. In such a case we assume O&M costs in 2010 to equal the costs in 2020. The second category of costs we had to make assumptions about is the hydrogen car cost: If no hydrogen car was active in the MARKAL model in a certain size category, in a certain year, and in a certain MS, we assigned the price of the technology with the lowest price in this class to the car type under consideration, even if it was not active. Normally the price of a different car type (e.g. large hydrogen cars in 2020) consists of the weighted average of the costs of different technologies, like for example internal combustion engine cars and fuel cell engine cars (e.g. both large hydrogen cars in 2020).

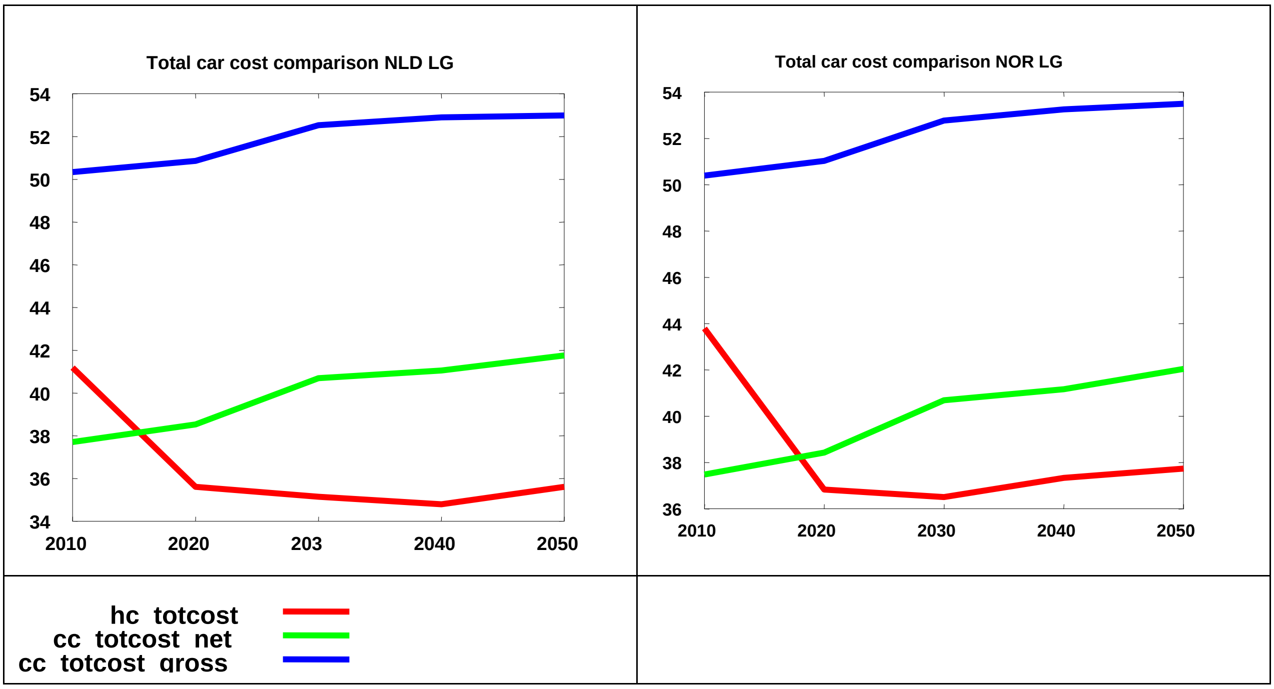
We now compare the lifetime costs of hydrogen and conventional cars. As already explained before, two important aspects have to be distinguished:

1. From the **macroeconomic** point of view car lifetime costs **net of taxes** are essential for the competitiveness of hydrogen and conventional cars.
2. From the **consumer**’s point of view car lifetime costs **including taxes** are essential for the car purchasing decision.

Figure 5 shows the development of the lifetime costs of large conventional cars including taxes (cc_totcost_gross) and excluding taxes (cc_totcost_net) as well as the total lifetime costs of large hydrogen cars (hc_totcost) between the years 2010 and 2050.

Figure 5: Cost comparison of large cars





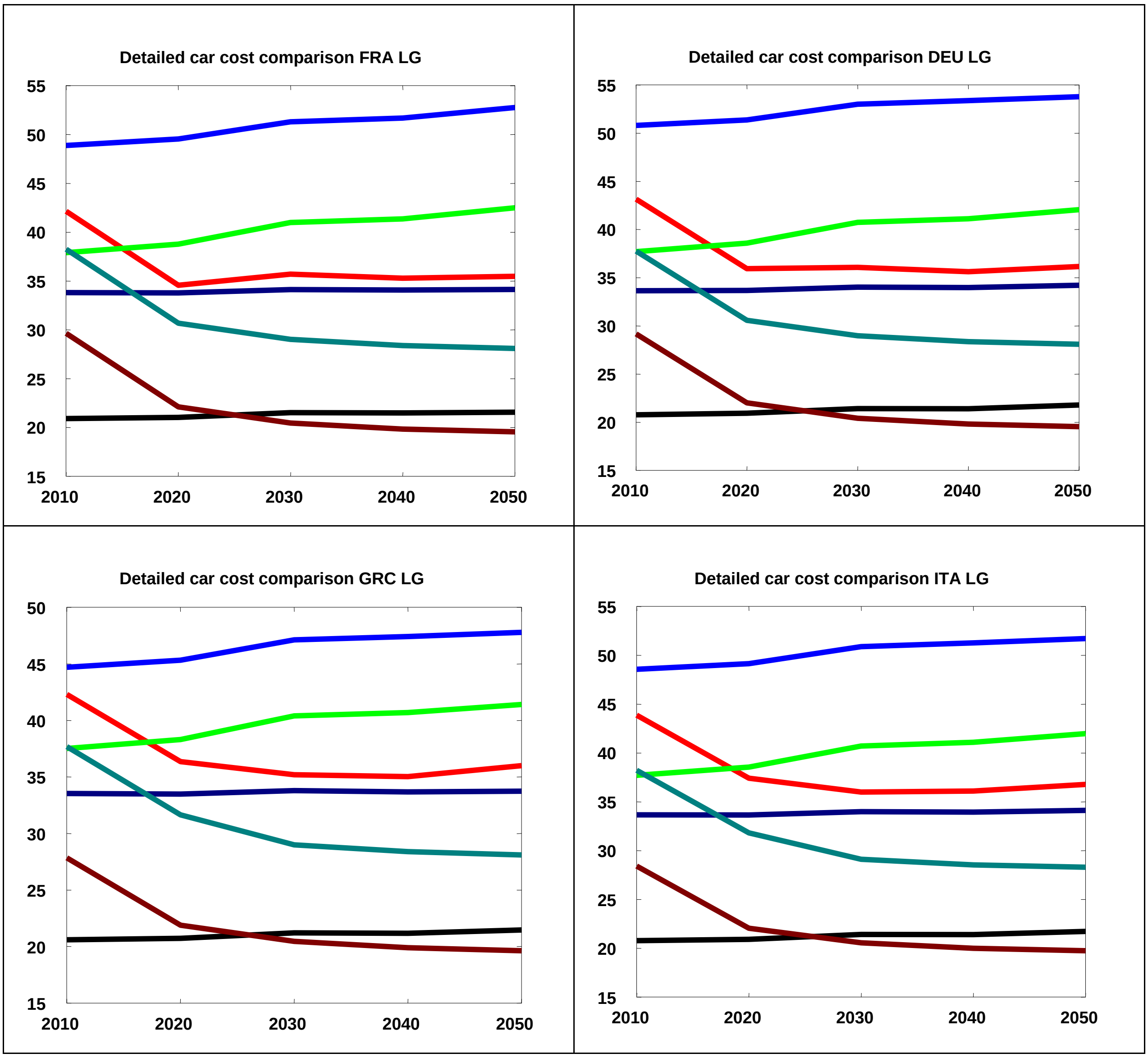
First consider the lifetime car costs net of taxes. When hydrogen cars are introduced in 2010, they are more expensive than their conventional counterparts. However, the lifetime costs of hydrogen cars decline very fast so that in 2020 the costs for large hydrogen cars are below the costs for large conventional cars in all six MS. The reason for this large decrease of the lifetime costs of hydrogen cars is the reduction of the producer price caused by technological progress, described by the learning curves. Thus from the macroeconomic perspective, large hydrogen cars are preferable in all MS from 2020 on.

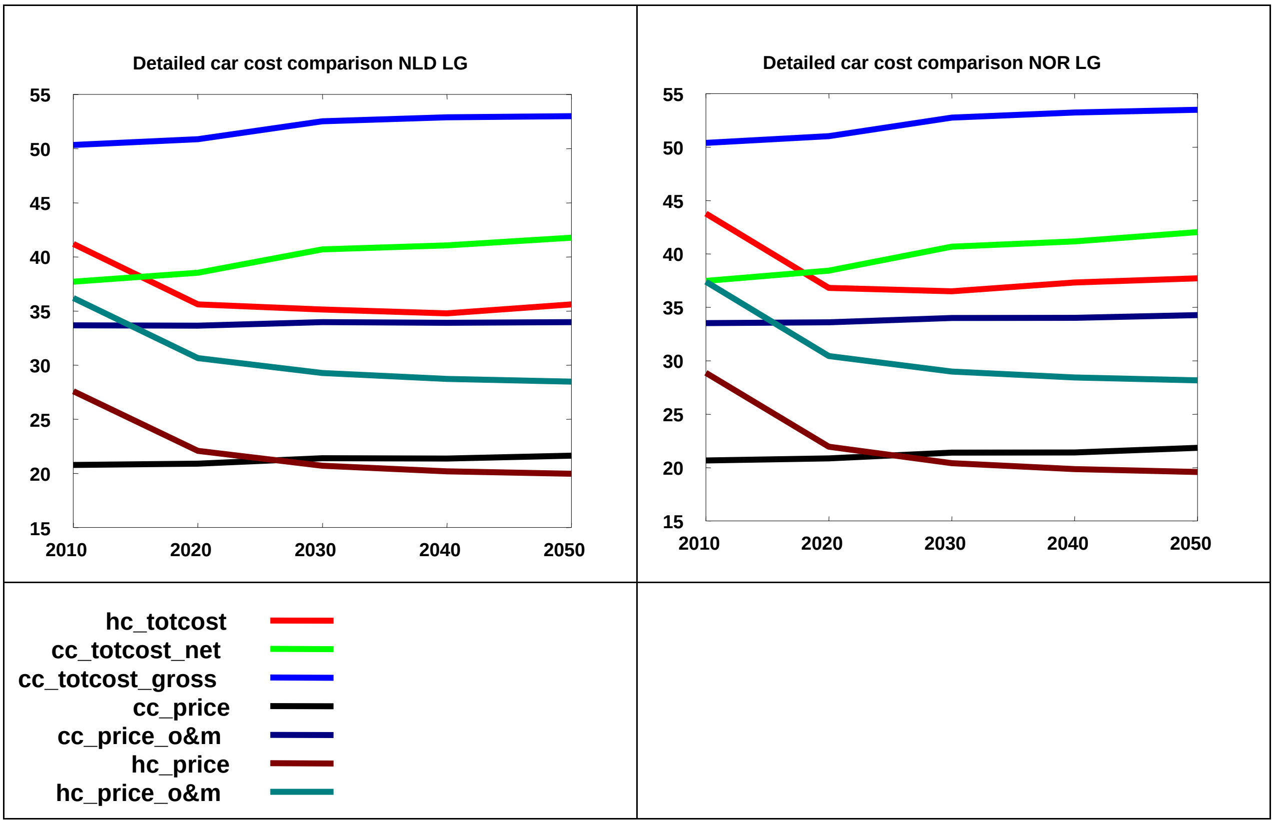
Now turn to the lifetime cost comparison of hydrogen and conventional cars including taxes. The difference between cc_totcost_net and cc_totcost_gross stems from the tax payments for conventional cars during their lifetime. When the representative consumer in the model has to decide between buying a conventional or a hydrogen car, he compares the lifetime costs of both car types and thereby takes into account all tax payments during this time. Thus cc_totcost_gross shows the amount the consumer would have to pay for a conventional car during its lifetime. If both car types (conventional and hydrogen) should stay in the market, the lifetime costs of both options have to be the same for the consumer. Consequently, the seller can demand a consumer price surcharge amounting to the difference between cc_totcost_gross and hc_totcost. Or expressed differently: It is possible to levy a tax on hydrogen cars which amounts to the gross lifetime costs of conventional cars (cc_totcost_gross) minus the lifetime costs of hydrogen cars (hc_totcost).

Figure 6 provides a much more detailed comparison of costs incurred during the lifetime of the different car types. The lifetime costs of conventional cars net of taxes (cc_totcost_net) are composed of the consumer price for conventional cars (cc_price), O&M lifetime costs (cc_price + O&M costs = cc_price_o&m), and lifetime fuel outlays (cc_price_o&m + fuel costs =

cc_totcost_net). The lifetime costs of hydrogen cars (hc_totcost) are similarly split into the consumer price for hydrogen cars (hc_price), O&M lifetime costs (hc_price + O&M costs = hc_price_o&m), and the lifetime fuel outlays (hc_price_o&m + fuel costs = hc_totcost).

Figure 6: Detailed cost comparison of large cars



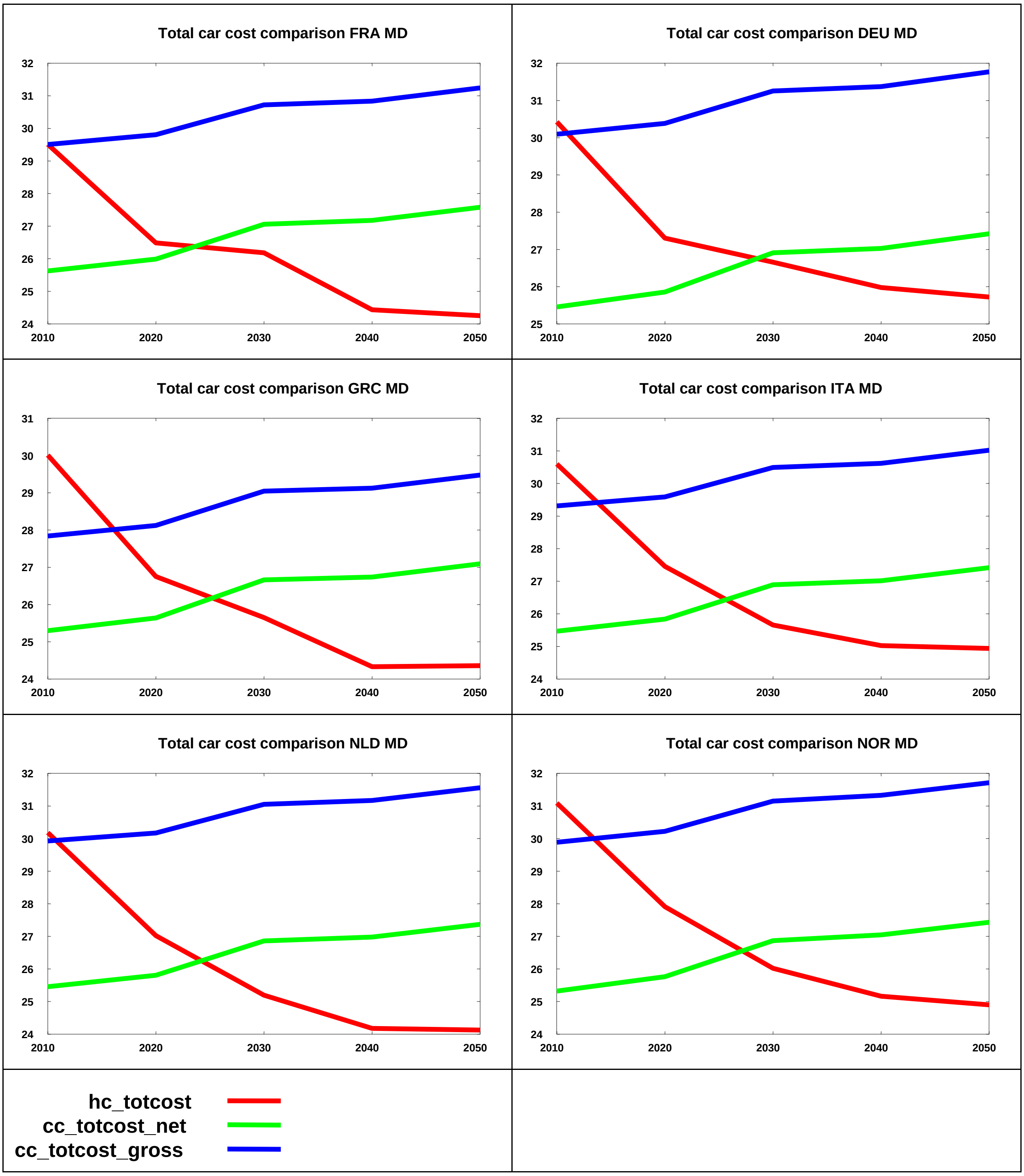


As becomes obvious from Figure 6, the driving force for the decrease of hydrogen lifetime costs between 2010 and 2020 is the decline in production costs in all MS. Furthermore, it is worth mentioning that the lifetime costs of large conventional cars permanently increase over time, while the lifetime costs of large hydrogen cars fall for most of the considered period. The cost decomposition in Figure 6 impressively shows that the main driving factor for this rise is the increase in fuel costs for conventional cars.

All in all, the results for the different MS are almost identical. Large hydrogen cars are competitive from 2020 on, even net of taxes. Also the shape of the different cost curves is similar across the MS. There are however some differences in the levels of costs across the MS. This especially holds true for the gross lifetime costs of conventional cars (cc_totcost_gross) which depend on the different fuel taxes across the MS as outlined in Tables 1 and 2. According to the high taxes on gasoline and diesel in Germany and Norway, both countries exhibit the highest lifetime costs (gross) for conventional cars. Furthermore, total costs for hydrogen cars (hc_totcost) are influenced by the different development of hydrogen fuel costs in the MS.

Now have a closer look at the cost comparison of medium size cars. This is shown in Figure 7.

Figure 7: Cost comparison of medium cars

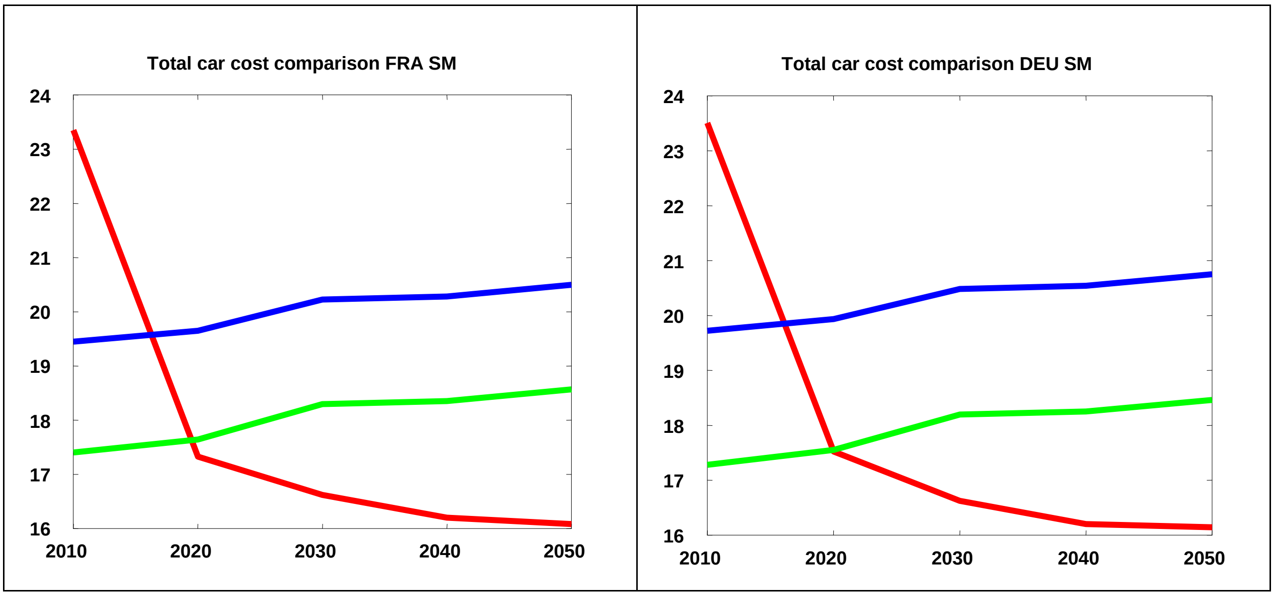


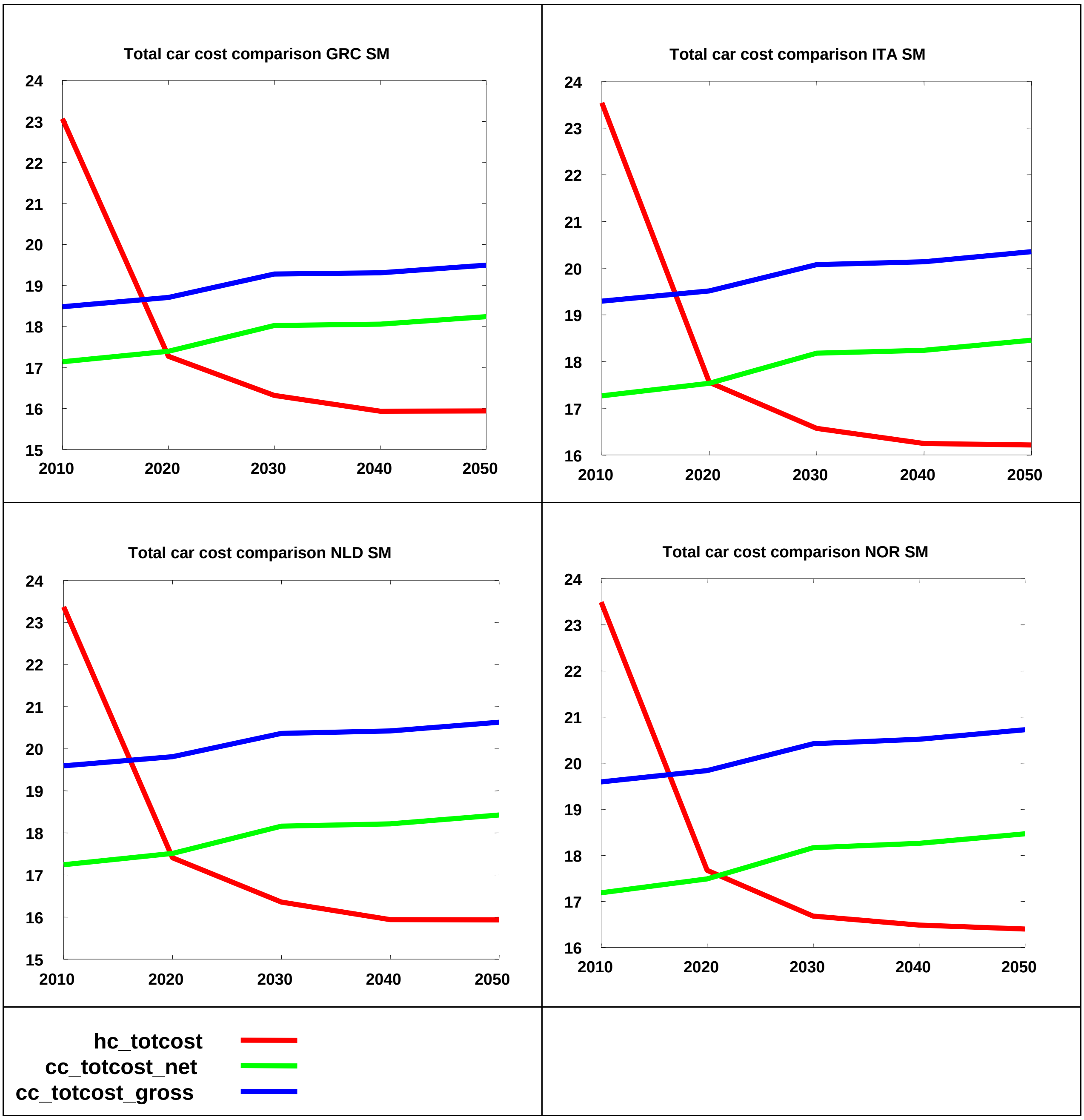
Again we compare the lifetime costs gross and net of taxes for conventional cars with the lifetime costs of hydrogen cars. The general development of the cost curves for medium-sized cars is similar to the cost curves of large cars. Of course the level of costs for medium cars is lower than for large cars in all MS. However, there are two main differences compared to the development of costs for large cars. First, lifetime costs for medium hydrogen cars in 2010 exceed the costs for conventional cars including taxes in Germany, Greece, Italy and Norway, while they are equal in France and the Netherlands. The cost difference is largest in Greece where the taxation of gasoline and diesel is lowest. Second, lifetime costs for medium hydrogen cars are higher than the lifetime costs of conventional cars net of taxes up to 2020. Thus, while large hydrogen cars are already competitive in 2020, medium hydrogen cars become competitive later, i.e. from 2030 on.

A more detailed cost comparison of medium cars is provided in Figure 29 in Annex 10.2. The cost curves have to be interpreted as the ones for large cars. The explanation is the same as before.

Finally, we need to have a closer look at the development of lifetime costs of small cars which is shown in Figure 8.

Figure 8: Cost comparison of small cars





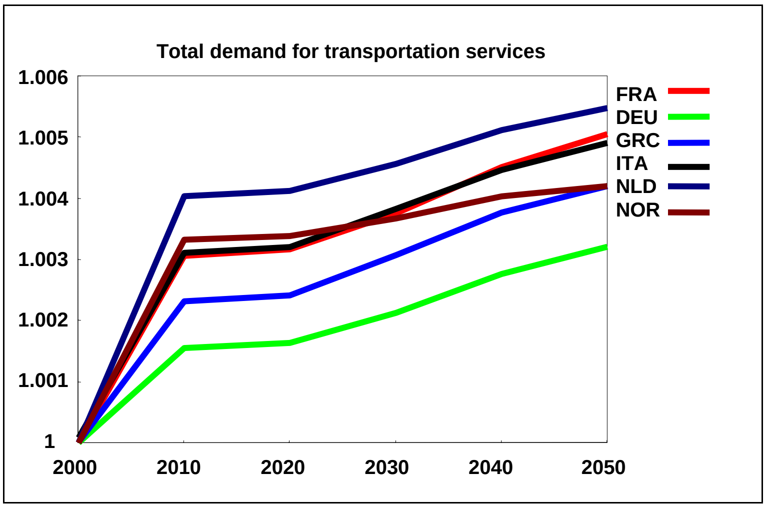
As for medium and large cars, we again consider the paths for the lifetime costs of small hydrogen cars and for the lifetime costs of small conventional cars gross and net of taxes. Obviously, lifetime costs of hydrogen cars in 2010 exceed those of conventional cars in all six MS by far. This finding impressively shows the initial high costs of hydrogen production. In 2020, hydrogen car lifetime costs are equal to the conventional car lifetime costs net of taxes in almost all MS, i.e. they become competitive earlier than medium-sized cars. From 2030 on, lifetime costs for hydrogen cars are below the net costs of conventional cars. The detailed cost comparison of small cars is given in Figure 30 in Annex 10.2.

This concludes the cost comparison of conventional and hydrogen cars. We now turn to the change in transport demand, real consumption, welfare, GDP, and wage rates in the MS associated with the introduction of hydrogen in the transport sector.

6.1.3 Transport demand, real consumption, welfare, GDP, and wage rate

First, it is interesting to analyse whether the penetration rates for hydrogen cars yield a higher or a lower transport demand. Figure 9 shows how the transport demand changes due to the introduction of the hydrogen technologies. Note that the graphs show deviations from the respective period in the baseline without hydrogen technologies. Consequently, the curves do not describe the transport demand over time but the multipliers to get the transport demand in the scenario in a certain period. For example, a value of 1.003 in 2010 indicates that transport demand in the year 2010 has increased by 0.3 percent compared to the respective baseline value in 2010. Since the year 2000 is the calibration year, the curves start with a value of one.

Figure 9: Transport demand



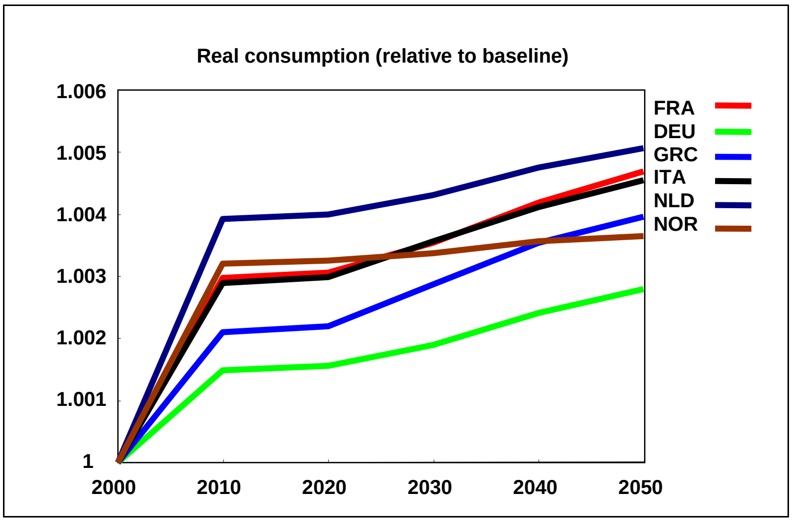
Obviously, the introduction of hydrogen technologies leads to an increase in transport demand compared to the baseline. The level of changes however is rather small. The largest increase occurs in the Netherlands where transport demand in 2050 exceeds the baseline value by almost 0.6 percent. In contrast, transport demand in Germany increases the least of all MS. Here the year-2050 value is only 0.3 percent above the respective value in the baseline. The other MS range in between the Netherlands and Germany.

Transport demand is primarily determined by the budget of the representative consumer and the price for transportation services. Since penetration rates are introduced such that the total lifetime costs of the cars per size category, period and MS are the same in the baseline and the scenarios, the overall prices (including taxes) for transportation services do not change with the introduction of hydrogen cars. But the budget of the representative consumer is affected. Due to the introduction of the hydrogen technology, the average lifetime costs of cars (producer costs, O&M costs, delivery costs, and fuel costs net of taxes) decrease over time. This releases additional resources which lead to an increase in the representative consumer's budget. These additional resources can be assigned to other uses.

Note that transport demand already increases from 2010 on, although hydrogen cars are not introduced before 2020, i.e. cost savings due to the introduction of hydrogen technologies do not occur before 2020. The reason is that the representative consumer maximises his lifetime utility by taking into account the prices in future periods. Thus he can smooth his consumption pattern over time. In the considered scenario this means that the representative consumer anticipates that his budget will be higher in later periods (compared to the baseline). Therefore he already can spend more money for transportation services (than in the baseline) in earlier periods.

The impact of the assumed scenario on real consumption is very similar to transport demand. Real consumption will increase if the budget of the representative consumer increases and the overall price level remains unchanged. The introduction of the penetration rates does no affect the overall price level. Thus, as already explained above, the integration of the hydrogen technology raises the budget of the representative consumer. It is therefore not surprising that the development of real consumption with respect to the baseline (see Figure 10) is similar to the development of transport demand.

Figure 10: Real consumption



Obviously, the shape and the levels of the curves for real consumption are very similar to those for transport demand in all MS. This is intuitive since the representative consumer spends a certain share of his income on transportation.

The differences across the MS are mainly caused by two factors. These are the hydrogen production costs in each country and the penetration rates in the different car classes. As described above, when introducing hydrogen, the difference between the lifetime costs of hydrogen and conventional cars net of taxes affect real consumption. This difference varies between the MS since they differ in their hydrogen production costs. The different penetration rates in the three car size categories lead to deviations of the lifetime cost differences between hydrogen and conventional cars in the three car classes. This also influences the increase in real consumption. Moreover, the cost saving potential in periods after 2030 is highest for large cars since on average these cars drive the most. Therefore they need more fuel than small and medium cars. As a consequence, fuel cost savings are higher for large cars. Additionally, the differences in penetration rates from 2030 on are the most decisive since the cost differences between the car types are most in favour of hydrogen cars.

The Netherlands experience the largest increase in real consumption of approximately 0.5 percent in 2050 (compared to the respective baseline value) with the introduction of hydrogen technologies. This is mainly due to low hydrogen production costs. In France and Italy real consumption also increases to a relatively large extent. This reflects the large cost saving potential with the introduction of hydrogen cars in both countries. It is interesting to see that Norway also experiences a relatively large increase in real consumption although hydrogen production costs are relatively high. One of the reasons is the high hydrogen penetration rate for large cars which is the largest across all MS from 2040 on. Hydrogen production costs in Greece are almost as low as in the Netherlands (Netherlands is the lowest in 2020, 2030 and 2040, Greece is the lowest in 2050). Anyhow, real consumption in Greece rises only by approximately 0.35 percent in 2050 compared to the baseline. This reflects the relatively low lifetime costs of conventional cars which implies a much lower cost savings potential compared to other countries. Not surprisingly, real consumption in Germany increases the least of all MS due to the relatively high hydrogen production costs.

Table 3 reports the social welfare of introducing hydrogen in the transport sector for each MS. Social welfare is thereby defined as a weighted average of real consumption.

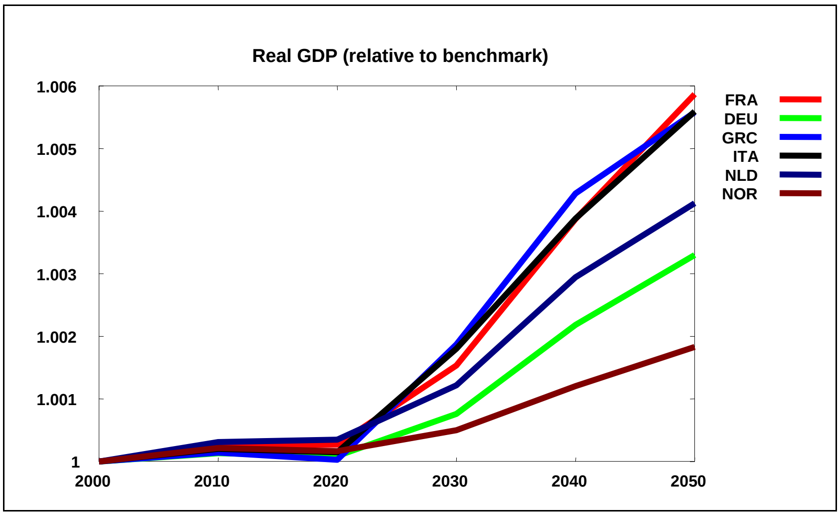
Again the reported values are rather low. All MS experience small welfare gains with the introduction of hydrogen cars. This is the consequence of the possibility to have a more efficient transport system (cars with lower lifetime costs net of taxes). Of course, the values reflect the findings already discussed before. Real consumption increases the most in the Netherlands (see Figure 10) and thus the increase in social welfare is the largest among all MS. In contrast, social welfare rises the least in Germany where real consumption growth is the lowest. The other MS range in between these two extremes depending on the increase in real consumption over the considered period.

Table 3: Social welfare

Country	**Increase in %**
France	0.379
Germany	0.211
Greece	0.303
Italy	0.372
Netherlands	0.450
Norway	0.345

The development of real GDP as shown in Figure 11 slightly differs from the development of transport demand or real consumption. In the periods before 2020 GDP remains almost unchanged to the baseline since there are only few hydrogen cars in the market. Even if the number of hydrogen cars in 2020 is higher than in 2010, the effect on GDP is still quite small. The reason is that on average (weighted over car classes) total lifetime costs of hydrogen cars in 2020 are very close to the costs of conventional cars net of taxes. From 2030 on, total lifetime costs of hydrogen cars are remarkably below the ones of conventional cars (net of taxes). This cost difference increases until 2050. At the same time penetration rates rise in all MS. The combination of these two developments leads to an increase in real GDP up to 2050 with the differences across the MS depending on the magnitudes of cost savings and hydrogen penetration within each country.

Figure 11: Real GDP

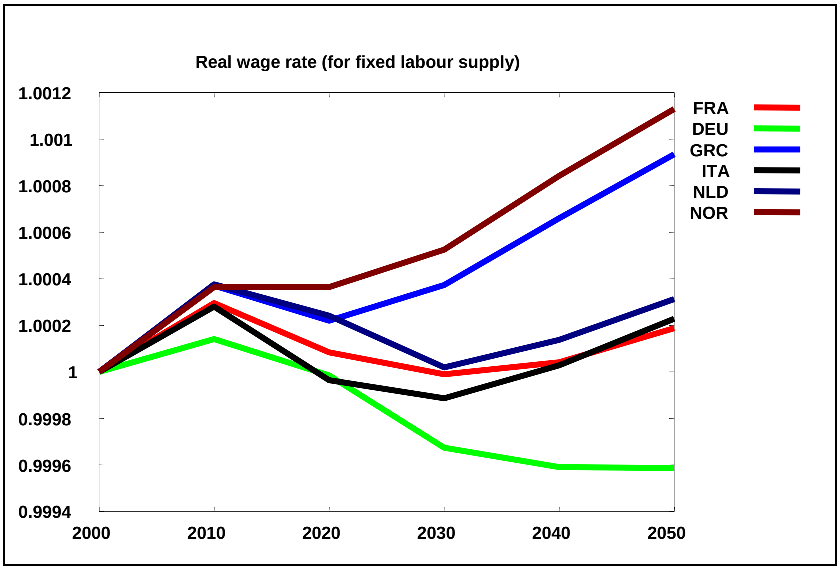


But again, the effects of the introduction of hydrogen on GDP are fairly small. GDP in France, Greece, and Italy, is expected to exceed the year-2050 baseline value by almost 0.6 percent, whereas the Netherlands, Germany, and Norway experience smaller increases of 0.4, 0.3 and 0.2 percent, respectively.

Finally, Figure 12 shows the development of real wages in the six MS. These wage changes are almost negligible; borrowing statistical terms, one can certainly state that the changes do not differ significantly from zero. Therefore, wage changes hardly account to any of the welfare changes reported in Table 3. The simulated welfare gains are rather due to the cost reductions achieved with the introduction of the hydrogen technology.

Almost all MS experience small wage increases over the considered period compared to the baseline. The one exception is Germany where wages slightly decrease. It is very difficult to explain these differences in a general equilibrium setup. They result from the combination of sectoral production levels and sectoral factor intensities which are all endogenous to the model and in turn depend on prices. A decreasing wage in Germany is related to a falling “relative” demand for labour in the whole production system and thus cannot be traced back to a single reason.

Figure 12: Real wage rate



To conclude, transport demand, real consumption, GDP, and welfare slightly increase in all MS with the introduction of hydrogen in the transport sector. These findings are mainly driven by the development of fossil fuel prices and the costs of hydrogen as well as conventional cars. The development of the changes is very similar across the MS. There are however differences in the levels of divergence between baseline and scenario across the MS. These differences can be explained inter alia by diverse hydrogen production costs and penetration rates in the MS.

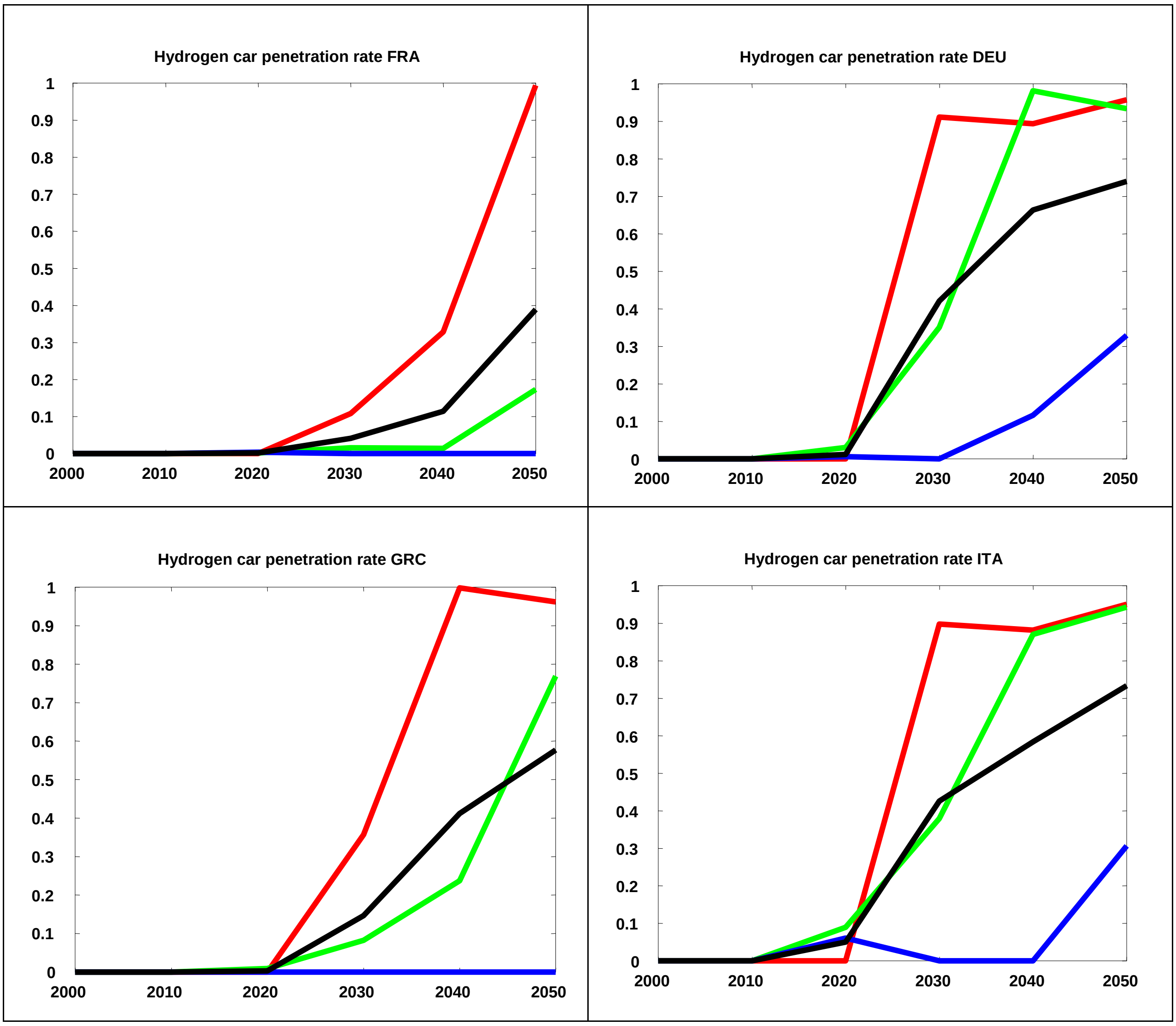
6.2 Low hydrogen penetration (H2L)

Now we turn to a scenario where we assume low hydrogen penetration rates but again a steep learning curve (H2L). The only difference to the analysis of the high penetration rate scenario in section 6.1 is the implementation of lower penetration rates.

6.2.1 Penetration rates

As before, penetration rates are adopted from the MARKAL model. Figure 13 shows the development of the penetration rates for new cars in the H2L scenario. Again penetration rates are defined as the share of new hydrogen cars in overall new cars per size category, per period, and per MS.

Figure 13: Hydrogen penetration rates for new cars in different countries

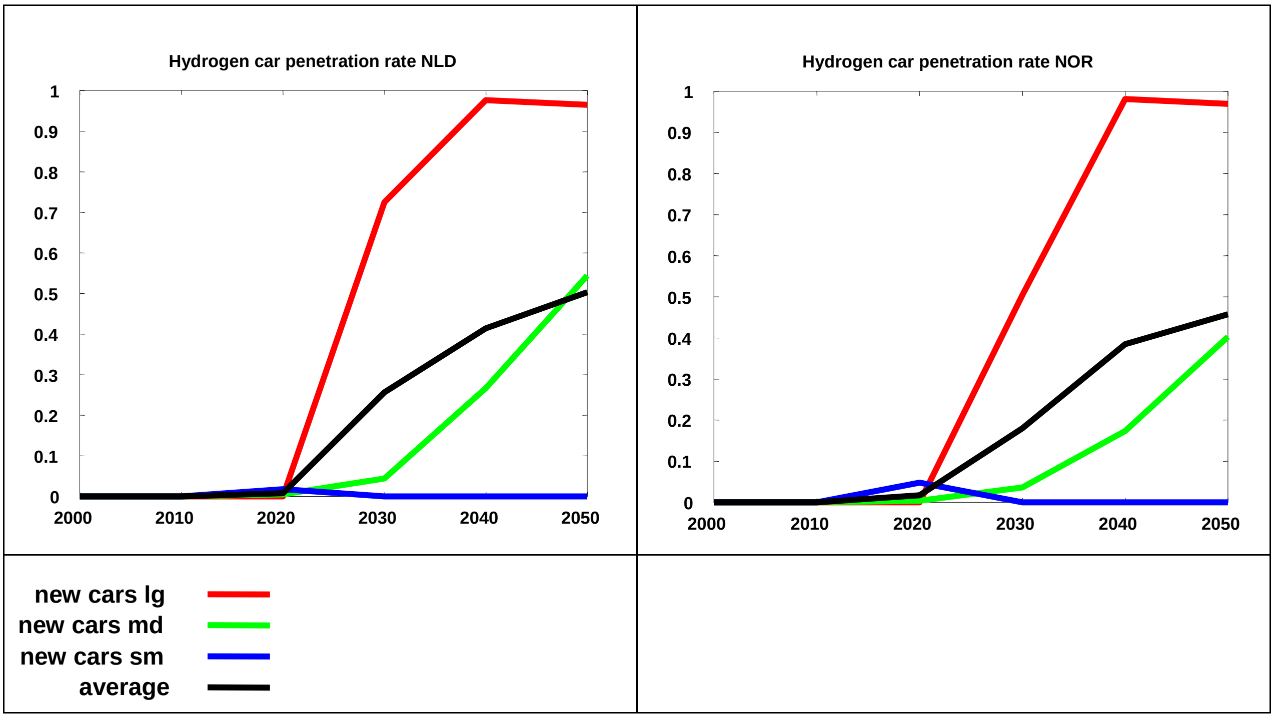


Hydrogen car penetration rate FRA

Hydrogen car penetration rate DEU

Hydrogen car penetration rate GRC

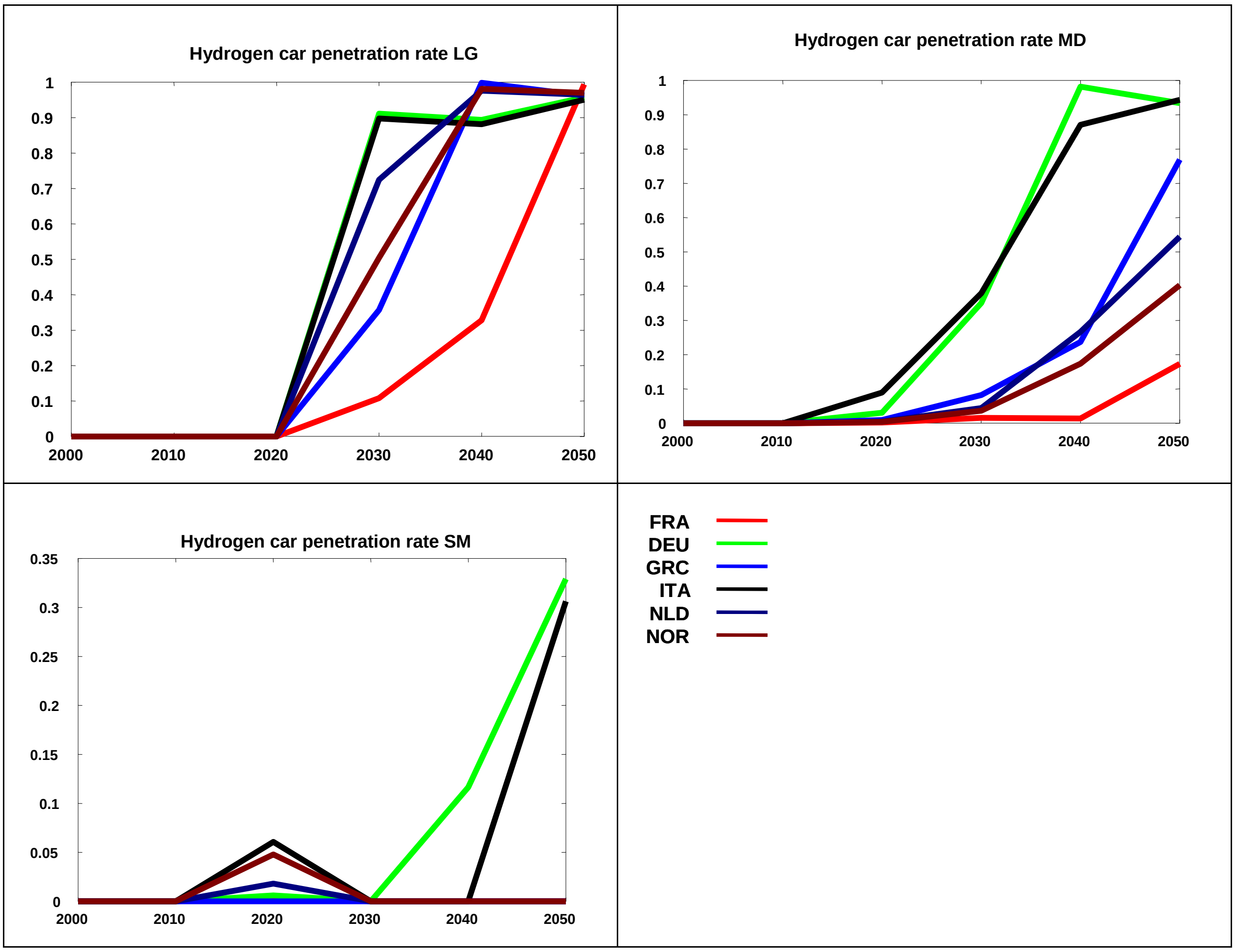
Hydrogen car penetration rate ITA



As the name of the considered scenario already indicates, penetration rates are now lower than in the H2H scenario. Stated differently, compared to the H2H scenario the same levels of hydrogen penetration are reached in later periods. Interestingly, there are now four countries (France, Greece, the Netherlands, and Norway) without any small hydrogen cars in 2050. The country with the biggest differences to the H2H scenario is France where penetration rates in the H2L scenario are much smaller. Similar to the H2H scenario, the penetration rates for small cars are the lowest in all countries from 2030 on while the penetration rates for large cars are – with the exception of Germany – the highest.

Figure 14 shows the development of the hydrogen penetration rates for the different countries per size category.

Figure 14: Hydrogen penetration rates for new cars in different size classes



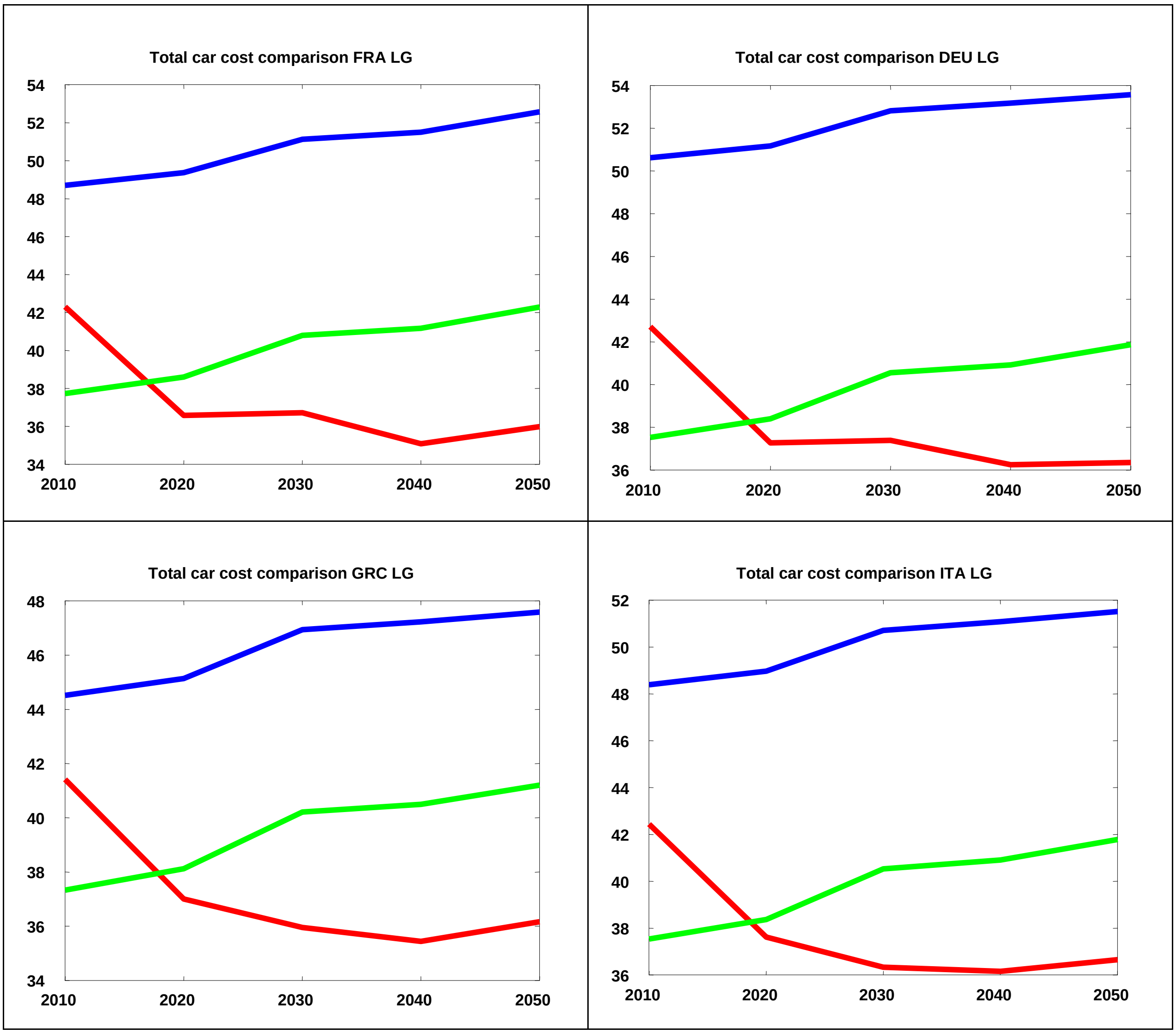
As already indicated, France is the country with the lowest penetration rates by far in all size categories. Germany and Italy reach the highest penetration for small cars in 2050 with about one third of new cars being hydrogen cars. It is furthermore striking that the penetration rates of medium-sized cars in 2050 are considerably lower in three MS (France, Greece, and Norway) while they are similar in Germany and Italy compared to the H2H scenario. Figures 31 and 32 in Annex 10.3 provide similar information as Figure 13 and 14 but report on the hydrogen share of cars in the stock (see the explanations in Section 6.1.1).

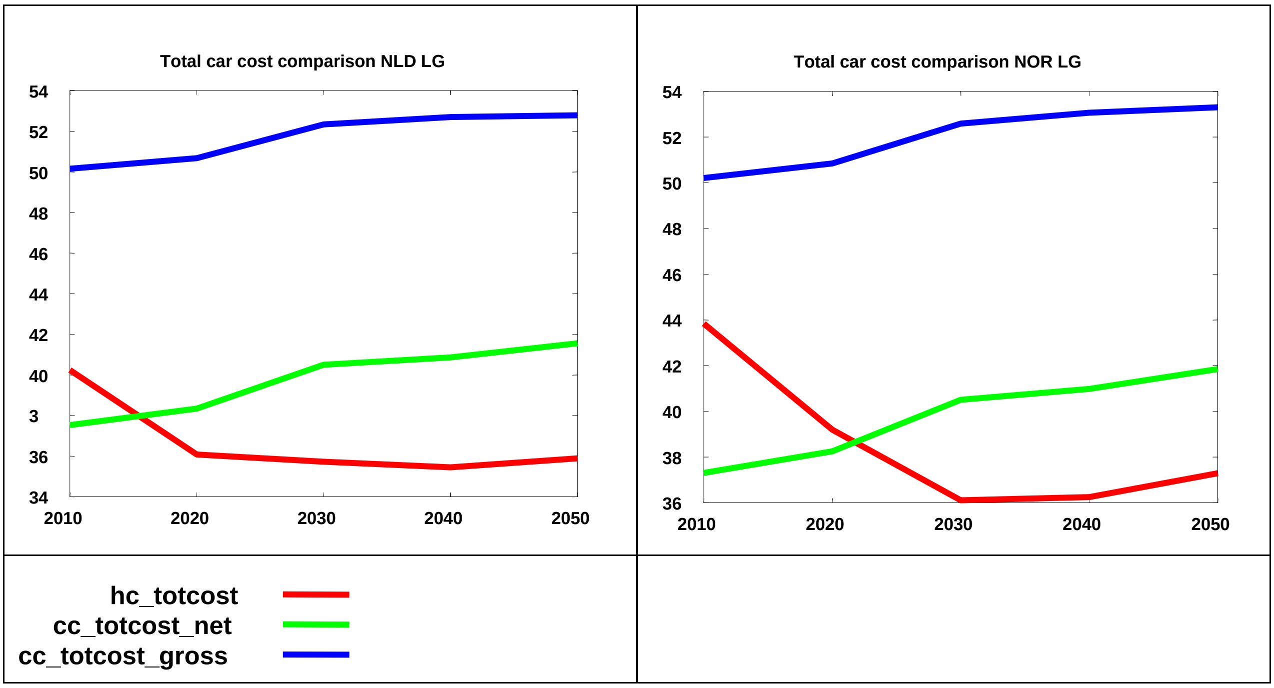
6.2.2 Cost comparison

The costs of the different conventional car categories are equal in both the H2H and the H2L scenario. However, hydrogen car prices in the H2L scenario deviate from the H2H scenario. Under the assumption of unchanged learning curves, lower penetration rates lead to a slower cost reduction of hydrogen cars. Take for example the price of a medium-sized hydrogen car in France in 2040. In the H2H scenario the producer price amounts to 18,614 Euro while it is still 20,012 Euro in the H2L scenario.

Again, the costs given from the MARKAL output are prepared as outlined in Section 5. The calculation of missing O&M costs in the year 2010 as well as of missing hydrogen car costs is done analogously to the H2H scenario (for a more detailed description see Section 6.1.2). Figure 15 shows the development of the total lifetime costs of large conventional cars net and gross of taxes as well as the total lifetime costs of hydrogen cars for each MS in the H2L scenario.

Figure 15: Cost comparison of large cars





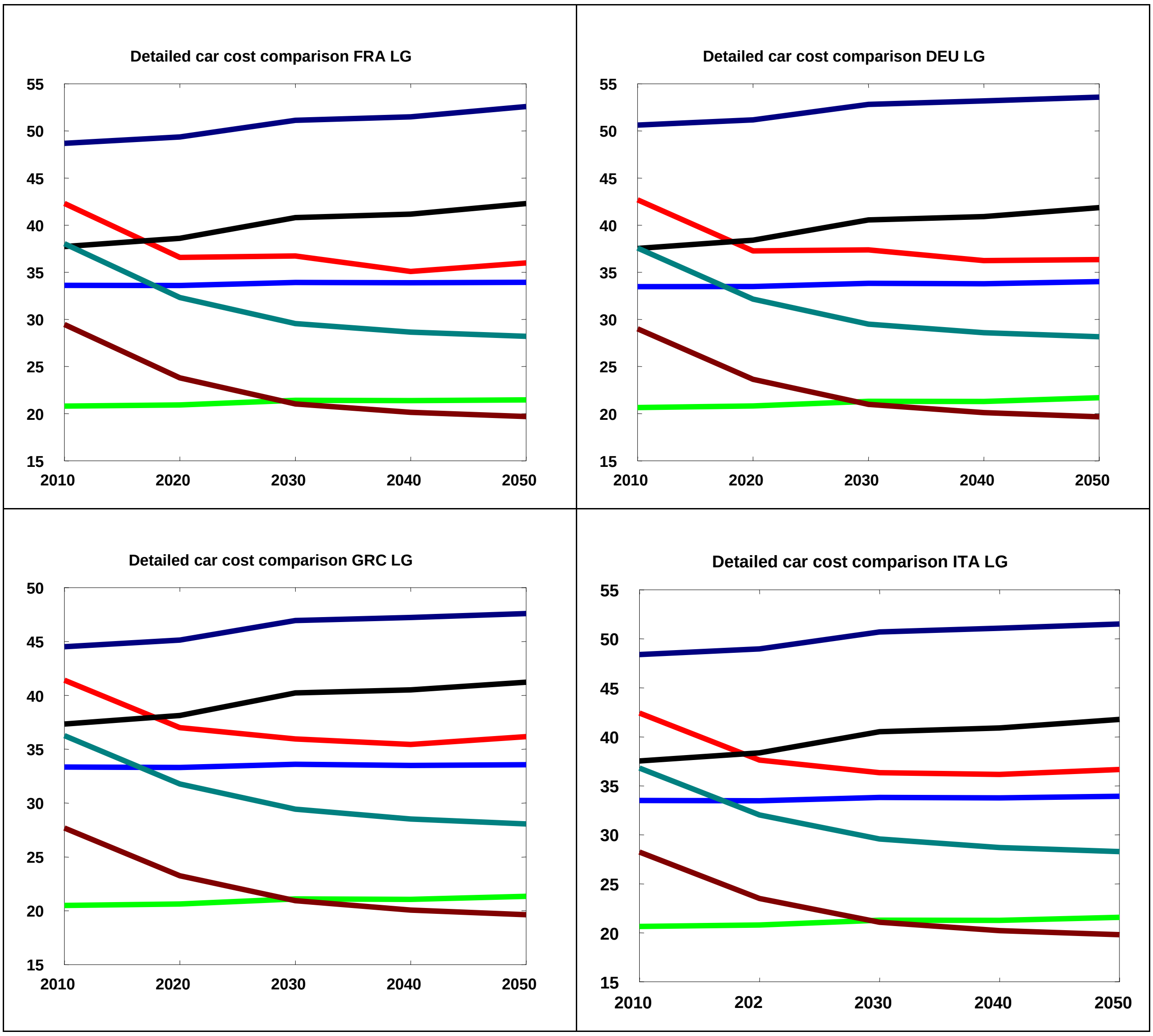
Even with low penetration rates, large hydrogen cars are cost competitive from 2020 on (hc_totcost is below the respective cc_totcost_net) in all MS. Thus technological learning from producing relatively few hydrogen cars in advance (before hydrogen becomes competitive) results in a cost decrease which is large enough to make the hydrogen technology become competitive quite soon. When the consumer chooses between a large hydrogen and a large conventional car, he compares the total lifetime costs of both car types including taxes. The relevant cost curve for conventional cars is therefore cc_totcost_gross. As before, in order to make both car types stay in the market, lifetime costs of conventional and hydrogen cars have to be equal. Consequently, hydrogen cars can be taxed up to the point where their lifetime costs amount to cc_totcost_gross.

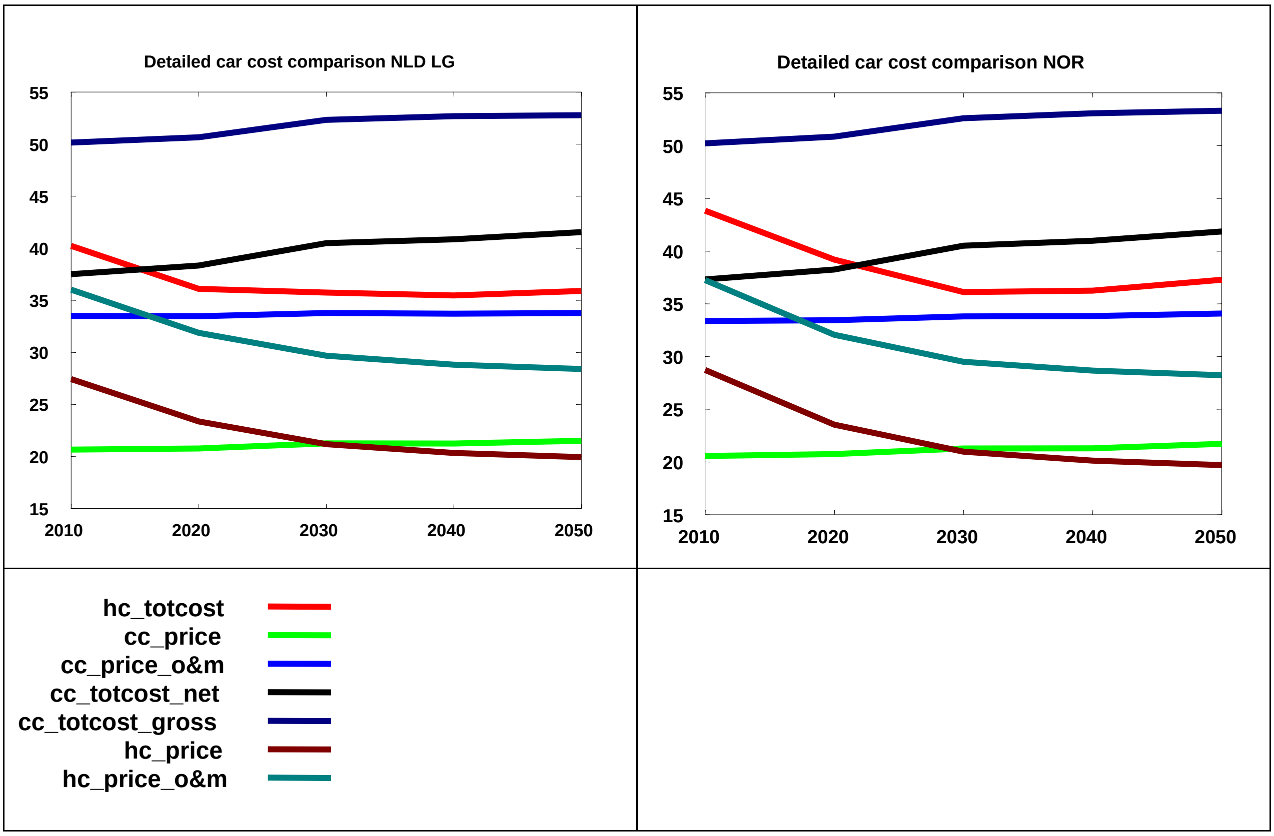
A more detailed comparison of the lifetime costs of large hydrogen and conventional cars is given in Figure 16.

The graphs have to be interpreted in the following way: hc_price shows the producer price for hydrogen cars. Adding the lifetime costs for O&M yields hc_price_o&m. When including lifetime fuel costs, one receives the total lifetime costs of hydrogen cars (hc_totcost). The breakdown of costs is similar for conventional cars. The producer price (cc_price) plus lifetime O&M outlays yield cc_price_o&m. When adding the fuel costs net of taxes, one receives the lifetime costs net of taxes (cc_totcost_net), and when adding the fuel costs including taxes, one receives the lifetime costs gross of taxes (cc_totcost_gross).

Comparable to the H2H scenario, it is the decline in hydrogen car producer costs (hc_price) which decreases hydrogen car lifetime costs (hc_totcost) so that these cars become competitive from 2020 on. This finding is the same in all MS. But the graphs also reveal some important differences between the MS. First, fuel costs for hydrogen cars differ due to the various hydrogen production technologies. Second, while total lifetime costs of conventional cars net of taxes are very similar across the MS, the tax differentials lead to major deviations in lifetime costs gross of taxes.

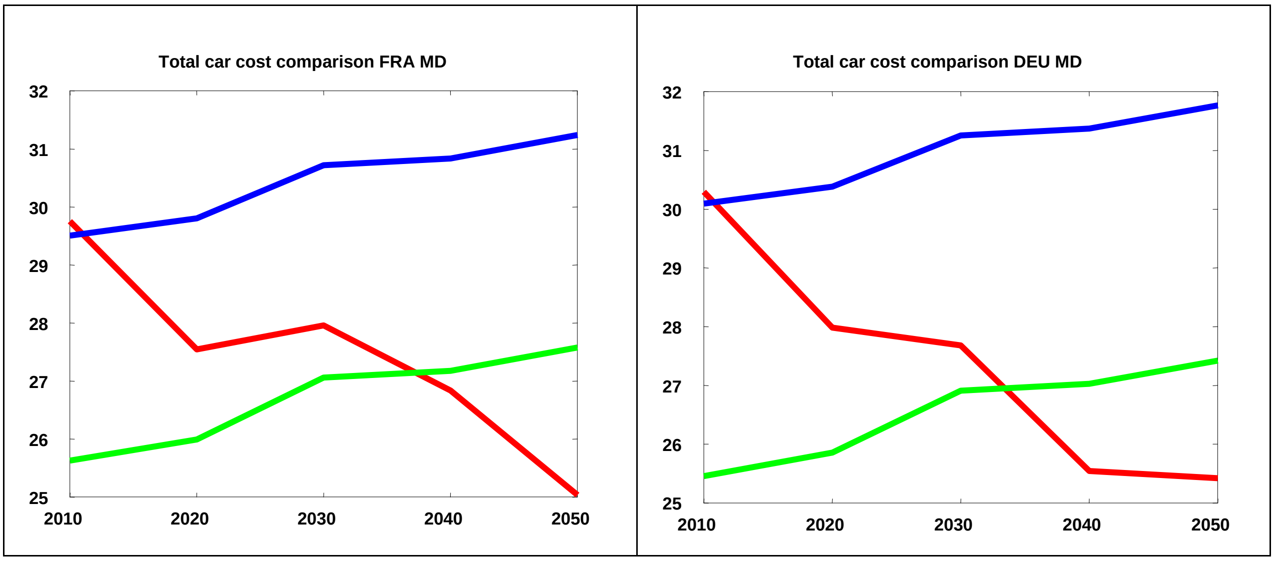
Figure 16: Detailed cost comparison of large cars

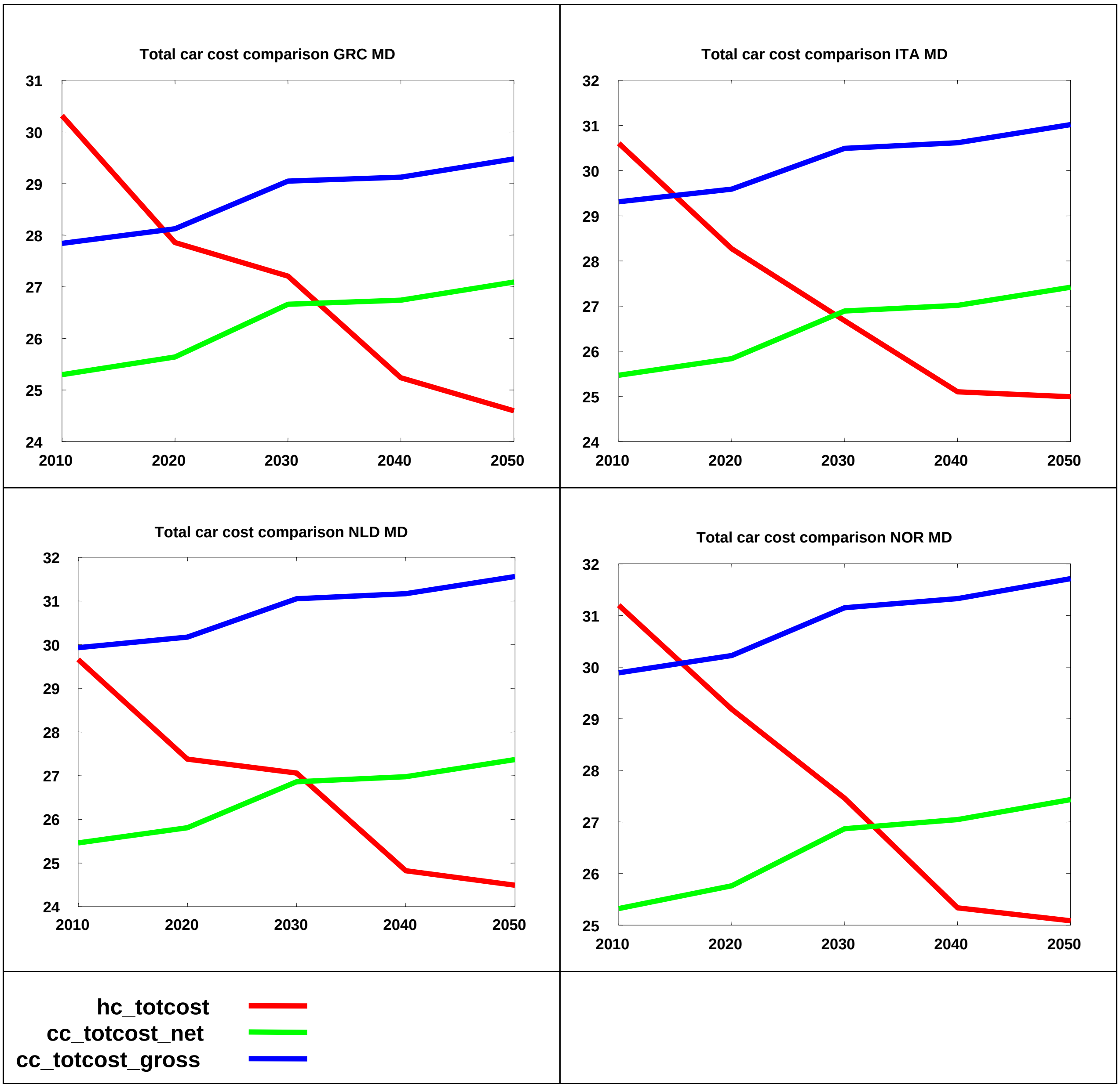




Now we turn to the cost comparison of medium-sized cars as provided in Figure 17.

Figure 17: Cost comparison of medium cars





Total car cost comparison GRC MD

Total car cost comparison ITA MD

Total car cost comparison NLD MD

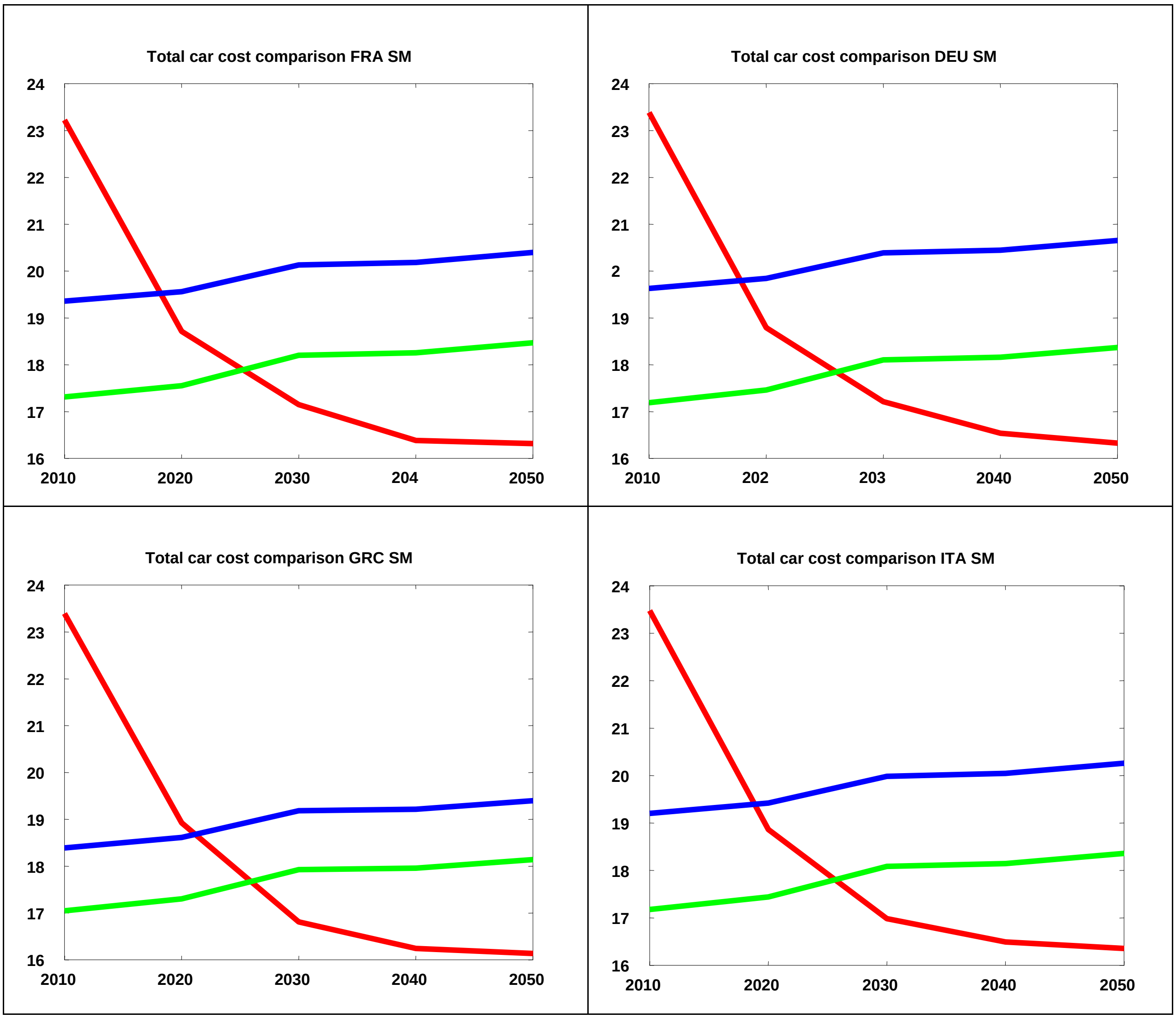
Total car cost comparison NOR MD

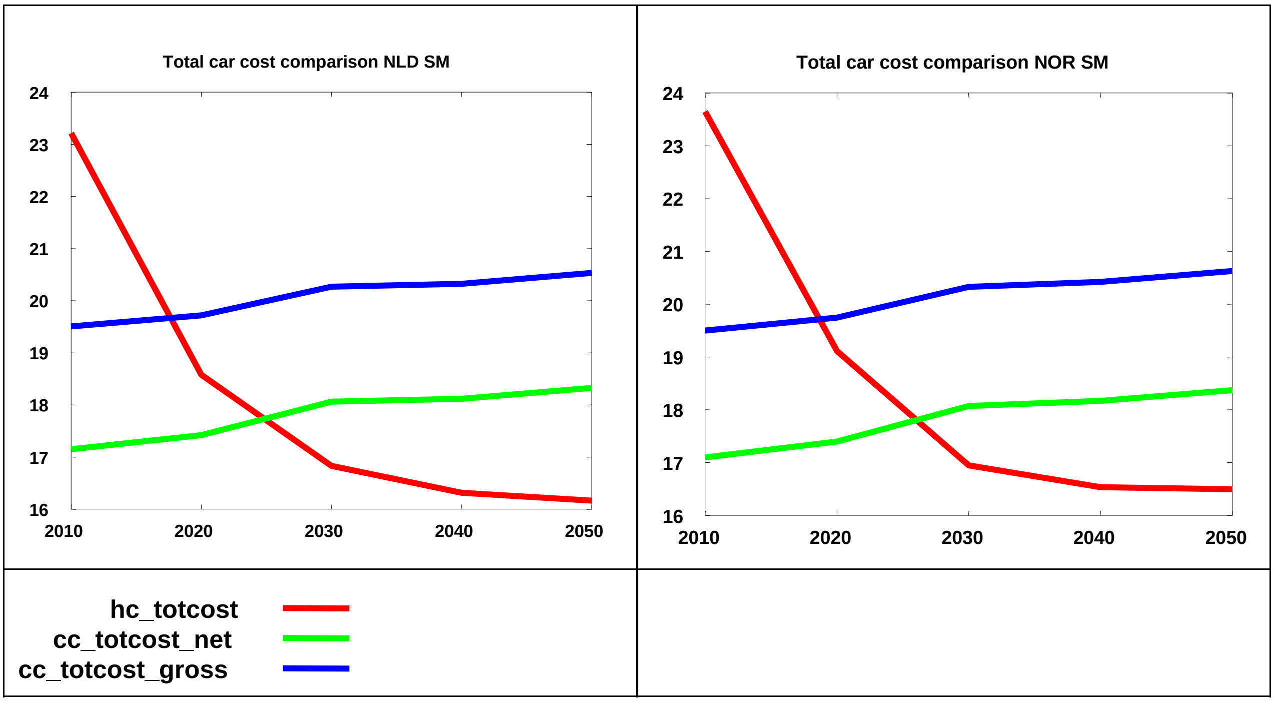
Figure 17 impressively shows the consequences of having lower penetration rates. While in the H2H scenario medium-sized hydrogen cars become cost competitive from 2030 on, they now become competitive not before 2040, i.e. one model period later. The reason is of course the slower decrease of producer costs for hydrogen cars due to the reduced penetration rates. The initial costs for medium hydrogen cars in 2010 are almost identical between the H2H and the H2L scenario since penetration rates in this period are zero in both cases. Bigger differences occur later in time when the effects of lower penetration rates in the H2L scenario and thus a smaller cost decrease of hydrogen cars prevail. The detailed cost comparison for medium cars is given in Figure 33 in Annex 10.4. The interpretation of the graphs is similar to the one for large cars.

Next we have a closer look at the cost development for small cars (see Figure 18).

As already anticipated, small hydrogen cars also become competitive later than in the H2H scenario. In the H2L scenario, the total lifetime costs of small hydrogen cars (hc_totcost) are below the respective costs of conventional cars net of taxes (cc_totcost_net) from 2030 on. From 2020 on, the total lifetime costs of conventional cars including taxes (cc_totcost_gross) exceed those of hydrogen cars, i.e. consumers would always prefer untaxed hydrogen cars to taxed conventional cars. It is thus again necessary to tax hydrogen cars in order to make both car types remain in the market.

Figure 18: Cost comparison of small cars



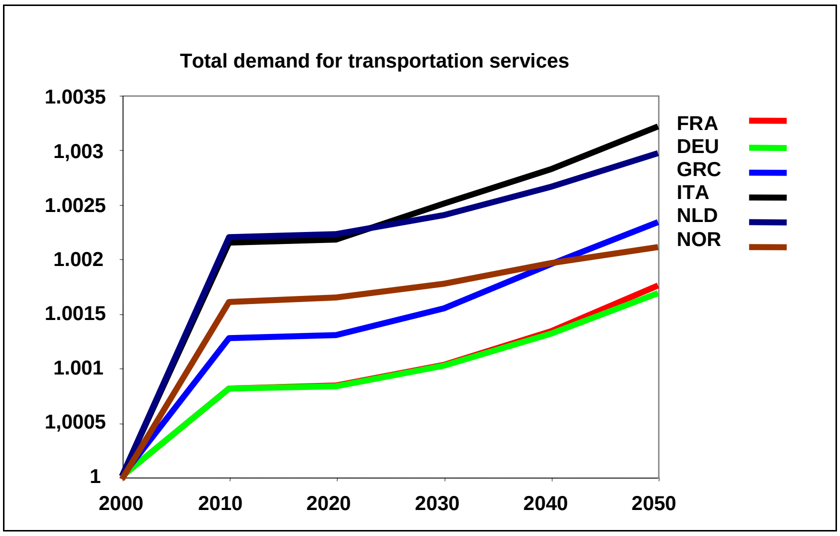


These explanations should suffice to highlight the differences between the H2H and the H2L scenario. We now turn to the impact of lower penetration rates on transport demand, real consumption, welfare, GDP, and the wage rate.

6.2.3 Transport demand, real consumption, welfare, GDP, and wage rate

This section deals with the macroeconomic implications of implementing lower hydrogen penetration rates. We first consider the effects on total demand for transport services as shown in Figure 19.

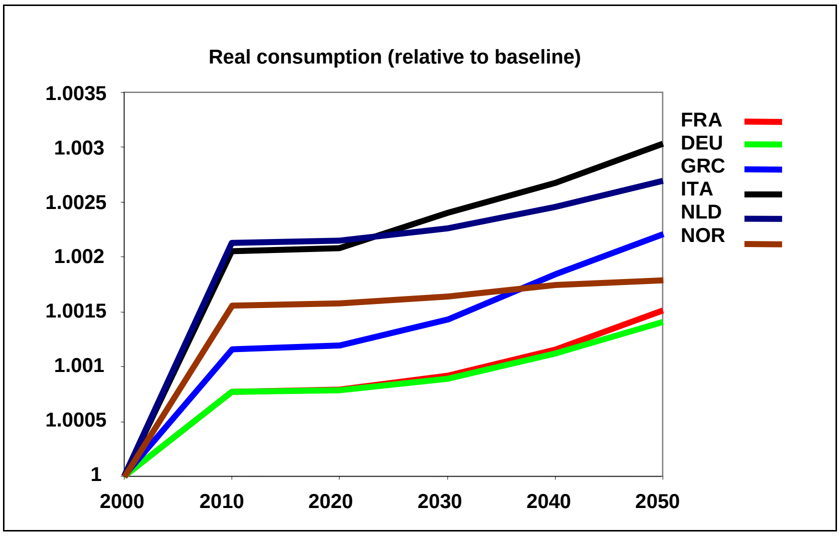
Figure 19: Transport demand



Comparable to the H2H scenario, transport demand increases in all countries with respect to the baseline. The mechanism behind this development is exactly the same as in the H2H scenario: Constant transport prices together with an increasing budget of the representative consumer lead to a rise in transport demand. But now these changes are remarkably smaller. The largest increases occur in Italy and the Netherlands where transport demand in 2050 exceeds the respective baseline values by approximately 0.3 percent. Again, Germany is the country with the smallest rise of only 0.15 percent in 2050 compared to the baseline. The development of transport demand in France deviates from the H2H scenario to a quite large extent. Transport demand now increases much less which is due to the massive change of the penetration rates in the H2L scenario. This finding in France is similar for real consumption, GDP and welfare (see below). Of course, the smaller increase in transport demand in all MS reflects the lower cost saving potential associated with a slower cost decrease for hydrogen cars. Again, the possibility to smooth consumption over time leads to increases in transport demand already in 2010.

Now we have a closer look at the development of real consumption as shown in Figure 20.

Figure 20: Real consumption



As already explained before, the deviation of real consumption from the baseline is similar to the one of transport demand. The cost savings potential due to the introduction of hydrogen cars is reflected by a higher budget of the representative consumer. This in turn increases real consumption compared to the baseline. It is not surprising that real consumption growth is lower than in the H2H scenario since the H2L scenario assumes a slower cost decrease for hydrogen cars. Again, real consumption increases the most in Italy and the Netherlands while Germany and France experience very small changes. The other countries range in the middle.

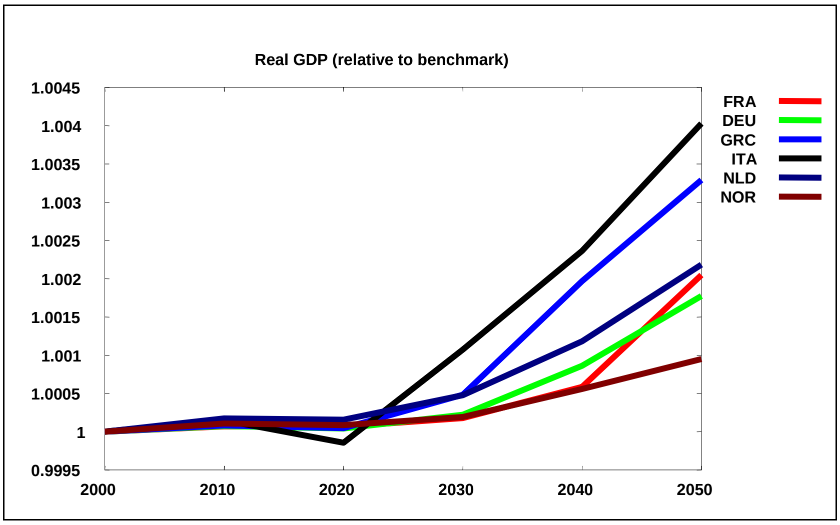
We now turn to the welfare effects of the H2L scenario as reported in Table 4. Again social welfare is calculated as a weighted average of real consumption. Obviously, all MS can expect welfare gains even with lower hydrogen penetration rates. These effects are however rather small which just reflects the smaller increases in real consumption. According to the growth in real consumption, Italy experiences the largest welfare gains of 0.251 percent while the gains are smallest for France and Germany with 0.109 percent and 0.105 percent, respectively.

Table 4: Social welfare

Country	**Increase in %**
France	0.109
Germany	0.105
Greece	0.163
Italy	0.251
Netherlands	0.239
Norway	0.168

Figure 21 shows the impact of lower hydrogen penetration rates on real GDP.

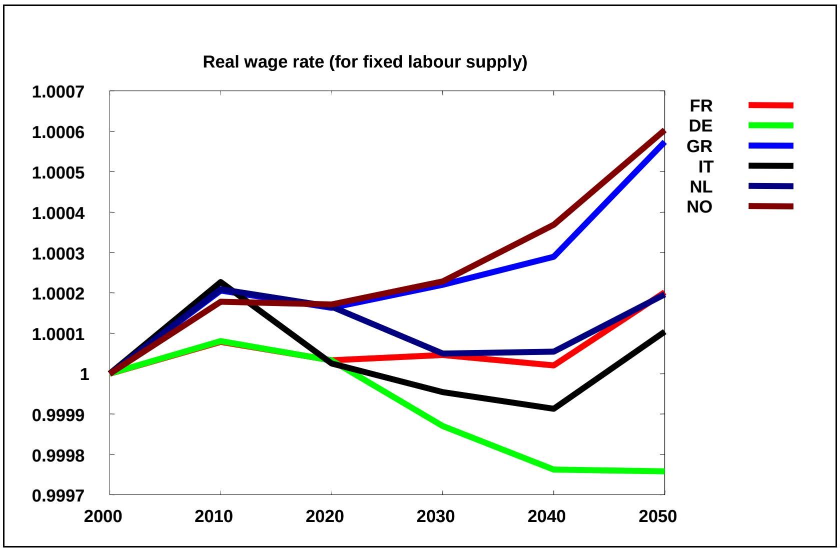
Figure 21: Real GDP



As expected, the development of GDP is again similar to the H2H scenario. The changes compared to the baseline are rather small. Until 2020, GDP develops almost the same as in the baseline in all six MS. From 2030 on, GDP increases in all MS. The rise is the largest in Italy where GDP in 2050 exceeds the baseline value by 0.4 percent. Norway experiences the least growth of only 0.1 percent in 2050. Again, the two essential factors causing the increase in GDP are the introduction of hydrogen cars from 2030 on and the cost decrease of hydrogen cars.

Finally, Figure 22 shows the effects of the low-penetration rate scenario on the real wage rates in the six MS.

Figure 22: Real wage rate



The influence of the hydrogen introduction on wage rates is almost negligible. The “largest” increase of 0.06 percent is observed in Norway, while the wage rate in Germany decreases by approximately 0.02 percent. The overall development is very similar to the H2H scenario but again any effects of implementing lower penetration rates are even smaller. Thus, the changes of the wage rates hardly impact welfare in the six MS.

To conclude, the effects of lower penetration rates on transport demand, real consumption, welfare, and GDP are slightly positive for all MS. The development over time is mainly influenced by future fossil fuel prices and the cost development of hydrogen and conventional cars. The magnitude of the macroeconomic impact differs across the MS due to the various hydrogen production costs and the path for penetration rates. As the dicussed results suggests, the effects in the H2L scenario are smaller than in the H2H scenario.

6.3 Sensitivity analysis: Lower cost reduction

This section aims to analyse the sensitivity of the previous results. It thus reports the most important simulation results if we assume a less steep learning curve, i.e. a smaller cost reduction for hydrogen production.

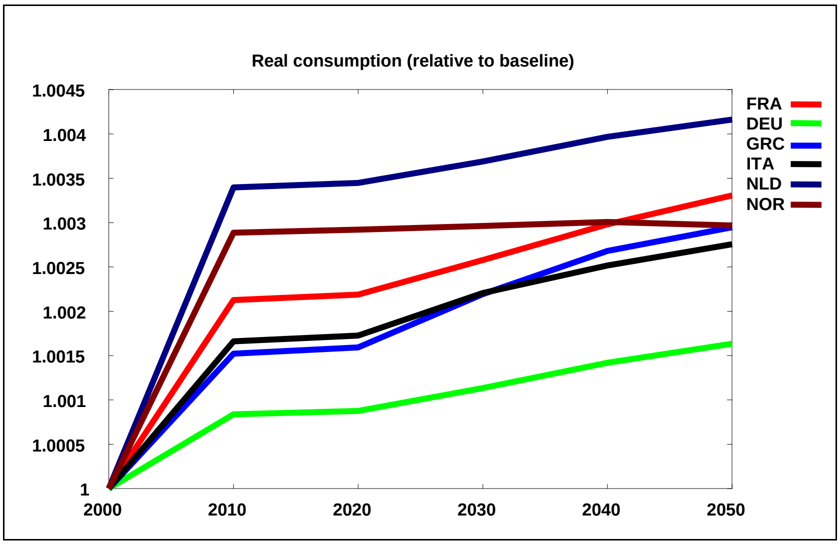
6.3.1 High hydrogen penetration (L2H)

First we assume again a high hydrogen penetration rate in all six MS as outlined in Section 6.1.1 but combine it with the smaller cost decrease of hydrogen production. As in the previous scenarios, the input data on the learning curves are adopted from the results of the MARKAL model. We now abstract from a detailed cost comparison since the development of lifetime costs for conventional and hydrogen cars in all size categories is almost the same as in the H2H scenario. The only difference appears of course for lifetime hydrogen costs which are now somewhat lower.

Since the deviations from the previous simulations are fairly small, we just report the development of the most important variables. As will become clear in the discussion below, the smaller cost decrease of hydrogen cars translates into smaller deviations of the simulation results from the baseline which is simply due to the lower cost saving potential.

Figure 23 shows the development of real consumption in the L2H scenario compared to the baseline.

Figure 23: Real consumption



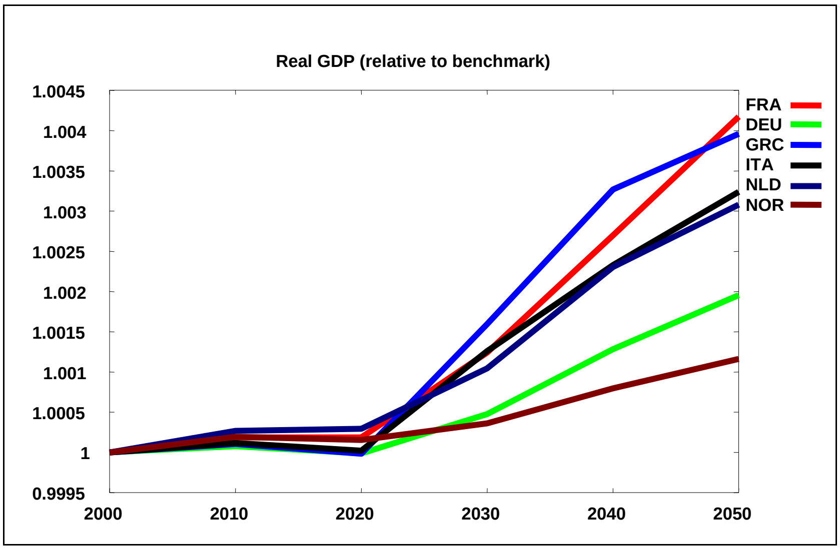
Obviously, the differences of the development of real consumption compared to the steep learning curve approach as shown in Figure 10 are fairly small. The ranking of the increases in the different MS is unchanged. Also the increase in the Netherlands remains almost the same. The other countries experience a somewhat lower rise in real consumption. For example, it is 0.015 percent in Germany in 2050 compared to 0.02 percent with the larger cost decrease. Of course, these small changes stem from the smaller decrease in hydrogen production costs. This leads to a smaller difference in the lifetime costs of hydrogen and conventional cars and thus to smaller increases in the consumer's budget which consequently dampens real consumption increases. The same holds true for the development of transport demand in the MS.

Table 5: Social welfare

Country	**Increase in %**
France	0.271
Germany	0.123
Greece	0.226
Italy	0.223
Netherlands	0.378
Norway	0.295

The more moderate increase in real consumption is also reflected in the effects on social welfare (see Table 5). The Netherlands again experience the highest welfare gain of 0.38 percent due to the introduction of hydrogen cars. But not surprisingly, this effect is lower than in the scenario with a high cost decrease where the welfare gain is 0.45 percent. Germany has the lowest increase in welfare among all MS. Also all other MS experience smaller welfare gains which simply reflects the smaller increase in real consumption which is caused by the higher hydrogen production costs during the considered period.

Figure 24: Real GDP



Finally, consider the effects on GDP as reported in Figure 24. The findings here are the same as before. The increase in GDP from the introduction of hydrogen cars in all MS is less pronounced than in the previous scenarios. The rationale behind this is again the smaller cost decrease in hydrogen production.

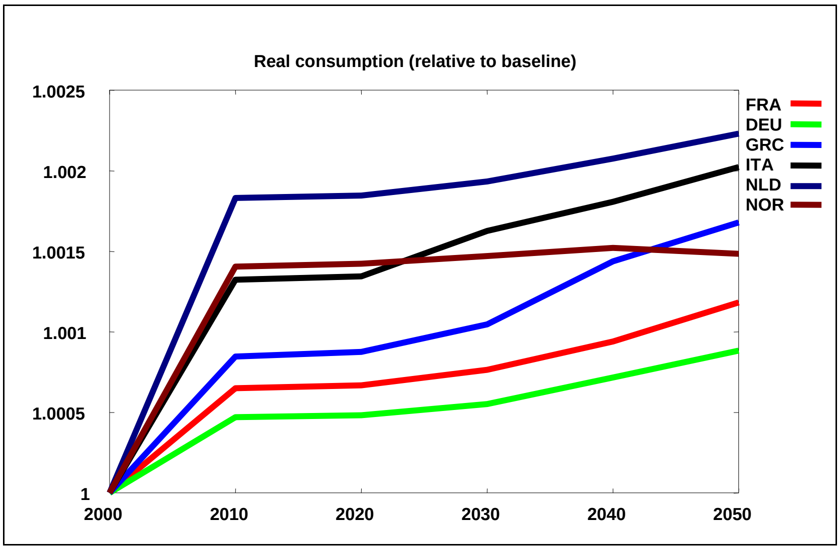
The general finding of this sensitivity scenario is that the positive effects of the introduction of hydrogen cars on consumption, welfare, and GDP are smaller than with a higher rate of cost decrease for hydrogen production. This lowers the cost savings potential which again reduces the budget increases of the consumer and thus any further spending on consumption. The deviations from the H2H scenario are very similar across the six MS.

6.3.2 Low hydrogen penetration (L2L)

The final policy scenario assumes low hydrogen penetration rates and a low rate of cost decrease for hydrogen production. The combination of lower penetration rates and a smaller cost decrease in hydrogen production translates into a smaller cost savings potential which is even less than in the scenario before. This leads to increases in transport demand and real consumption that are the lowest among all considered scenarios.

Figure 25 shows the development of real consumption compared to the baseline. Increases in real consumption are now fairly small in all countries. The Netherlands can expect an increase by approximately 0.2 percent in 2050 in comparison to the baseline. In Germany the rise in real consumption amounts to only 0.1 percent. Thus low penetration rates and a low cost decrease hardly makes any difference to the baseline in any of the six MS.

Figure 25: Real consumption



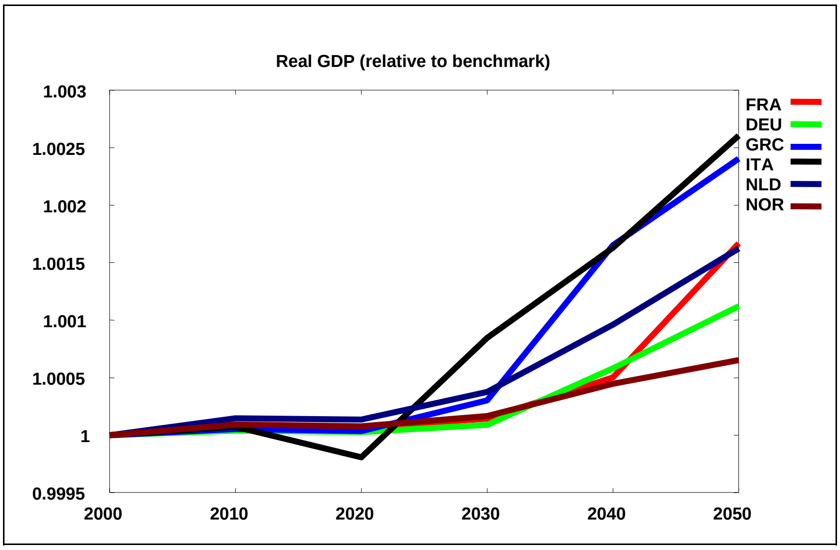
As Table 6 indicates, social welfare is also almost unaffected. While still all MS experience welfare gains from the introduction of hydrogen cars, the size of these effects is rather small. In Germany and France, welfare increases by 0.07 percent and 0.09 percent, respectively. As expected, Italy and the Netherlands again gain the most but welfare increases in both countries by only 0.17 percent and 0.20 percent, respectively.

Table 6: Social welfare

Country	Increase in %
France	0.089
Germany	0.066
Greece	0.124
Italy	0.167
Netherlands	0.202
Norway	0.147

As shown in Figure 26, the effects of introducing hydrogen cars on real GDP are also rather small. Norway is expected to experience the lowest increase of 0.05 percent in 2050 compared to the baseline. GDP in Italy and Greece rises by approximately 0.25 percent.

Figure 26: Real GDP



To conclude, assuming low penetration rates of hydrogen cars in all MS and, at the same time, a rather small cost decrease for hydrogen cars leads to the smallest macroeconomic impact on consumption, welfare, and real GDP among all considered scenarios. This finding simply reflects the fact that the cost savings potential in this scenario is fairly low. As a consequence, consumers experience only very small increases of their budget so that economic indicators are affected to a rather small extent.

7 Lessons learnt

The results in the considered scenarios indicate several determinants of the macroeconomic impact. The most important driving factors for the extent to which the economy is affected by the introduction of hydrogen cars are the development of penetration rates and the learning curves.

First, it is important how fast the costs for hydrogen production decrease over time. The difference between lifetime costs for conventional and hydrogen cars shows the cost saving potential from implementing a new technology. Cost savings are highest the largest the cost decline for hydrogen cars will be in the future. Second, the penetration rates indicate how much of this cost savings potential will become active in the MS. Altogether these factors heavily determine the consequences on the consumer's budget which again affects transport demand, real consumption and thus GDP. Welfare is then determined by the deviation of real consumption to the baseline.

Of course, one must not forget that the extent to which the introduction of hydrogen cars affects the macroeconomic development also depends on the lifetime costs for conventional cars. This not only concerns car production costs but more importantly the development of future fuel prices. The difference between lifetime costs of conventional and hydrogen cars determines the level of the cost savings potential from the introduction of a new technology which finally impacts the macroeconomic variables.

The changes of transport demand, real consumption, welfare, GDP and the wage rate in the scenarios compared to the baseline are rather small and must be cautiously interpreted. General equilibrium effects tend to work against possibly large partial or first-round effects in increased hydrogen use. The differences in economic outcomes between MS can be traced back to the net of tax cost differences between hydrogen and conventional car lifetime costs. These cost differences in turn are partly explained by the hydrogen production technologies chosen in the MS.

Finally, as already discussed, the results in PACE-T are also affected by the assumption to treat hydrogen and conventional cars as perfect substitutes. This causes households to simply choose the cheapest technology. Of course, this assumption is critical given that car demand depends on further factors like e.g. noises or driving properties of the car. Relaxing this assumption might probably impact the simulation results. However, it is simply impossible to calibrate a more flexible demand function since there are no empirical data on hydrogen car demand available.

8 Conclusions

The introduction of hydrogen cars impacts the future macroeconomic development. The simulation results of combining high or low penetration rates with either a steep or lower cost decrease of hydrogen cars can be summarized as follows:

- Transport demand increases in all MS. The change over time is similar for all MS with differences in the observed levels.
- Similar to transport demand, real consumption is expected to rise in the six MS. The changes over time are again similar across the MS, but there are differences in the levels of these deviations depending on hydrogen production costs and penetration rates.
- Welfare effects are slightly positive for all MS, but the effects differ in their extent due to different increases in real consumption across the MS.
- GDP is also expected to increase in all MS. The change over time is similar for all MS, but there are again differences in the levels.
- The extent of welfare, transport demand, real consumption, and GDP changes is rather small in all MS and must be cautiously interpreted.
- Differences between the baseline and the scenarios depend on the future development of fossil fuel prices as well as on the development of hydrogen and conventional car production costs.
- Differences across MS can mainly be explained by different hydrogen production costs and penetration rates.

While the effects of introducing hydrogen cars in all scenarios are oriented into the same directions, the simulation results suggest that, given the same cost decrease for hydrogen cars, the effects in the low penetration rate scenario are smaller than in the high penetration rate scenario. In addition, assuming the same development of hydrogen penetration rates, a lower cost decrease of hydrogen cars leads to more moderate macroeconomic effects than a relatively steep cost decrease. Thus, combining high penetration rates with a steep learning curve has the largest impact on the economic situation in the six MS. Turned the other way round, low penetration rates and at the same time a smaller cost decrease affect the economic outcome in the six MS the least.

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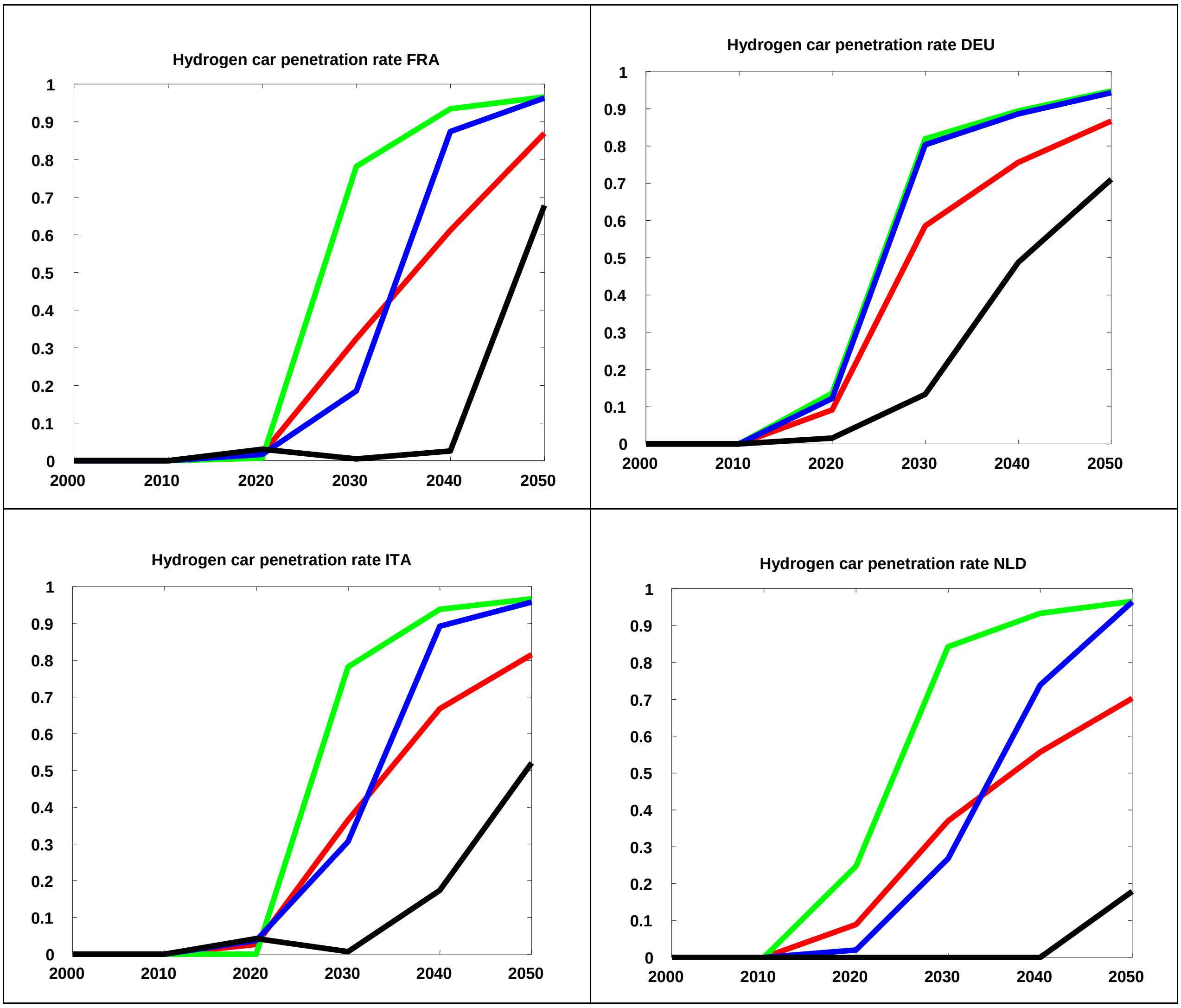
10 Annexes

10.1 High hydrogen penetration (H2H) – Share of hydrogen cars in the stock

Figure 27: Hydrogen penetration rates in different countries (stock)



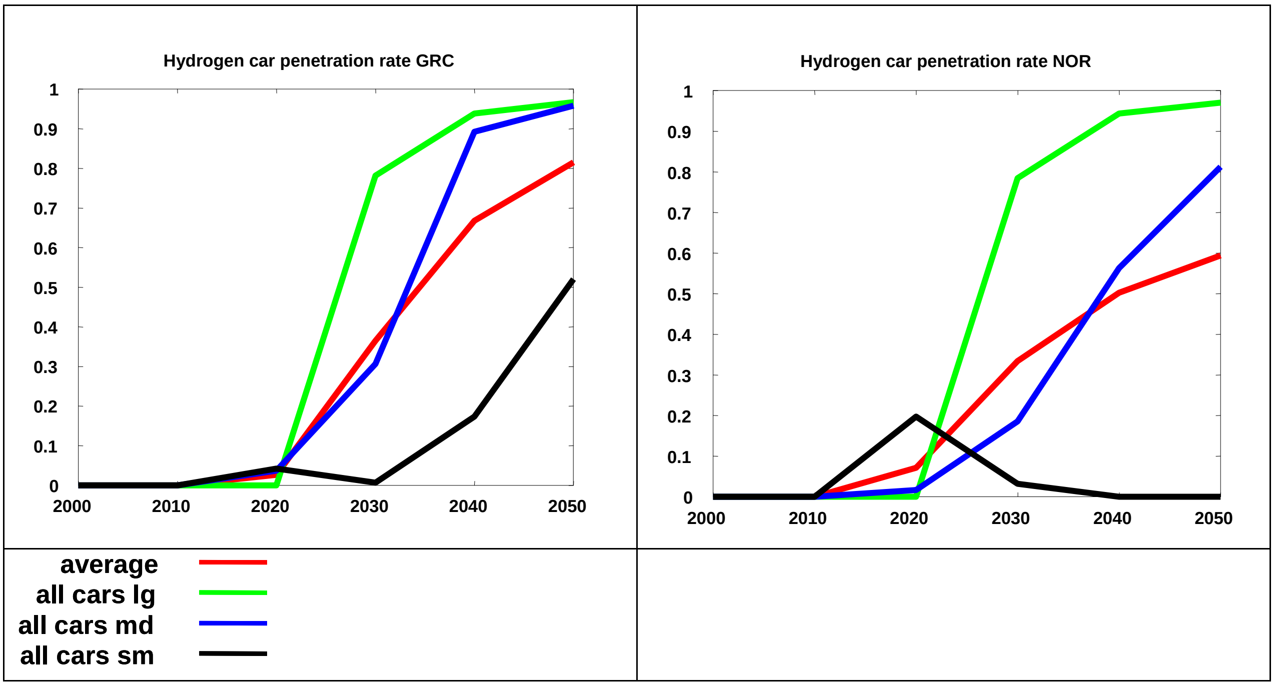
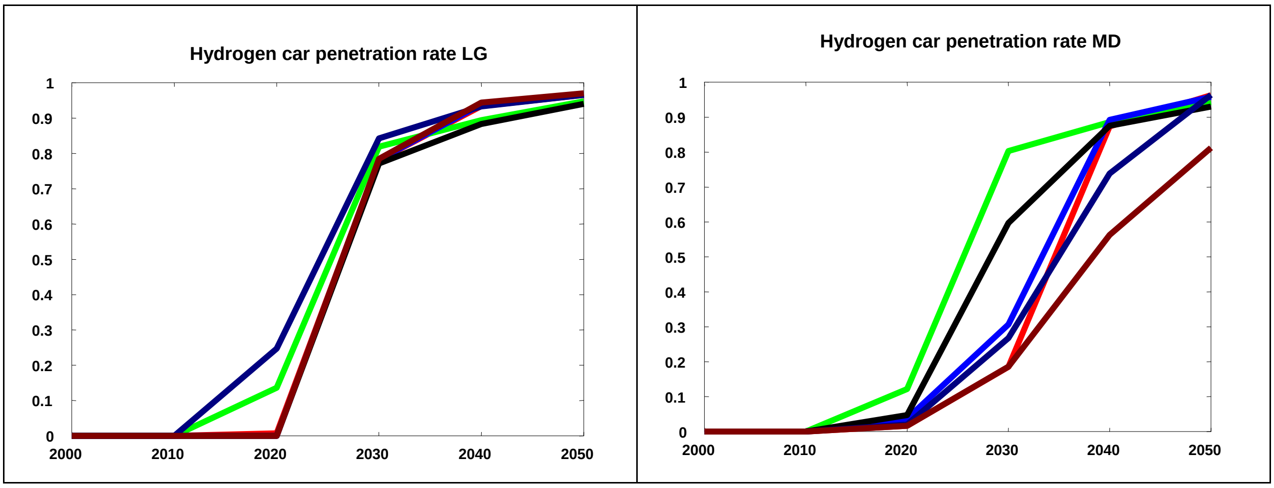
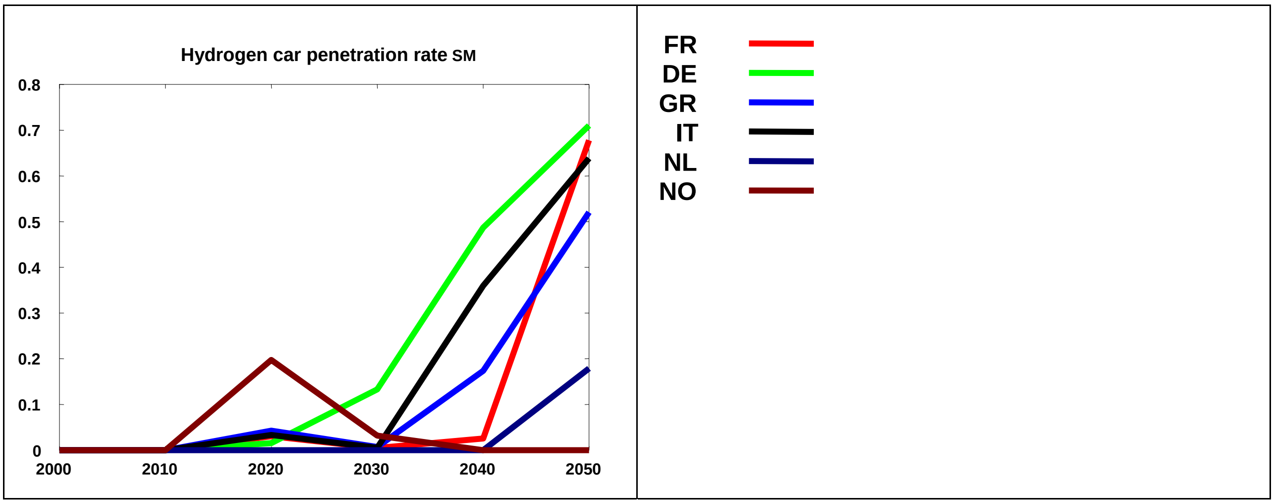


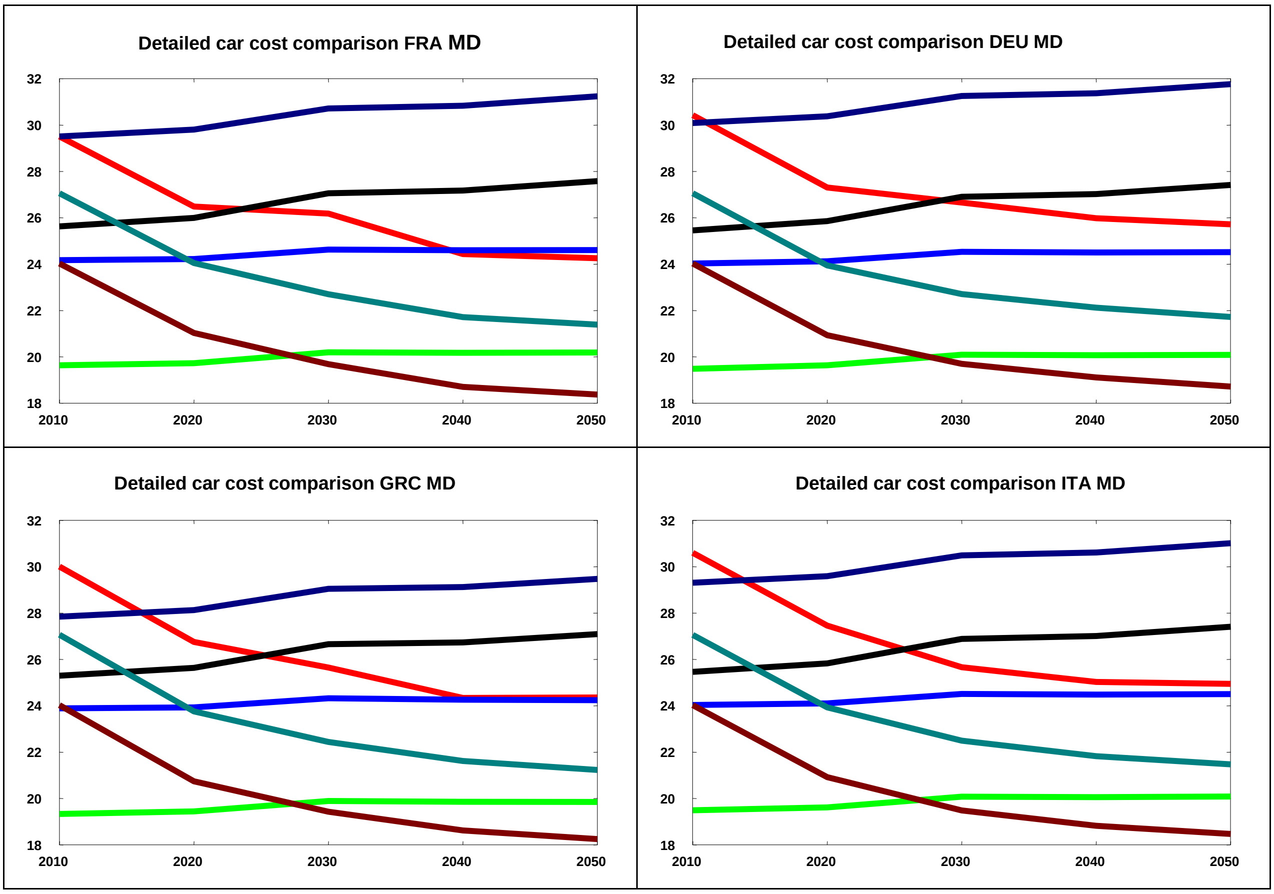
Figure 28: Hydrogen penetration rates for different car size classes (stock)





10.2 High hydrogen penetration (H2H) – Detailed cost comparison of cars

Figure 29: Detailed cost comparison of medium cars



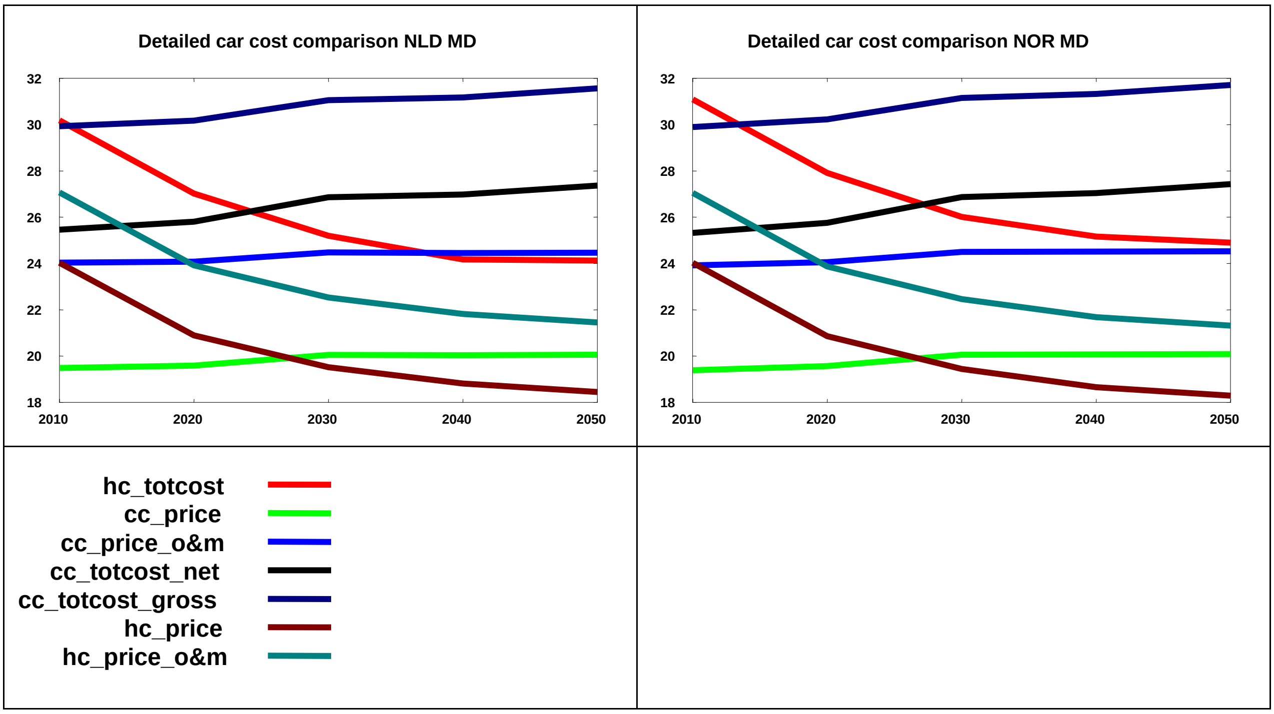
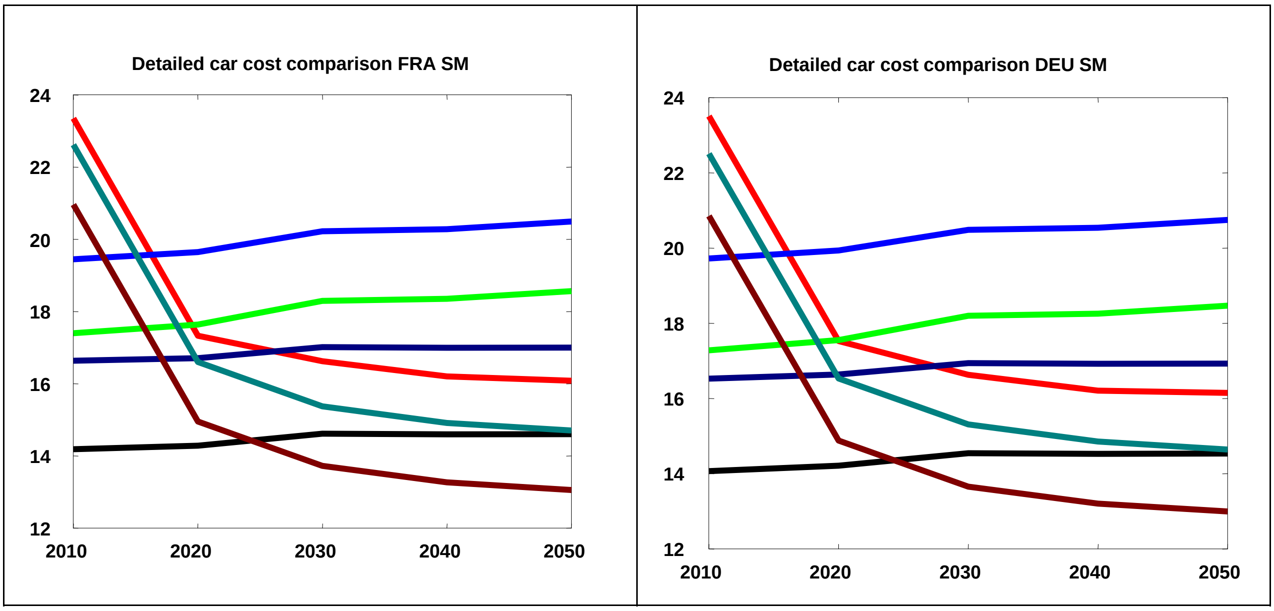
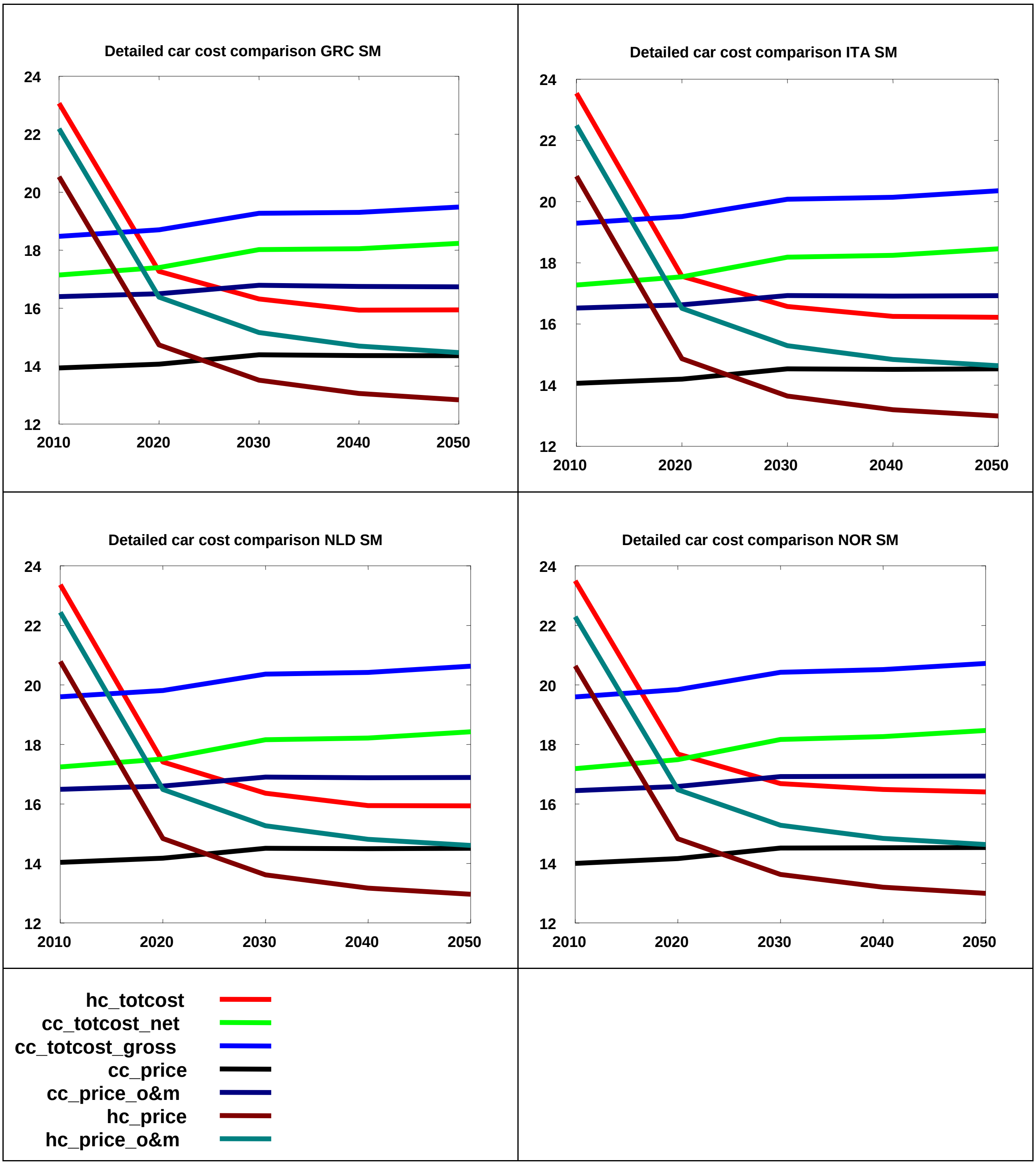


Figure 30: Detailed cost comparison of small cars




Detailed car cost comparison GRC SM
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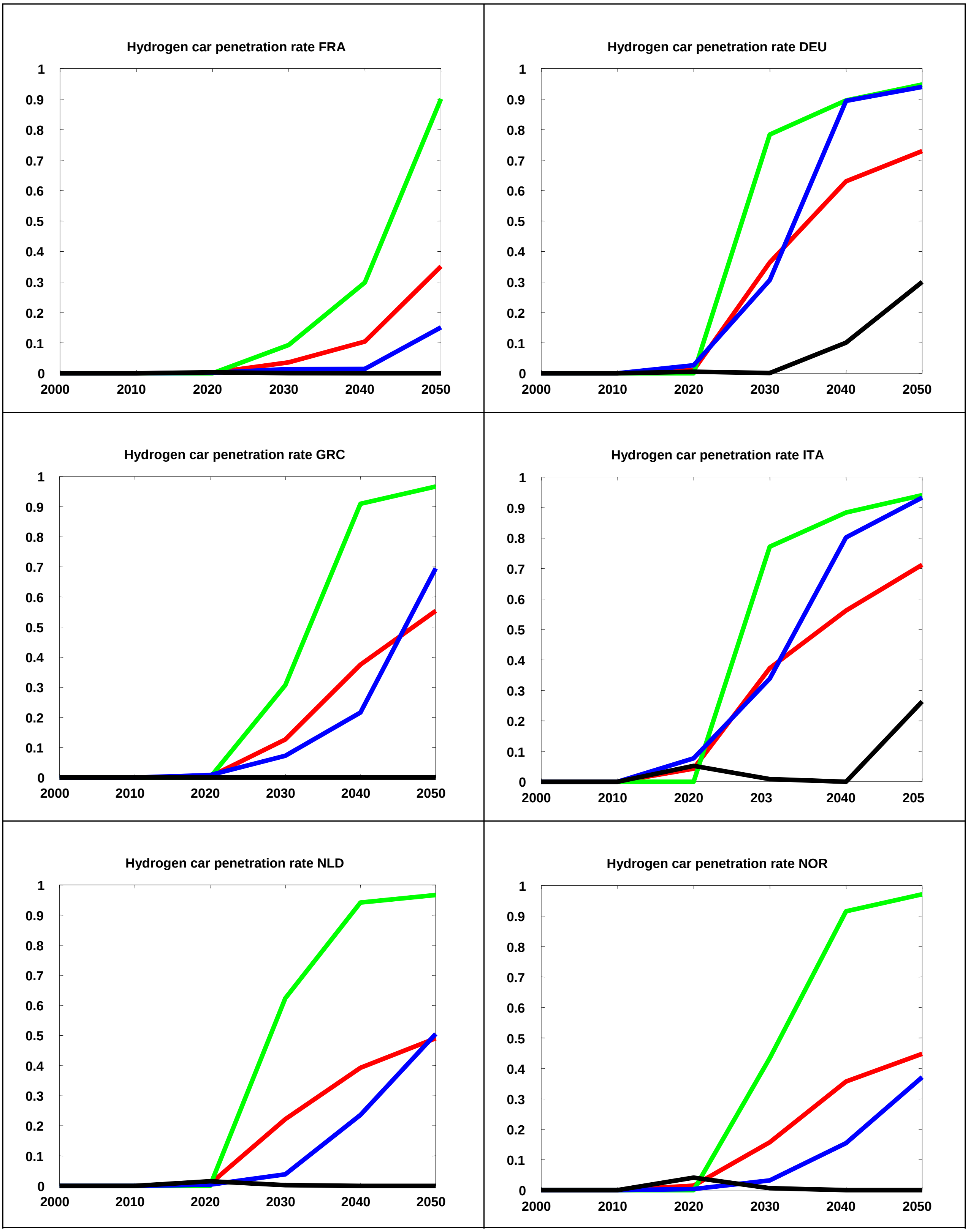
hc_totcost
cc_totcost_net
cc_totcost_gross
cc_price
cc_price_o&m
hc_price
hc_price_o&m

10.3 Low hydrogen penetration (H2L) – Share of hydrogen cars in the stock

Figure 31: Hydrogen penetration rates in different countries (stock)



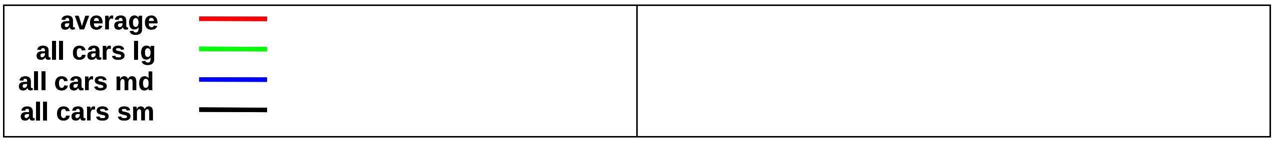
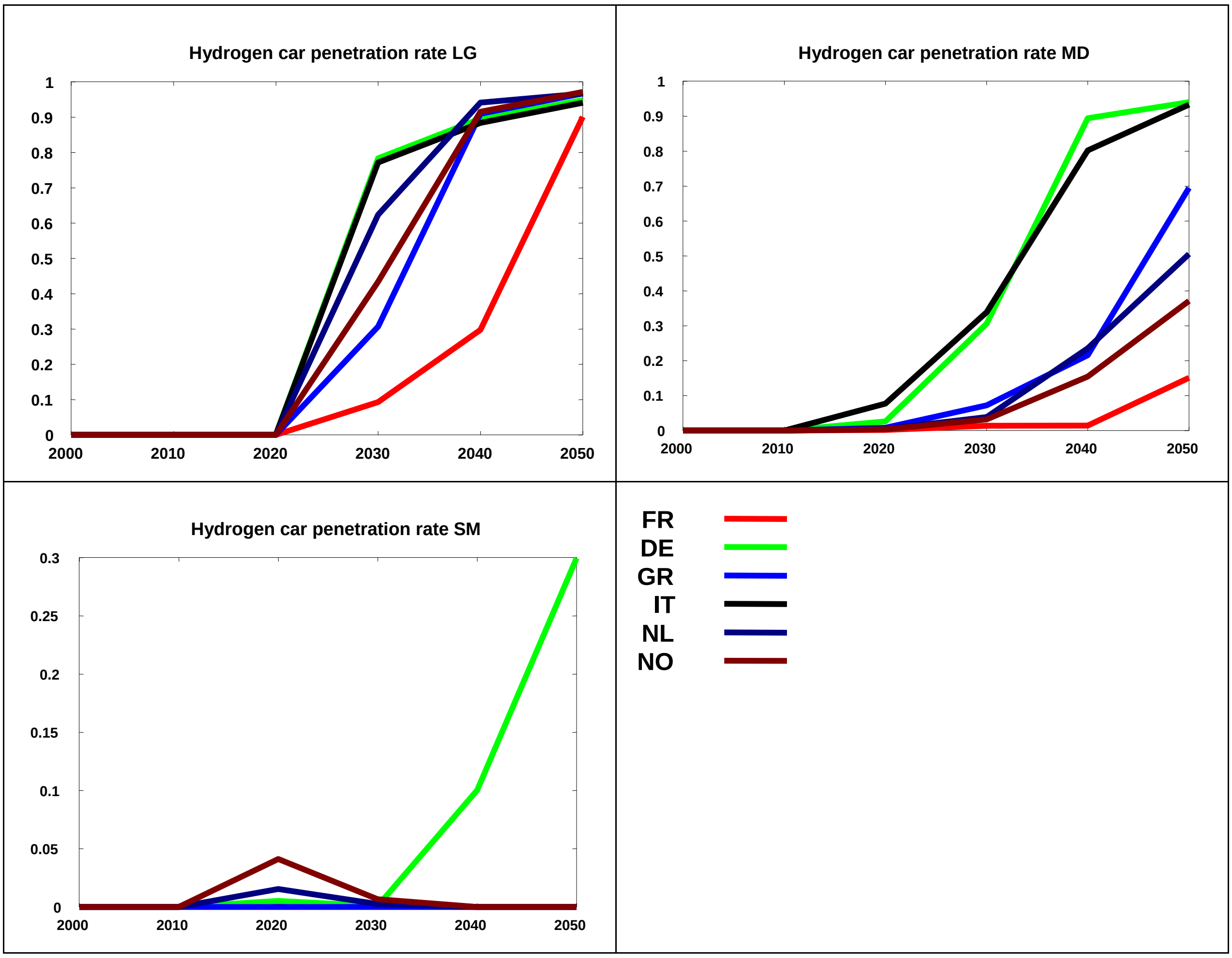
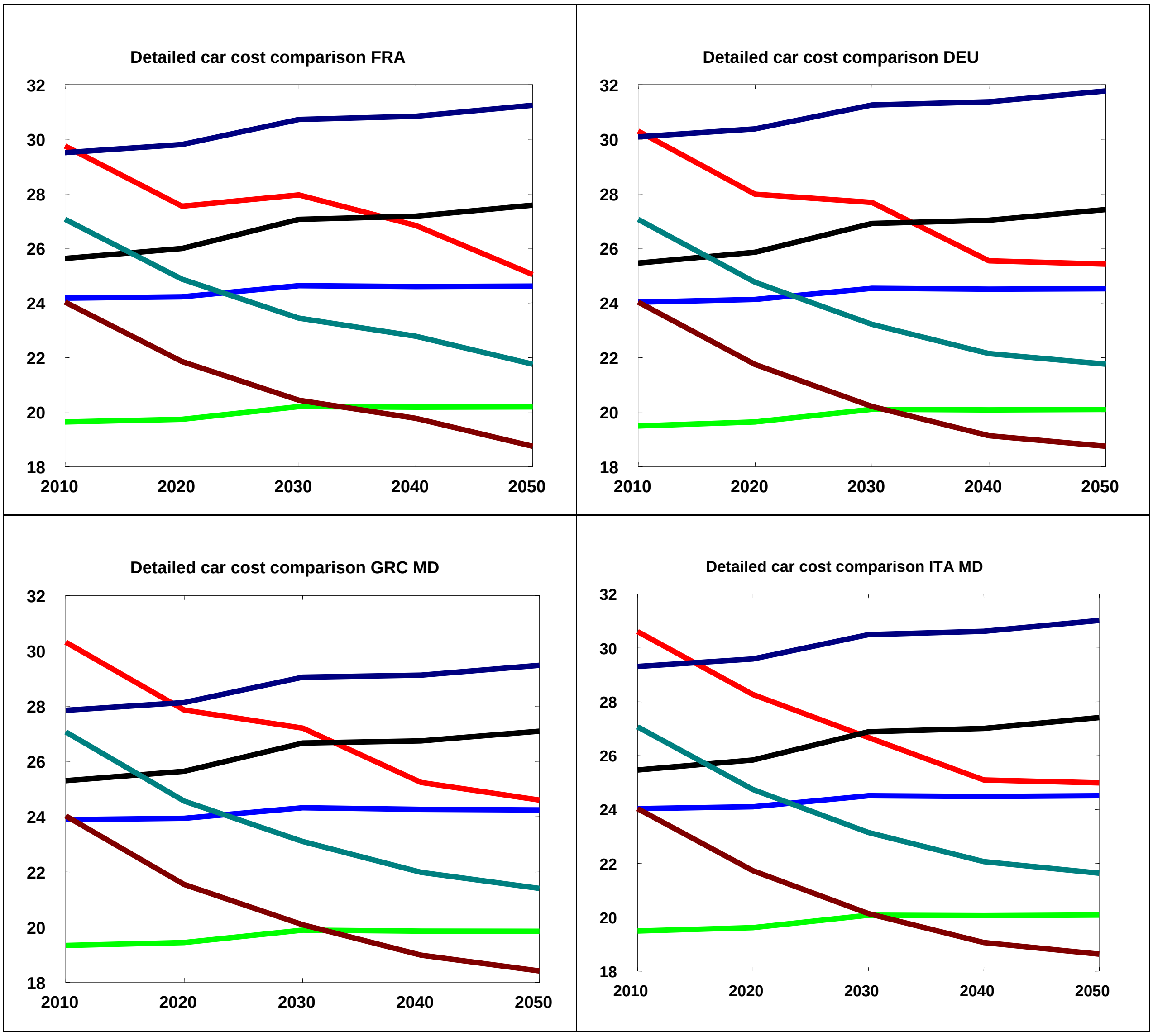


Figure 32: Hydrogen penetration rates for different car size classes (stock)



10.4 Low hydrogen penetration (H2L) – Detailed cost comparison of cars

Figure 33: Detailed cost comparison of medium cars


Detailed car cost comparison FRA

Detailed car cost comparison DEU

Detailed car cost comparison GRC MD

Detailed car cost comparison ITA MD

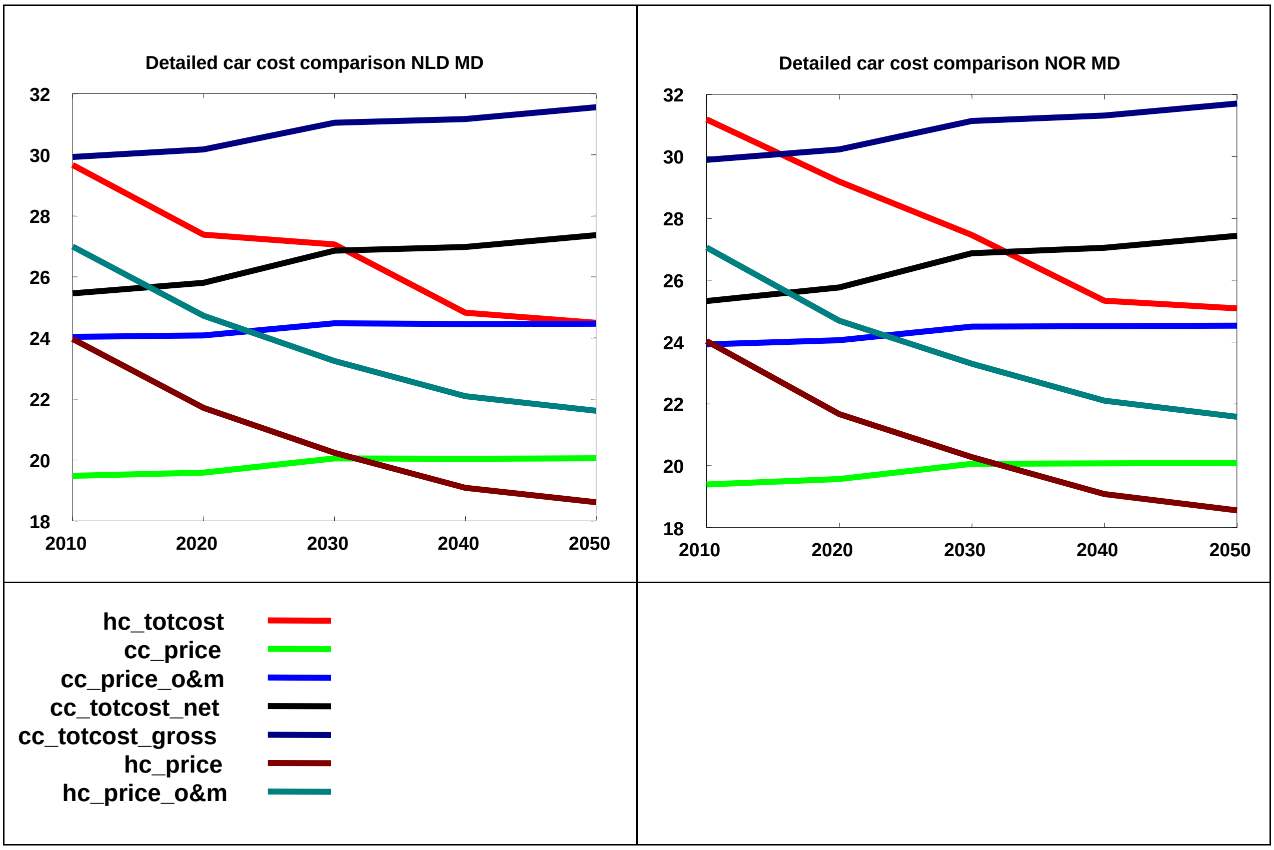
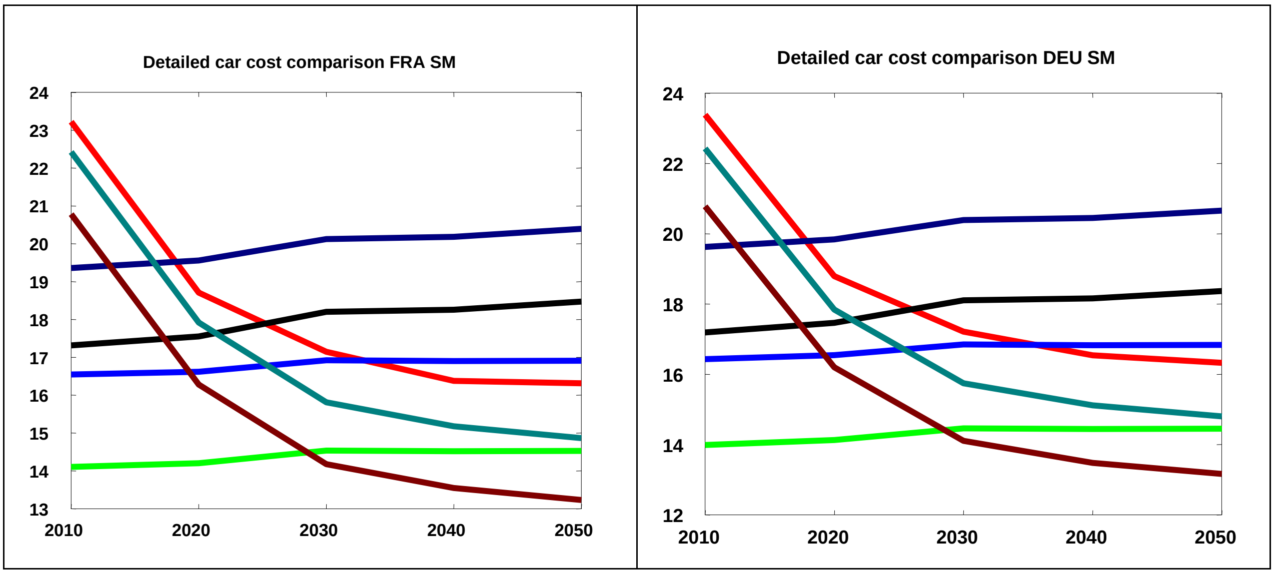
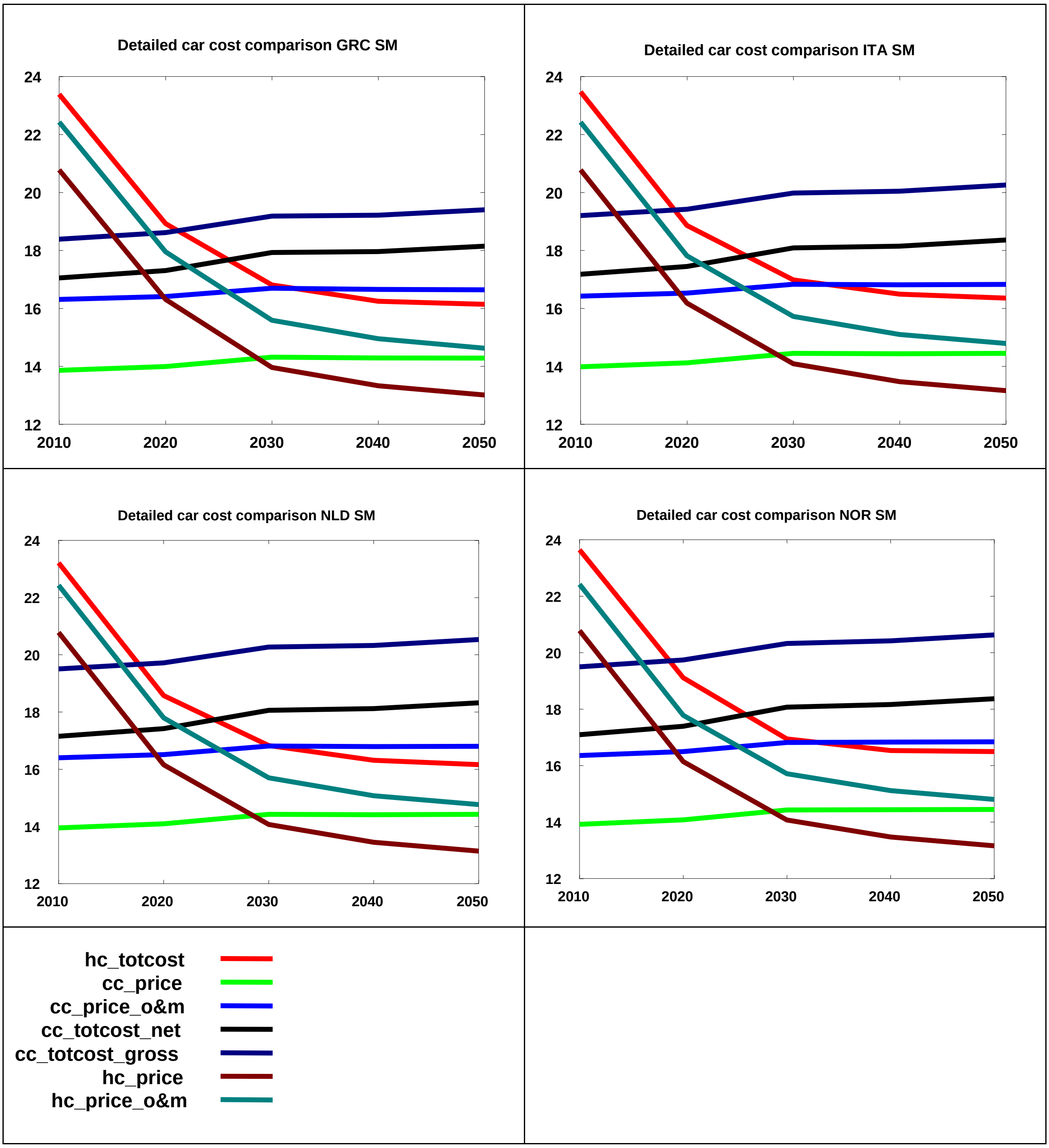


Figure 34: Detailed cost comparison of small cars





Detailed car cost comparison GRC SM

Detailed car cost comparison ITA SM

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Detailed car cost comparison NOR SM