HyWays

SECOND PHASE OF THE PROJECT

REPORT OF THE MACRO-ECONOMIC ANALYSIS

(DELIVERABLE D3.18)

VERSION 1

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

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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 analysed within the dynamic computable general equilibrium (CGE) model PACE-T, developed at ZEW. A CGE model 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 within the HyWays project focuses on the macroeconomic effects of introducing hydrogen cars in the transport sector which include changes in transport demand, real consumption, welfare, GDP and wage rates.

The multi-sectoral PACE-T model features 12 regions – 10 HyWays Member States (Finland, France, Germany, Greece, Italy, Netherlands, Norway, Poland, Spain, United Kingdom), the rest of the EU, and the rest of the world. Passenger cars in the model are split into six different car types. These are small, medium and large cars which are powered by either a conventional technology or hydrogen. Cars are implemented as durable consumption goods where conventional and hydrogen cars are assumed to be perfect substitutes. Consequently, the consumer's decision is based only on the price differentials between hydrogen and conventional cars which are based on capital services of the automobile stock present in the respective economy, fuel and expenditures for repair and maintenance.

The hybrid PACE-T model 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 GTAP database. 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 case, and capacity constraints. The trade shares of hydrogen and conventional cars are taken form the sector "Motor vehicles and parts" of the GTAP database. In order to implement passenger cars, which are powered by a conventional technology or hydrogen, demands further data on car and hydrogen production technologies. This so-called bottom-up data 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 principle findings of introducing hydrogen in the transport sector are very similar in all scenarios. Most Member States (MS) are expected to experience small increases in transport demand, real consumption, GDP (gross domestic production) and welfare. Only a few MS (Finland, Italy and the United Kingdom) experience temporary reductions in the macroeconomic variables.

Figure 1: Real consumption in the H2H scenario

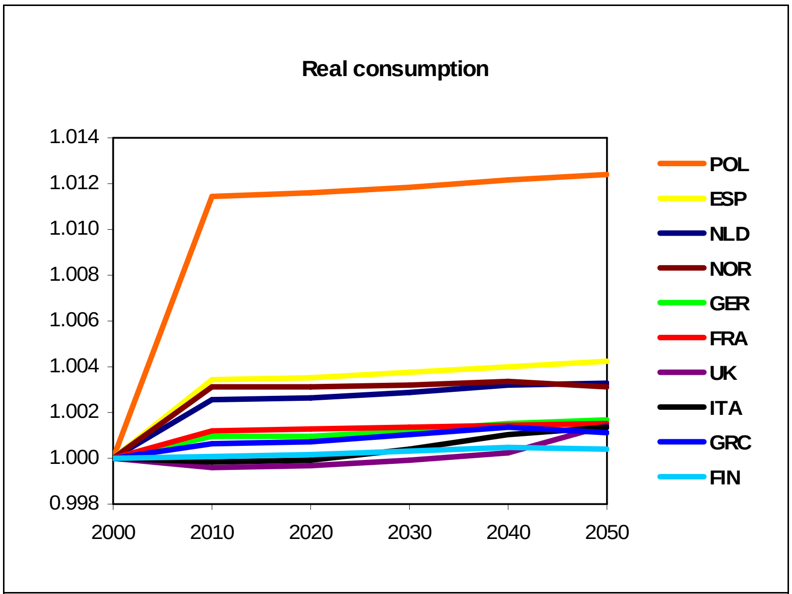
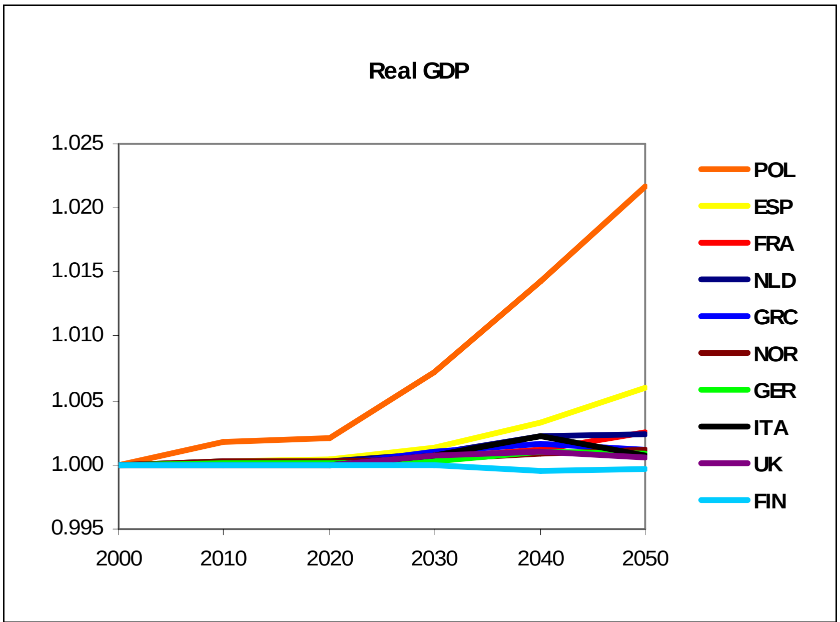


Figure 1 shows the development of real consumption in the ten MS assuming high hydrogen penetration rates and a steep learning curve (the H2H scenario). Obviously, Poland experiences the largest increase in real consumption of approximately 1.2 percent in 2050 compared to the baseline. In contrast, consumption in e.g. Germany and France rises by only 0.2 percent. The other countries range in the middle. Exceptions are Finland, Italy and the United Kingdom where consumption slightly declines during the first years of the transition but all three countries end up with slightly positive effects of up to 0.1 percent in 2050. These findings are mainly driven by the hydrogen production costs in the ten MS, the lifetime costs for hydrogen and conventional cars and the assumed hydrogen penetration rates in the different car classes. Since hydrogen fuel costs are lowest in Poland, the cost savings potential due to the introduction of hydrogen cars is largest and so is the effect on real consumption. In contrast, hydrogen fuel costs in e.g. Finland are relatively high during the considered period so that hydrogen cars hardly become competitive. This has a negative impact on the consumer's budget which results in lower consumption demand. Major beneficial cost savings only become apparent around 2050.

The observed changes in real consumption in the H2H scenario directly translate into small welfare gains in all MS. Not surprisingly, welfare gains are largest in Poland, Spain, Norway and the Netherlands where it rises by 1.19 percent, 0.38 percent, 0.31 percent and 0.29 percent, respectively. More modest improvements in welfare are observed in France, Germany, Greece and Italy. Here welfare rises by 0.13 percent, 0.13 percent, 0.09 percent and 0.06 percent, respectively. The lowest welfare improvements are reached in the United Kingdom (0.04 percent) and Finland (0.03 percent).

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 with respect to the baseline since there are only few hydrogen cars in the market. An exception is Poland where consumption already increases relatively much in 2010 due to the very low hydrogen fuel costs which immediately translates into positive effects on GDP. After 2020, however, GDP starts to rise in almost all MS. Thus GDP in 2050 exceeds the respective baseline value by approximately 2.2 percent in France, 0.6 percent in Spain, 0.3 percent in France, 0.2 percent in the Netherlands, 0.1 percent in Greece, Norway, Germany, Italy, and the United Kingdom. Only Finland experiences a permanent small decline in GDP of about 0.03 percent. 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 of course with smaller magnitude. Assume, for example, low penetration rates and a lower rate of cost reduction (the L2L scenario). Welfare in e.g. Poland and Spain now increases by only 0.46 percent and 0.15 percent, respectively. Germany and Italy now even experience small welfare losses of -0.03 percent and -0.07 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 1.1 percent in Poland and it decreases by 0.01 percent in the United Kingdom the other countries ranging in between these two extremes.

Assuming medium hydrogen penetration rates and a steep learning curve leads to very similar effects as the H2H scenario. Only the changes in macroeconomic variables are slightly dampened.

1.3 Conclusions

Under the assumptions of HyWays the introduction of hydrogen in the transport sector leads to small improvements in the macroeconomic variables in almost all MS. However, the economic effects 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 or do not become competitive in the future. Thus the cost differential between the lifetime costs of conventional and hydrogen cars determines primarily the consumers' budgets which finally drive the increase in consumption, welfare and GDP in the different scenarios.

2 Introduction

The sustainability of the energy system is one of the biggest challenges for the future. A widely discussed alternative to fossil fuels is often seen in the introduction of hydrogen as an energy carrier in the power and transport sector as well as a storage medium for renewable energy. The EU "HyWays" project aims to develop a roadmap for the introduction of hydrogen in the energy system which is validated and well accepted. In order to get a realistic quantification of the effects of a European hydrogen promotion policy, the project combines expertise from energy engineering, energy system modelling and economics. Therefore, data on a large array of hydrogen-related technology is collected and processed in different kinds of models that allow investigating the technical, socio-economic and emission challenges and impacts of realistic hydrogen supply paths under consideration of technological and economical needs.

In this report, the macroeconomic impacts of introducing hydrogen in the transport sector are assessed. The analysis is carried out within the framework of the computable general equilibrium (CGE) model PACE-T which takes into account the economy-wide repercussion effects of the hydrogen promotion policy. PACE-T is a dynamic, multi-region and multi-sector model with a special focus on passenger transport. The model is 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 12 regions – 10 Member States (Finland, France, Germany, Greece, Italy, Netherlands, Norway, Poland, Spain, United Kingdom), 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 three scenarios where the hydrogen technology becomes active: (1) a high-penetration rate scenario with high technological progress (H2H), (2) a low-penetration rate scenario with low technological progress (L2L) and (3) a medium-penetration rate scenario with high technological progress (H2M). The penetration rates were directly taken from the MARKAL model (for additional information see deliverable D 3.6). The first and the last scenario assume a steep learning curve, i.e. there is a relatively high rate of cost decrease for hydrogen fuelled cars, while the second scenario assumes a low rate of cost decrease for hydrogen fuelled cars. As the results of these three scenarios suggests, the effects of the introduction of hydrogen in the MS are fairly small. Transport demand and real consumption slightly increase in almost all MS compared to the references scenario. This is mostly due to the cost reduction of the cheaper hydrogen technology. As a consequence, most 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 this report we abstain from explaining the methodological approach of PACE-T and the input data used. The detailed explanations of these topic are given in Deliverable D3.8. We therefore concentrate in this report on the scenario analysis in Phase II of the HyWays project.

This report proceeds as follows. The next section presents the scenario description followed by the results of the three scenario simulations. Afterwards the main lessons learnt from the simulation results are summarized and Section 6 concludes. Note that the Annex provides detailed developments of penetration rates and car lifetime costs for all MS in the considered scenarios.

3 Scenario assumptions

In the following we analyse three scenarios, namely the high penetration rate scenario (H2H) assuming high technological progress, the low penetration rate scenario with low technological progress (L2L) and the medium penetration rate scenario (H2M) combined with high technological progress. 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[1]. By implementing the MARKAL results every assumption that influences the corresponding MARKAL results is indirectly adopted by 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. The first and third scenario 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. The second scenario assumes a slower cost decrease which is additionally combined with rather low hydrogen penetration rates.

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 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.

[1] Input data for the scenarios were taken from Markal_P2_V2.0.

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.

The results of the scenario calculations are described in the following chapter.

4 Results

The following three sections analyse in detail the scenarios H2H and H2M with the high learning curve approach and either high or medium hydrogen penetration rates and the scenario L2L which assumes low hydrogen penetration rates and a moderate technological progress. As already mentioned above, all considered scenarios are based on the structural identity scenario as outlined in the ISIS model.

Since the proceeding is equal for each of the ten 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.

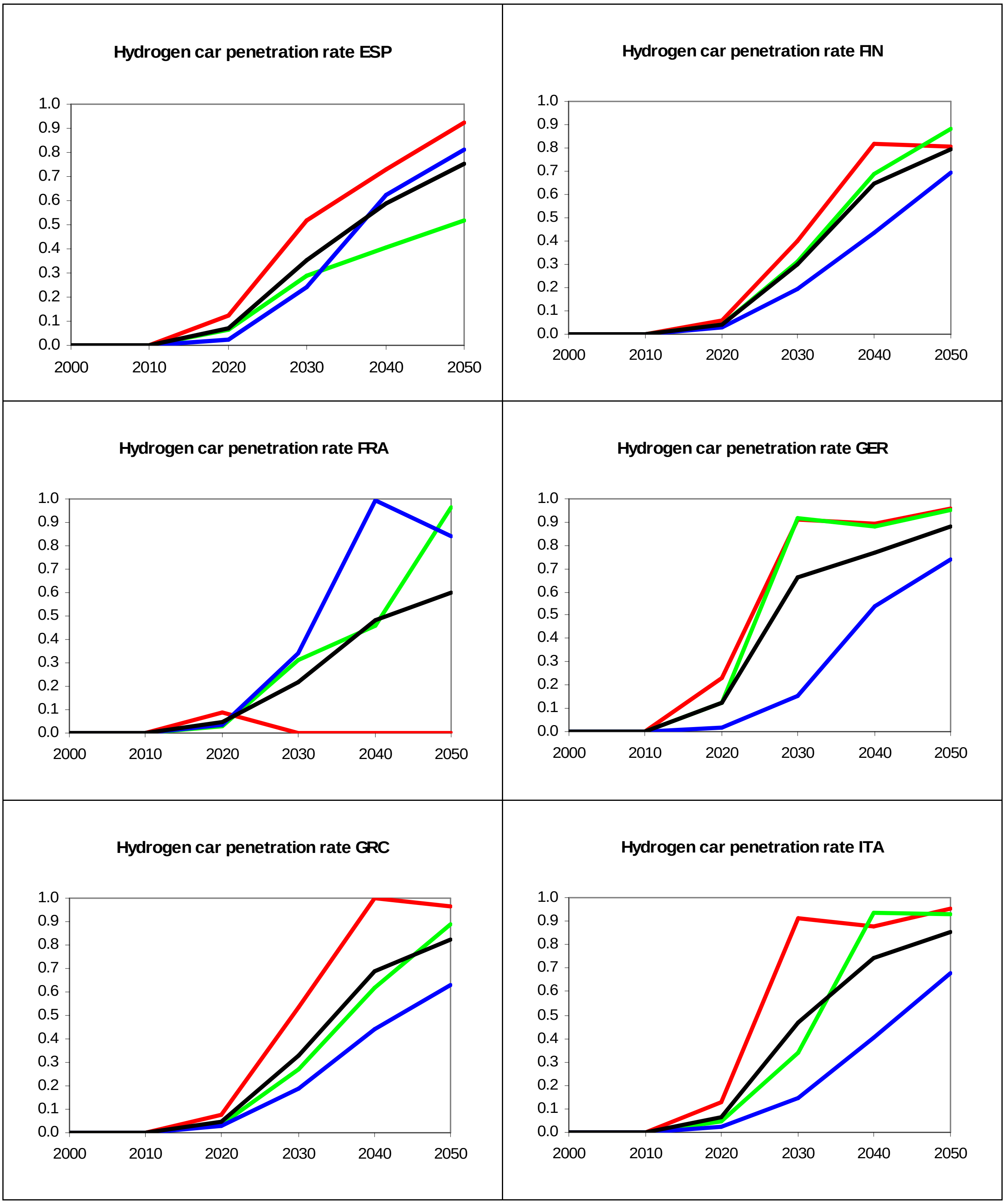
4.1 High hydrogen penetration (H2H)

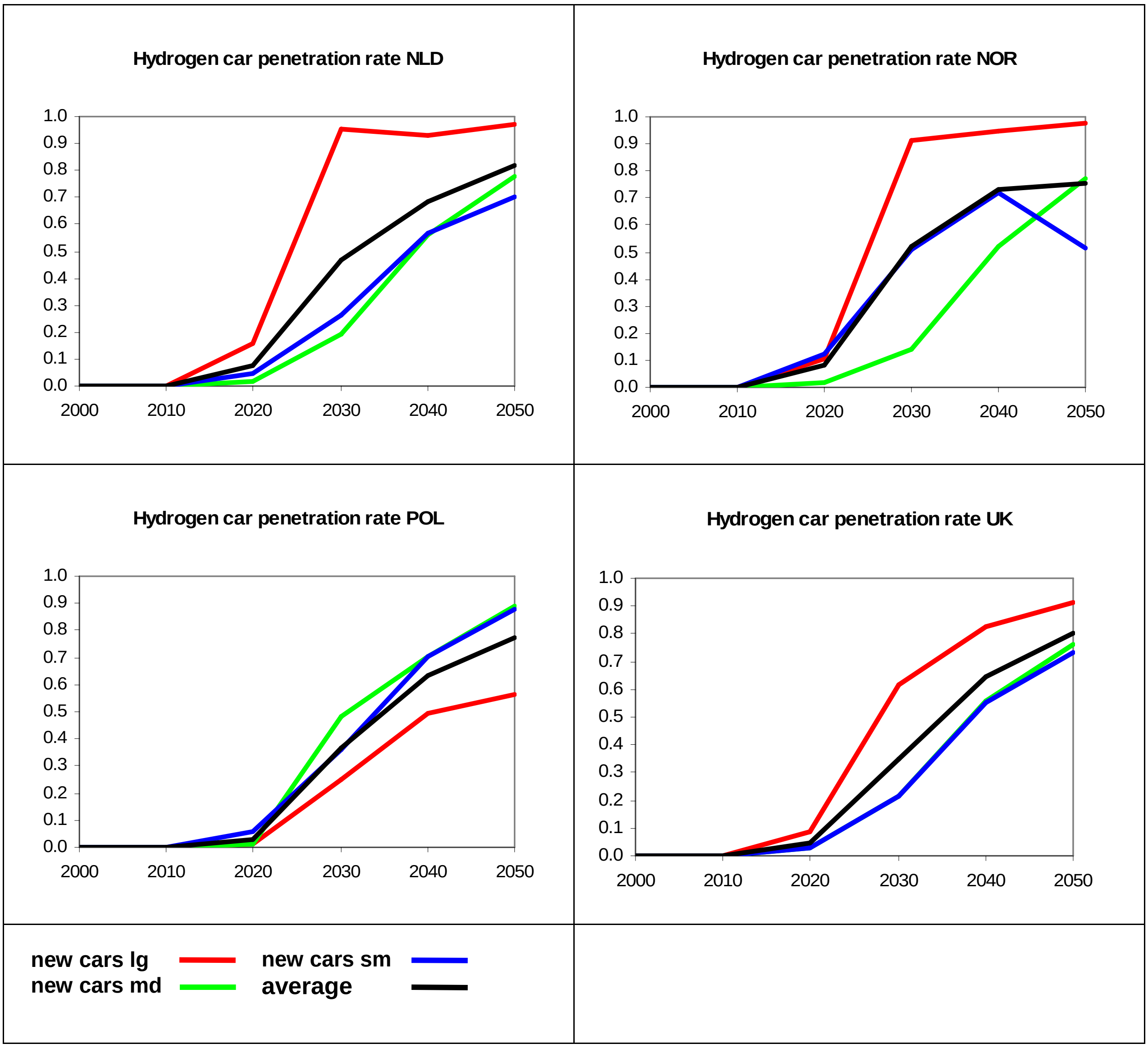
The first scenario considers the simulation results if the penetration rate for hydrogen is high and the rate of cost decrease is high. We first highlight the development of the penetration rates in the ten MS until 2050 and compare the costs of conventional and hydrogen cars in detail. Afterwards, the analysis proceeds with the macroeconomic effects of the introduction of hydrogen passenger cars by looking at the development of transport demand, real consumption, welfare, GDP, and the wage rate in the MS.

4.1.1 Penetration rates

For the macroeconomic analysis with PACE-T the share of hydrogen cars in each car size category, in each period and in each MS is directly adopted 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 ten 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.

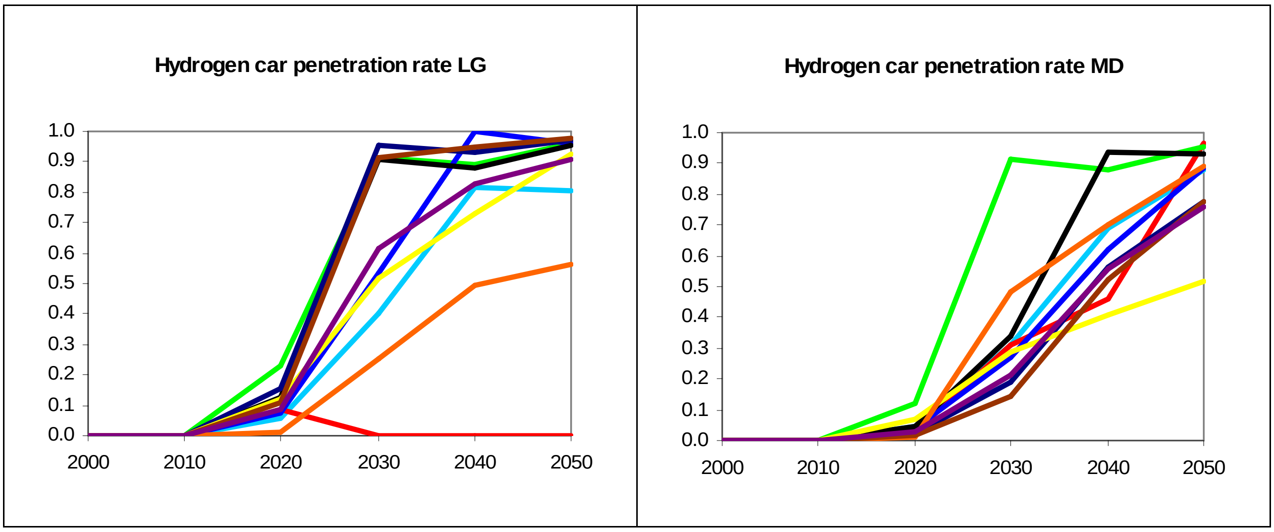
Obviously, the paths for the penetration rates in PACE-T are similar in the ten MS. In the early period of the hydrogen introduction (year 2020) the penetration rates of new cars range between 1 and 15 percent among all size classes. One exception is Germany where the penetration rate for new large hydrogen cars (new cars lg) is already 23 percent. After 2020 the penetration rates for all size categories increase steeply in the MS. In most countries penetration rates for medium and large hydrogen cars reach values between 80 and 100 percent in 2050. There are three exceptions. First, hydrogen penetration in France for new large cars is zero.

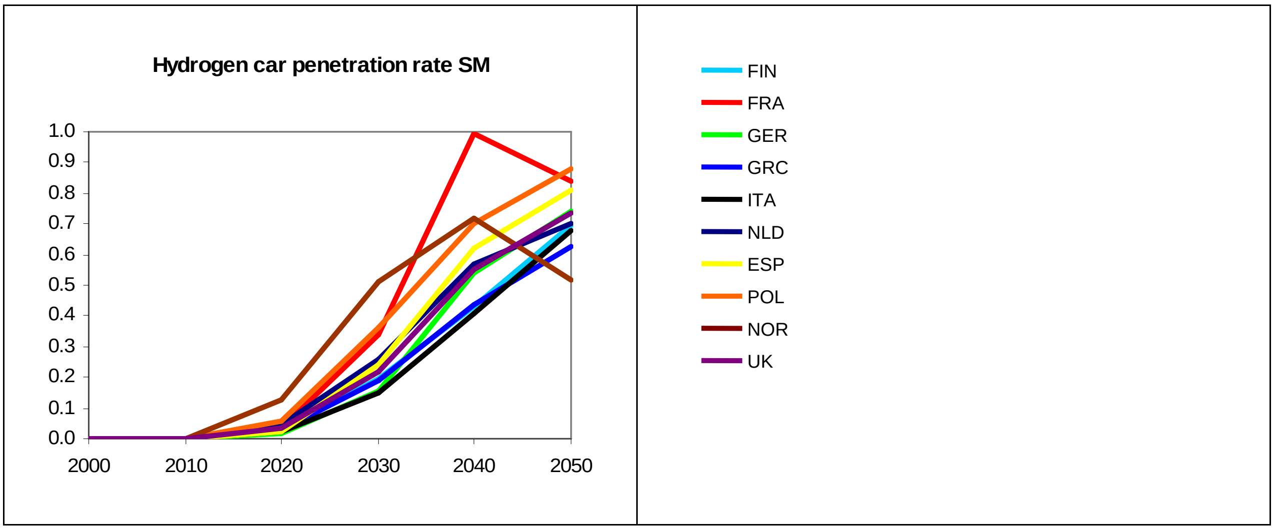
Only in 2020 there is a sizeable rate of 8.8 percent in the large car segment. Second, the share of large hydrogen cars in Poland increases steadily to 56 percent by 2050. Third, hydrogen penetration of medium cars in Spain rise to 52 percent over the considered period. In the small car segment, hydrogen penetration rates in 2050 range between 51 percent in Norway and 88 percent in Poland.

Having a look at the average penetration rates in Figure 3, one can observe 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 Germany and 85 percent in Italy. In most MS (Finland, Greece, Netherlands, Spain, Poland, Norway, United Kingdom) average hydrogen penetration in new cars reaches approximately 80 percent in 2050. Again, France is an exception with hydrogen penetration in 2050 reaching 60 percent. The reason for this rather low value is of course the fact that there are no new hydrogen cars in the large car segment (except in year 2020). Note that the average penetration rate for new cars in PACE-T may differ from the respective rate in MARKAL since 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 differentiated by size classes.

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





Obviously, the paths of the penetration rates for new large hydrogen cars are very similar across the MS. Hydrogen penetration rates steeply increase until 2040 and in most MS remain at their high levels afterwards. As already mentioned before, the two major exceptions are France and Poland. While in France the rates of hydrogen penetration are zero for large cars (except in year 2020), the rates in Poland rise modestly over time to reach 56 percent in 2050. In the medium size class, the paths of hydrogen penetration rates are again comparable across most MS. Countries like Finland, Greece, the Netherlands, Norway, Poland and the United Kingdom reveal similar developments, i.e. a steady increase in the hydrogen penetration rates for medium cars. In Spain, the share of hydrogen cars also increases steadily over time but to a smaller extent compared to the other countries. Germany experiences a very steep rise in hydrogen penetration rates from 12 percent in 2020 to more than 90 percent in 2030. Afterwards, the share of new hydrogen cars remains more or less stable. The development in Italy is very similar, however with a delay of ten years. The development of hydrogen penetration rates in the small car segment is almost identical across the MS. Two exceptions are however worth mentioning. First, Norway experiences an increase of hydrogen penetration up to more than 70 percent until 2040 which is followed by a decline to 51 percent in 2050. Second, the share of new hydrogen cars in France rises to almost 100 percent in 2040 and drops to 84 percent afterwards.

In the HyWays project car lifetime is assumed to be 12 years. 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. Consequently, the share of hydrogen cars in the car stock differs from the share in new cars. As shown in Deliverable D3.8, 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. This makes hardly any difference to the path of penetration rates. Therefore, we forbear from showing the penetration rates in the vehicle stock here.

4.1.2 Cost Comparison

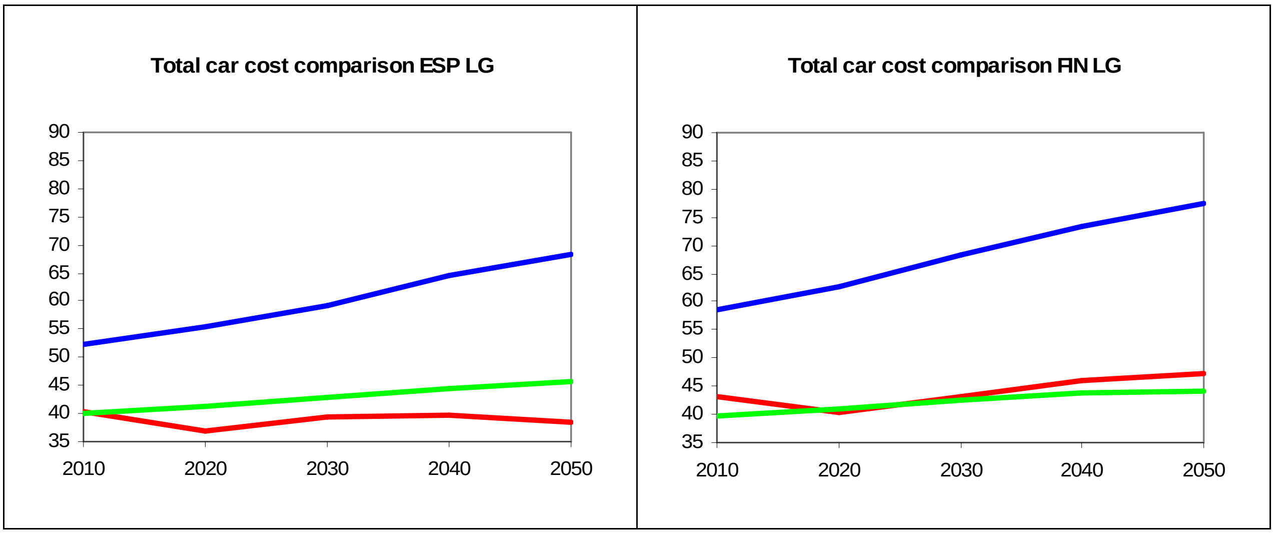
The breakdown of the MARKAL output into car costs, fuel costs and O&M costs in PACE-T is explained in detail in Section 5 of Deliverable D3.8. Note once again that few values that are needed for a cost comparison could not be taken directly from the MARKAL results. In case no hydrogen car was active in the MARKAL model in a certain size category, in a certain year, and in a certain MS, we therefore 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) in PACE-T 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).

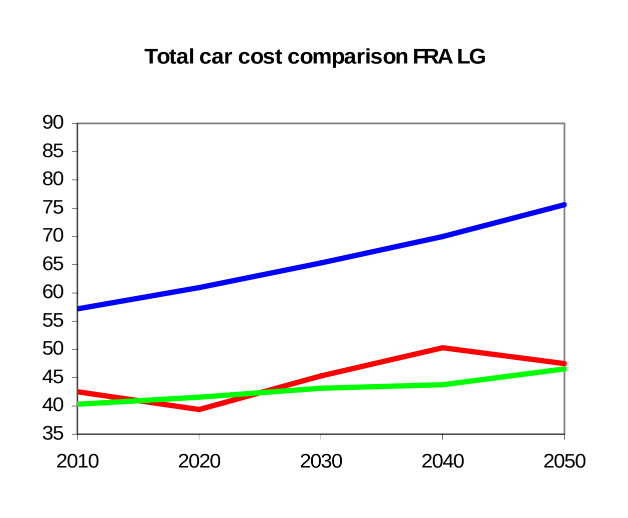
We now turn to the comparison of the lifetime costs of hydrogen and conventional cars. In doing so it is important to distinguish two aspects:

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

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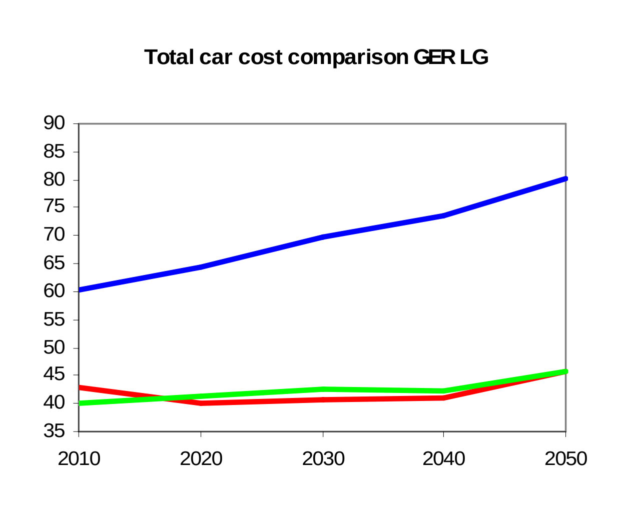
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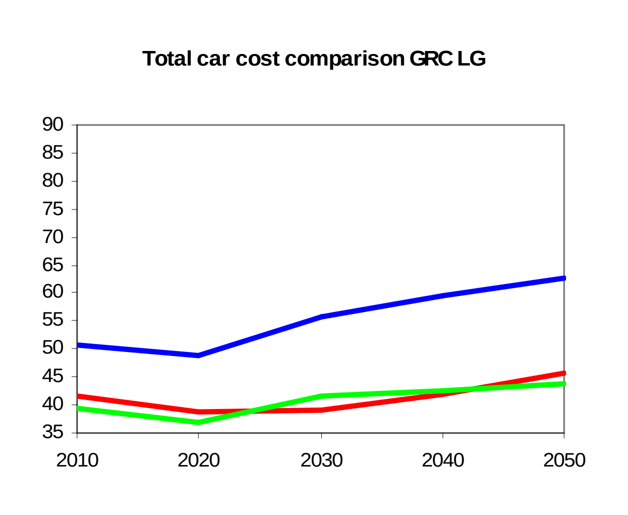
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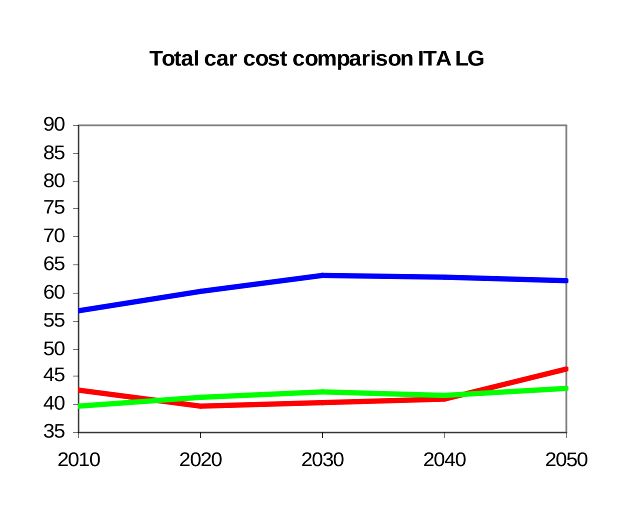
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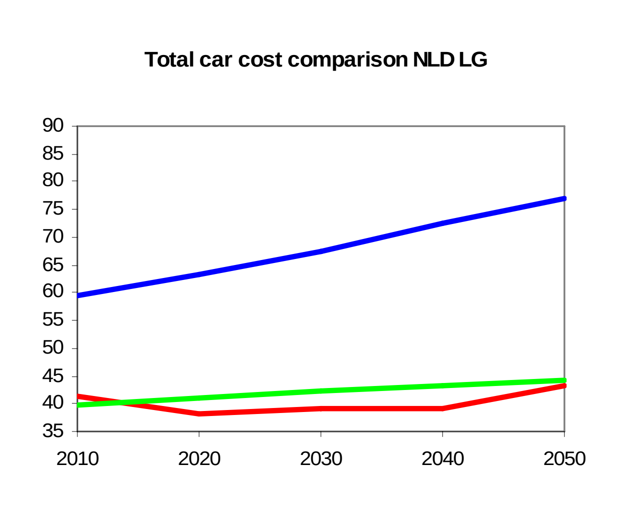
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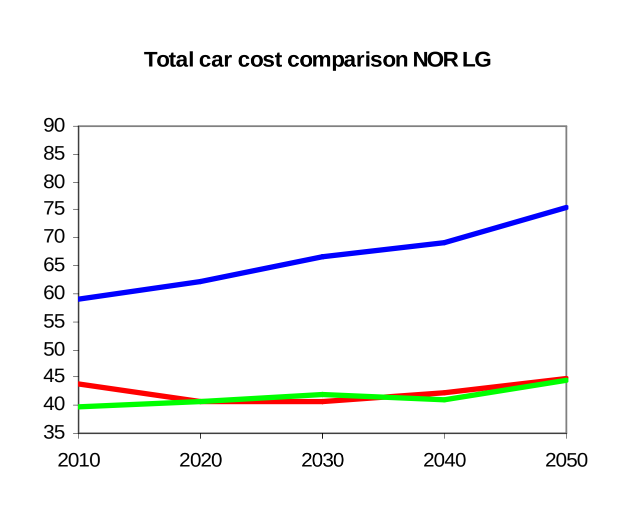
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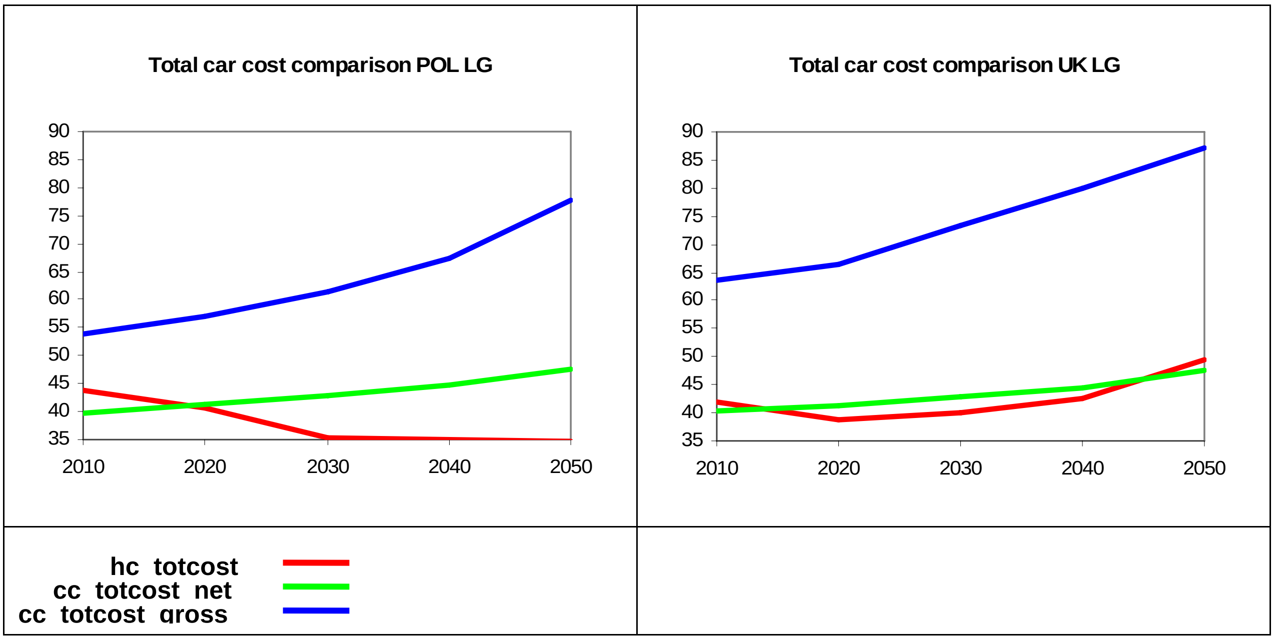


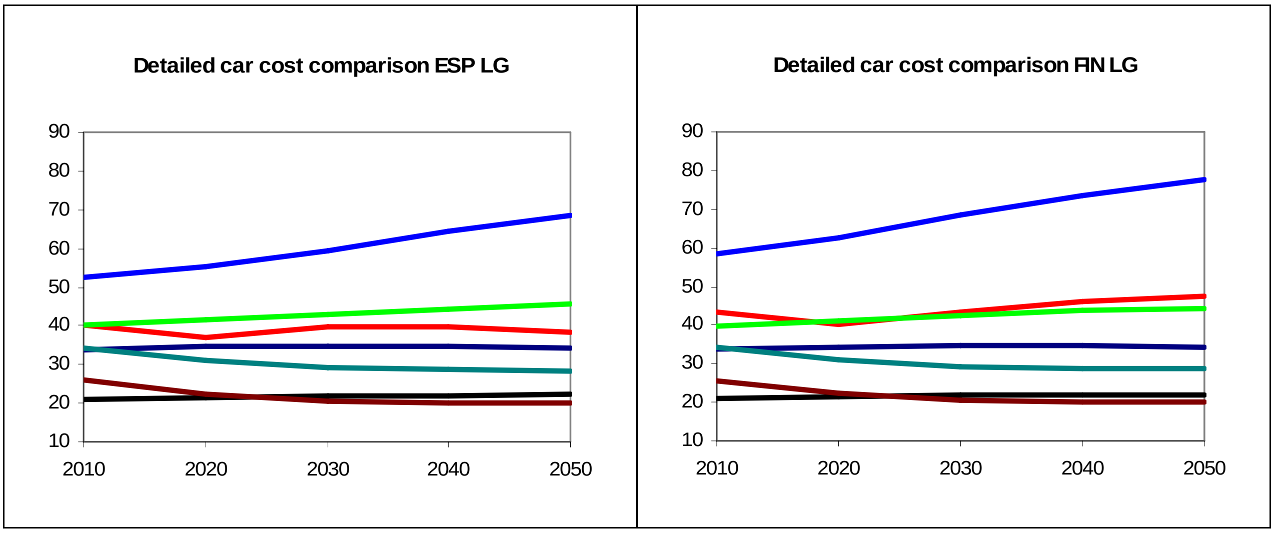
First, compare the development of car lifetime costs of hydrogen cars to those of conventional cars net of taxes. When hydrogen cars are introduced in 2010, they are more expensive than their conventional counterparts. This holds true in all MS. After 2010 lifetime costs of hydrogen cars start to decline so that hydrogen cars become competitive in most MS already in 2020. Only in Greece the lifetime costs of hydrogen cars are slightly above those of conventional cars. The reason for this initial decrease of the lifetime costs of hydrogen cars is the reduction of the producer price caused by technological progress, which is described by the learning curves. After 2030, the development of lifetime costs of hydrogen cars differs between the MS. In Spain, Germany, the Netherlands and Poland the costs of hydrogen cars fall short off those of conventional cars during the whole considered period but the cost differences are vary among these countries. In contrast, costs of hydrogen cars in Finland, France and Norway exceed those of conventional cars. These different developments mainly reflect the future paths of hydrogen production costs. While hydrogen fuel costs in Poland and Spain remain fairly stable over time or increase very modestly, like in Germany and the Netherlands, they increase significantly in countries like France, Finland and Norway. The latter development suffices to raise lifetime costs of hydrogen cars above the costs of their conventional counterparts. Some countries, like e.g. Greece, Italy and the United Kingdom, experience only temporarily lower lifetime costs for hydrogen cars. Especially in Greece and Italy the large increase in hydrogen lifetime costs between 2040 and 2050 is mainly due to relatively large jumps in hydrogen fuel costs.

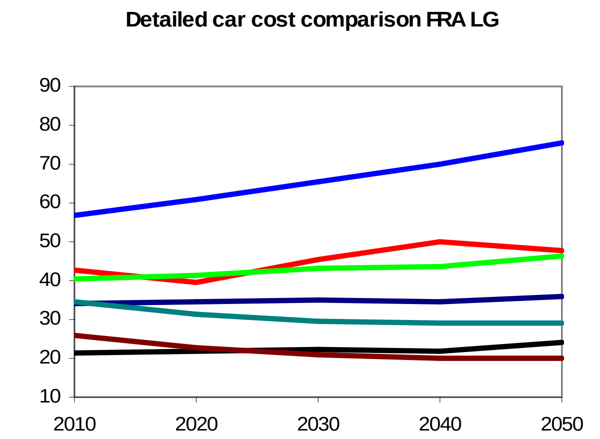
As a consequence of these different developments, large hydrogen cars are competitive from 2030 onwards only in Spain, Germany, the Netherlands and Poland. In all other MS large hydrogen cars are competitive only in those years in which the lifetime costs of hydrogen cars are below the costs of their conventional counterparts. Note also how small these cost differences are in most countries.

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 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

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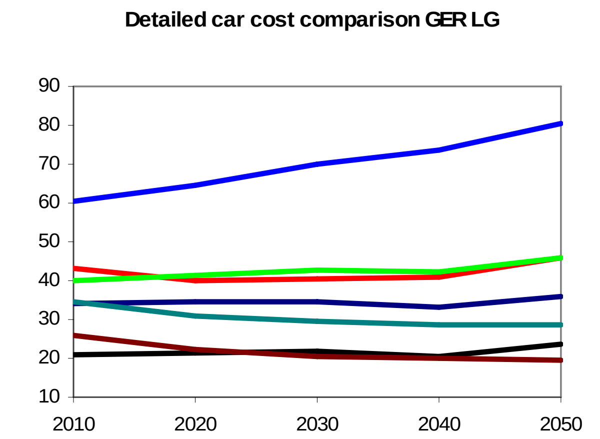
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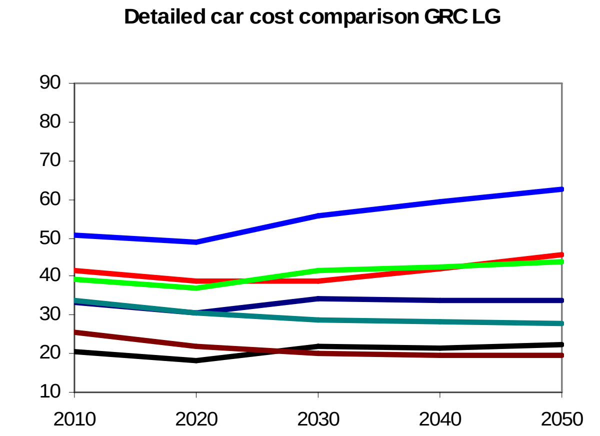
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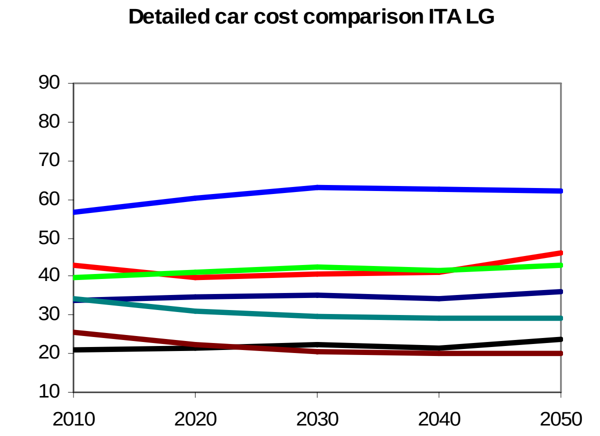
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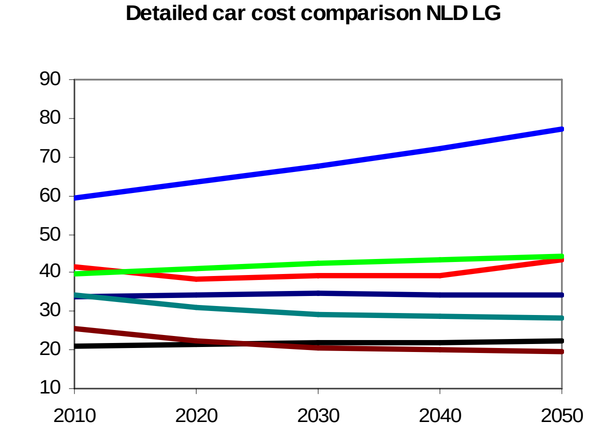
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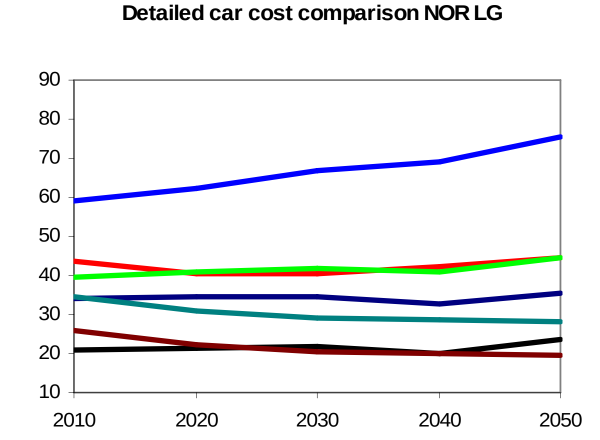
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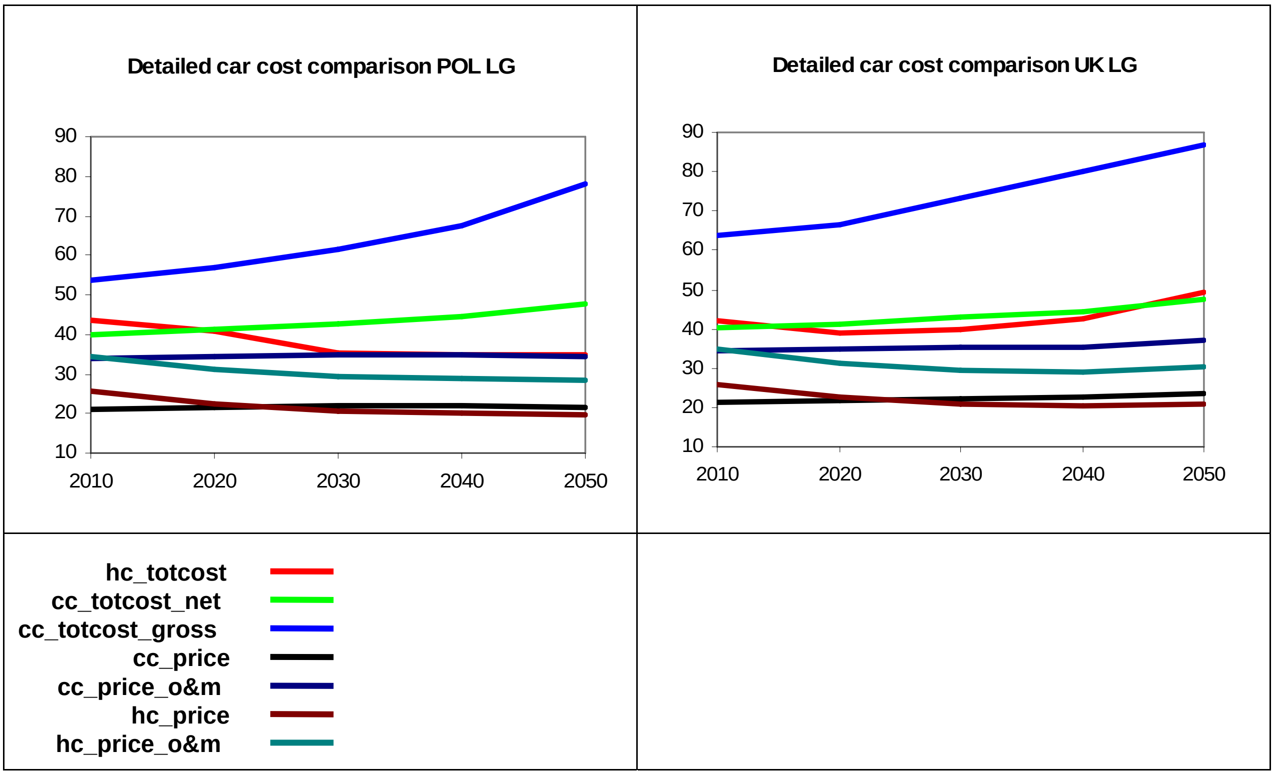
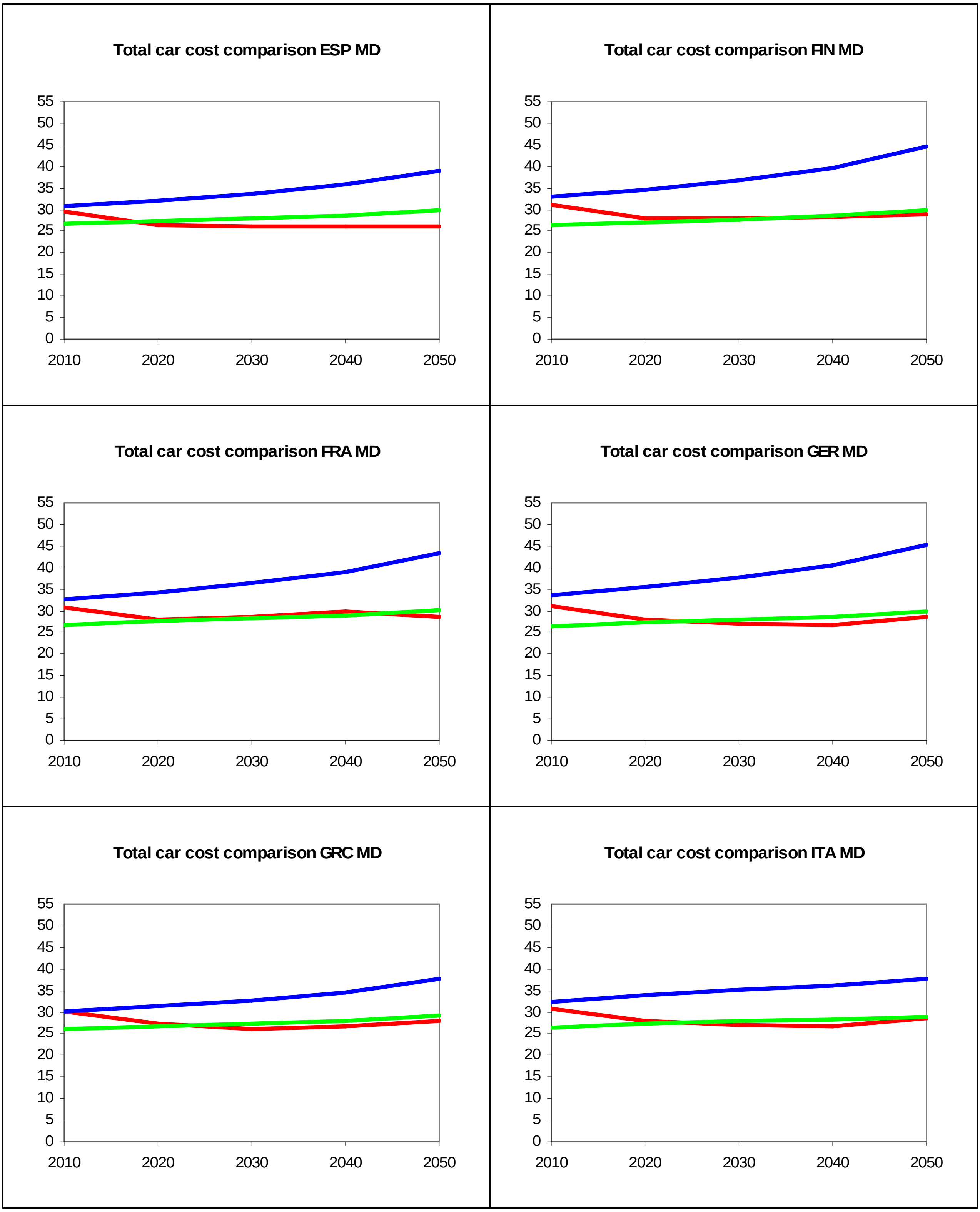


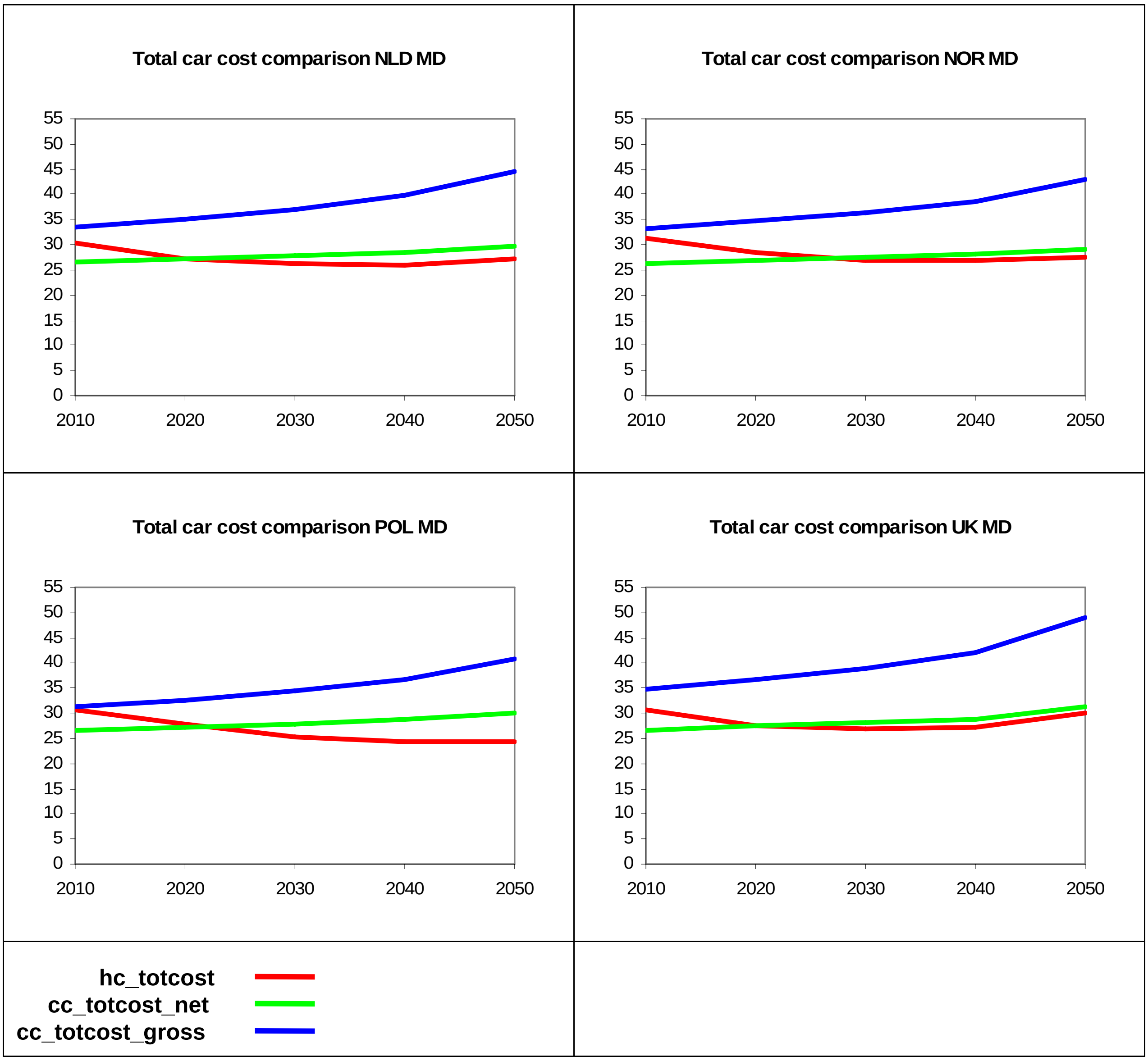
As Figure 6 indicates, it is the decline in production costs that is the driving force for the decrease of hydrogen lifetime costs between 2010 and 2020. Furthermore, it is worth mentioning that the lifetime costs of large conventional cars permanently increase over time in all MS. While the consumer price of large hydrogen cars falls for the whole considered period and remains below the price of conventional cars after 2030 in all MS, hydrogen fuel costs in most countries increase or remain stable over time. During the period until 2030 the decline in consumer prices outweighs the development in fuel costs. However, after 2030 the price decrease is counterbalanced by the rising fuel costs in most MS. Thus the development of hydrogen fuel costs mainly affects the path for the lifetime costs of hydrogen cars.

All in all, the cost developments for hydrogen cars are different across the MS. Mainly depending on future hydrogen fuel costs, lifetime costs for hydrogen cars are expected to decline or increase over time. In those countries where lifetime costs of hydrogen cars decrease (Germany, the Netherlands, Spain and Poland) hydrogen cars are competitive to their conventional counterparts from 2030 onwards. In all other countries hydrogen cars become competitive only in some years during the period between 2010 and 2050.

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

Figure 7: Cost comparison of medium cars



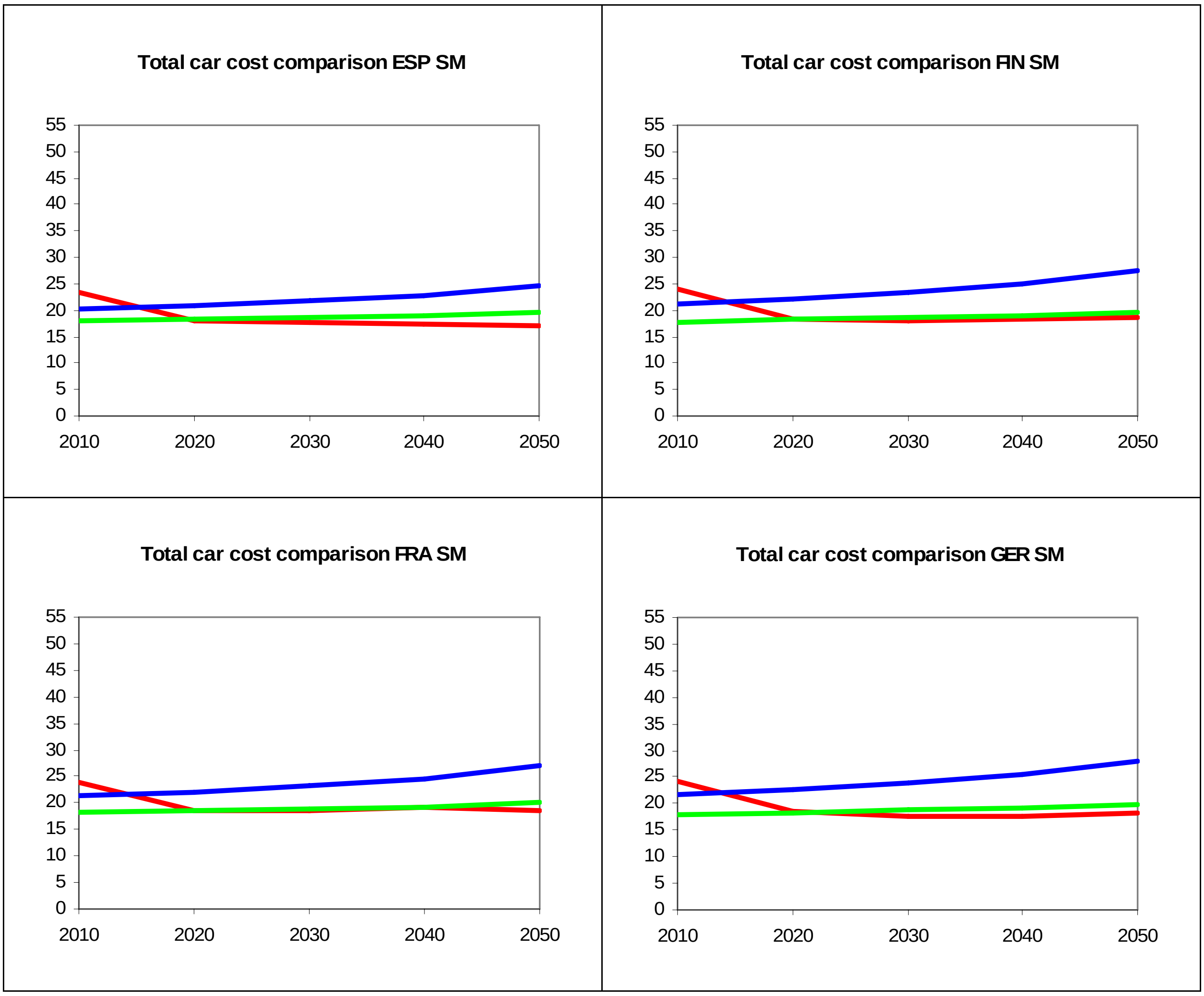


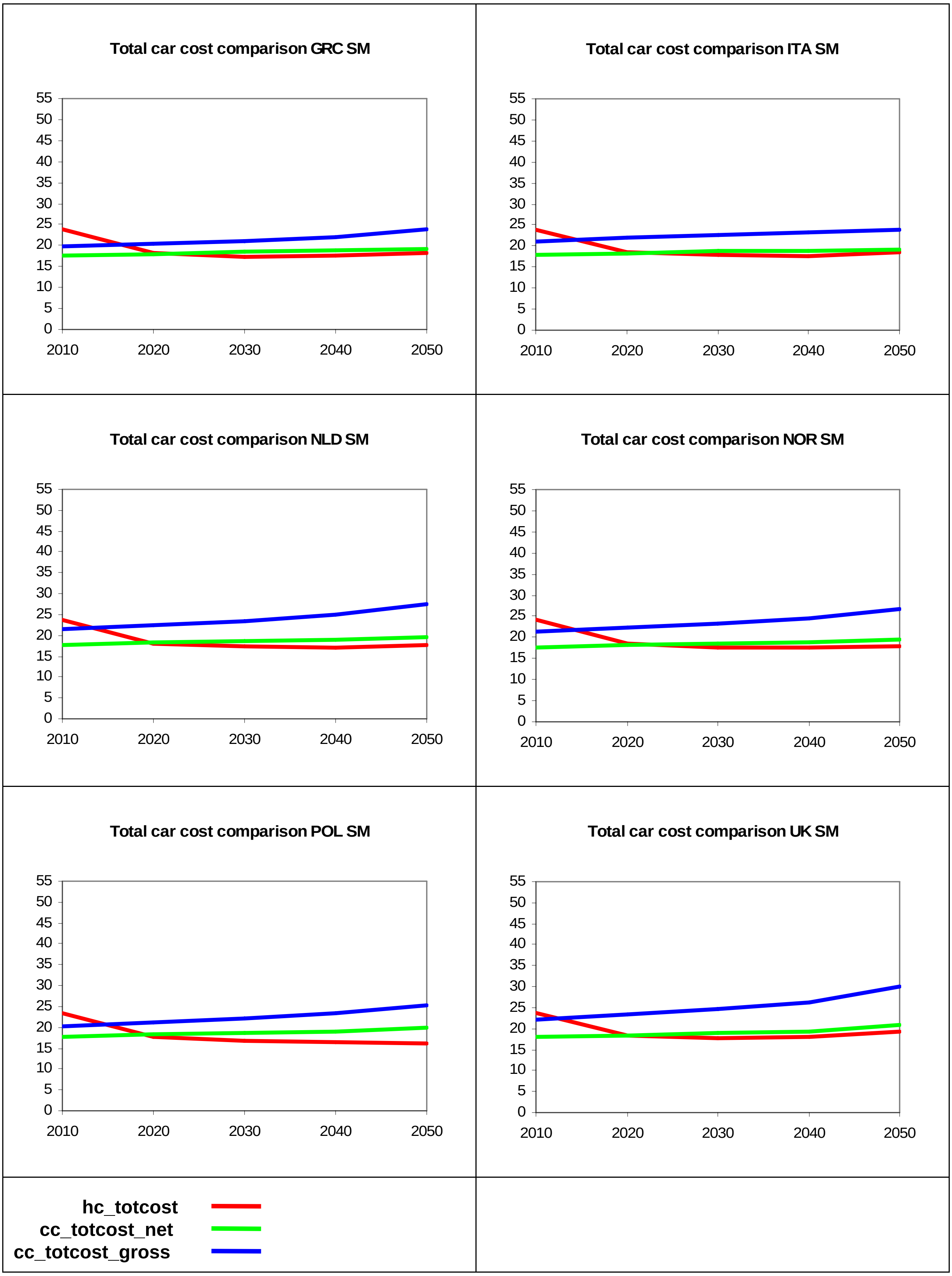
Again we compare the lifetime costs gross and net of taxes for conventional cars with the lifetime costs of hydrogen cars. The general development of the cost curves for medium-sized cars is similar to the cost curves of large cars. Of course the level of costs for medium cars is lower than for large cars in all MS. However, there are several differences compared to the development of costs for large cars. First, lifetime costs for medium hydrogen cars exceed the lifetime costs of conventional cars net of taxes until 2020 in most MS. Thus, while large hydrogen cars are already competitive in 2020, medium hydrogen carsin almost all MS become competitive later, i.e. from 2030 onwards. Exceptions here are Spain, where hydrogen cars are competitive in 2020, and Finland and France, where hydrogen cars do not become competitive before 2040 and 2050, respectively. Second, while in some MS lifetime costs of large hydrogen increased, the costs for medium hydrogen cars decrease over the considered period in most MS (except France). This shows the much lower and decreasing fuel demand of medium cars compared to their large counterparts. Third, the cost difference between hydrogen and conventional cars is much smaller for medium cars than for large cars.

The more detailed cost comparison of medium cars is provided in Figure 27 in Annex 7.1. The cost developments have to be interpreted similar to the ones for large cars.

Finally, consider the development of lifetime costs of small cars which is shown in Figure 8.

Figure 8: Cost comparison of small cars





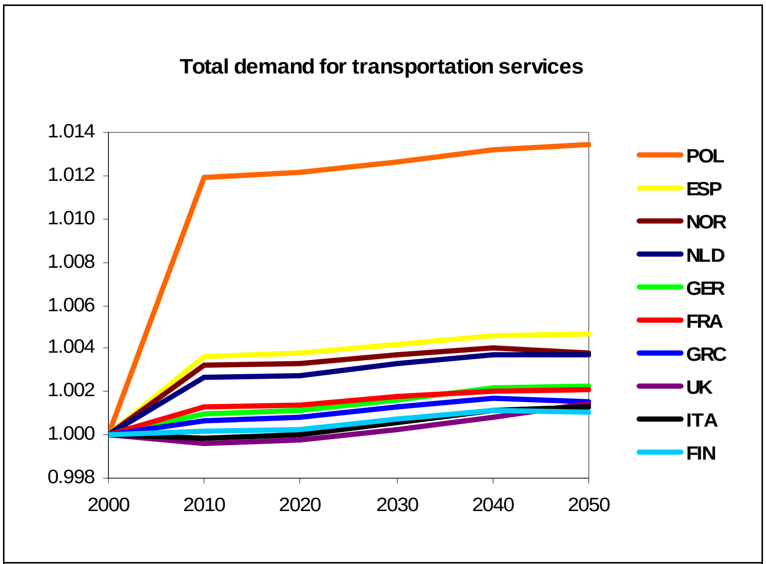
We again compare the paths for the lifetime costs of small hydrogen cars with those of small conventional cars gross and net of taxes. Obviously, lifetime costs of hydrogen cars in 2010 exceed those of conventional cars (net and gross of taxes) in all ten MS. This finding impressively shows the initial high costs of hydrogen production. From 2030 onwards hydrogen car lifetime costs are below the conventional car lifetime costs net of taxes, i.e. they become competitive in all MS (small hydrogen cars in the Netherlands, Spain and Poland are already competitive in 2020). Note however the very small cost difference between hydrogen and conventional cars which indicates only modest cost savings potentials from the introduction of the hydrogen technology. The detailed cost comparison of small cars is given in Figure 28 in Annex 7.1.

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.

4.1.3 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 with 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 has very different effects on transport demand. While almost all MS experience an increase in transport demand compared to the baseline, it temporarily decreases in Italy and the United Kingdom. The level of changes is however rather small. The largest increase in demand for transportation services occurs in Poland where transport demand in 2050 exceeds the baseline value by approximately 1.3 percent. In contrast, transport demand in Finland increases the least, by 0.1 percent in 2050 relative to the baseline. The other MS range in between these two extremes.

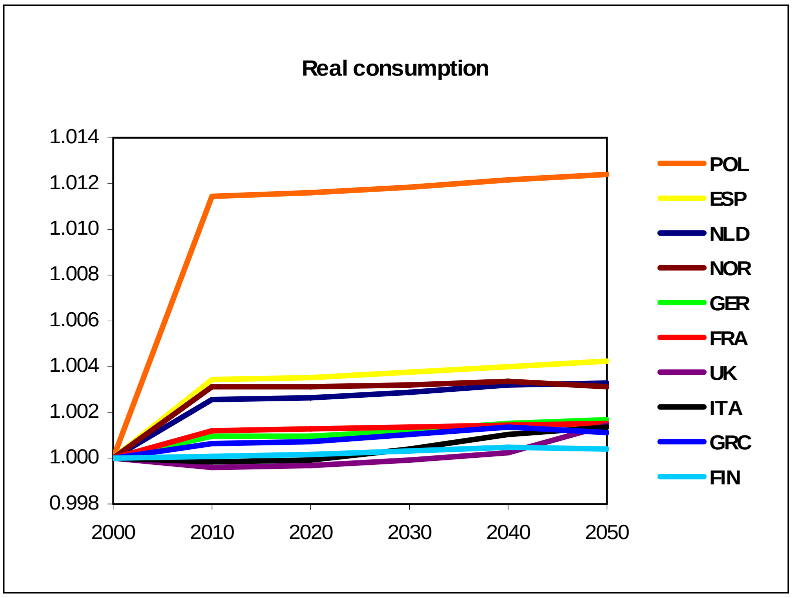
Transport demand is primarily determined by the budget of the representative consumer and the price for transportation services. Since penetration rates are introduced such that the total lifetime costs of the cars per size category, period and MS are the same in the baseline and the scenarios, the overall 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 or increase over time depending mainly on the development of hydrogen fuel costs (see explanation above). If the average lifetime costs of hydrogen cars fall short of those of conventional cars (excluding taxes), additional resources are released which lead to an increase in the representative consumer's budget. These additional resources can be assigned to other uses. If however lifetime costs of hydrogen cars exceed those of conventional cars (excluding taxes), the representative consumer's budget is lowered which results in lower demand.

It is furthermore important to note that transport demand is already affected from 2010 onwards, although hydrogen cars are not introduced 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 or lower in later periods (compared to the baseline). Therefore he already can spend more or less money for transportation services (than in the baseline) in earlier periods.

These interrelations explain the country-specific developments of demand for transportation services. In countries like Poland, Spain, Norway and the Netherlands transportation demand increases since they reveal the largest cost savings potentials with the introduction of hydrogen cars which affects the consumer's budget positively. In Germany and Greece the budget of the representative consumer experiences only moderate changes which automatically translates into smaller increases in transport demand. The temporary decline in demand for transportation services in Finland, Italy and Poland is due to the fact that the consumer anticipates already in earlier periods that lifetime costs for large hydrogen cars exceed those of conventional cars in 2050. At the same time, the cost savings in the other size categories are largest around 2040/2050. As a consequence the consumer reduces its transportation demand in earlier periods to gain the largest cost savings in later periods and to compensate for the losses in the large car segment. One issue is worth mentioning. On first sight it seems surprising that transportation demand in France increases over time given the relatively large cost disadvantage of large hydrogen cars. Here one has to bear in mind that hydrogen penetration rates of large cars are zero in all years except 2020. Thus the consumer's budget is hardly affected by the cost developments of large cars in France.

The impact of the assumed scenario on real consumption is very similar to transport demand. Real consumption will increase (decrease) if the budget of the representative consumer increases (decreases) 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 or lowers 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



As Figure 10 indicates, the shapes as well as 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 change in real consumption. Moreover, the cost saving potential is largest for large cars since these cars need more fuel than small and medium cars. As a consequence, fuel cost savings are higher for large cars. The differences in penetration rates are also important determinants since they indicate how much of the cost advantages (disadvantages) become active in each period.

Poland experiences the largest increase in real consumption of approximately 1.2 percent in 2050 (compared to the respective baseline value) with the introduction of hydrogen technologies. This is mainly due to low hydrogen fuel costs. In Norway, Spain and the Netherlands real consumption also increases. This reflects the relatively large cost saving potential with the introduction of hydrogen cars in the three countries. Comparable to the development of transportation demand, Greece, Finland, France and Germany experience an only small rise in real consumption. Finally, in Italy and the United Kingdom real consumption temporarily decreases compared to the baseline but slightly exceeds its baseline values in 2050. Here the explanation is the same as for the demand for transportation services. The representative consumer anticipates the higher lifetime costs for large hydrogen cars and the high cost savings potential in the small and medium size class in the future and therefore temporarily reduces consumption demand.

Table 1 reports social welfare of introducing hydrogen in the transport sector for each MS. Social welfare is thereby defined as a weighted average of real consumption.

Table 1: Social welfare

Country	**Increase/Decrease in %**
Finland	0.027
France	0.131
Germany	0.128
Greece	0.093
Italy	0.057
Netherlands	0.292
Norway	0.314
Spain	0.381
Poland	1.192
United Kingdom	0.036

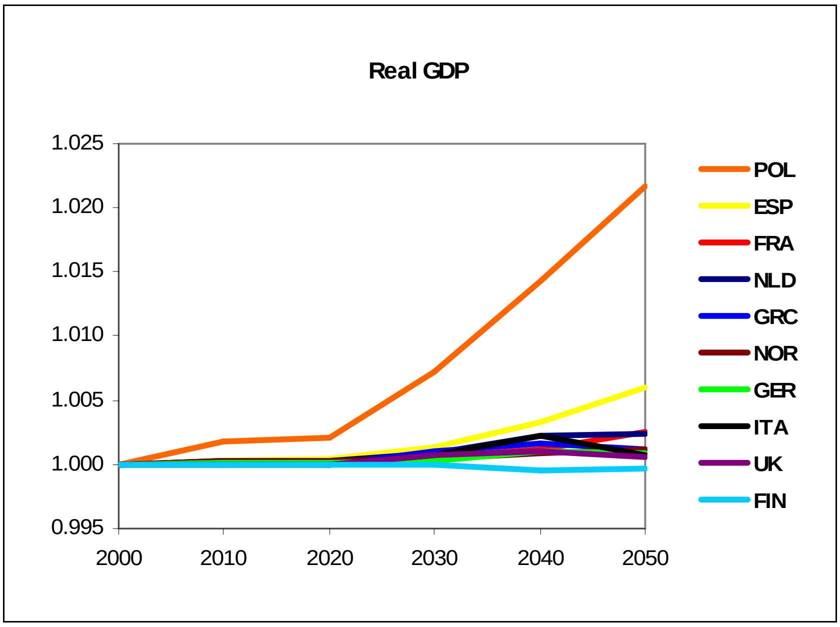
The reported changes in social welfare are rather low. All MS experience welfare gains with the introduction of hydrogen cars. This is the consequence of the possibility to have a more efficient transport system (cars with lower lifetime costs net of taxes for most of the considered period). Of course, the values reflect the findings already discussed before. Real consumption increases the most in Poland (see Figure 10) and thus the increase in social welfare is the largest among all MS. In contrast, real consumption in the United Kingdom temporarily decreases. This decline is the largest among all MS. Consequently, the increase in social welfare is the smallest across all considered countries. The other MS range in between these two extremes depending on the increase (or decrease) in real consumption over the period.

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 in most MS 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 hydrogen penetration rates rise remarkably in all MS (except for large cars in France). At the same time, most MS experience a decrease of total lifetime costs of hydrogen cars (net of taxes) which even fall short of those of conventional cars. 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. There is however one exception. GDP in Finland is slightly reduced over time since lifetime costs for large and medium hydrogen cars exceed those of their conventional counterparts over almost the whole considered period.

Similar to the development of consumption demand, the effects of the introduction of hydrogen on GDP are very modest. GDP in Spain is expected to exceed the year-2050 baseline value by almost 0.6 percent, whereas GDP in the other MS increases between 0.05 and 0.26 percent. The GDP loss in Finland amounts to less than 0.03 percent.

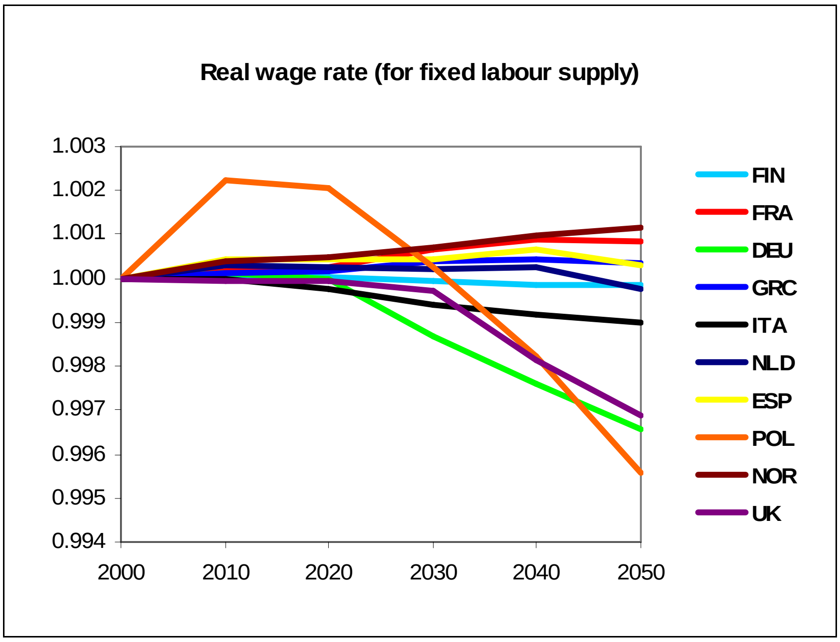
Note the relatively large positive GDP effects in Poland (compared to the other MS) which amount to 2.2 percent in 2050. On first sight this might be surprising. The reason for the larger changes is twofold. On the one hand, hydrogen fuel costs are the cheapest among all MS. Thus lifetime costs of hydrogen cars decline over time and release a growing cost savings potential with the introduction of hydrogen. This yields relatively large changes in transportation demand and real consumption which has positive effects on GDP already in 2010 (note that due to consumption smoothing real consumption already increases in 2010). On the other hand, GDP in Poland is much smaller than e.g. in France, Germany, Italy or Spain. As a consequence, relative changes compared to the baseline are relatively larger compared to other countries.

Figure 11: Real GDP



Finally, Figure 12 shows the development of real wages in the six MS. These wage changes are again very small and therefore hardly account to any of the welfare changes reported in Table 1. The simulated welfare gains are rather due to the cost changes associated with the introduction of the hydrogen technology.

Figure 12: Real wage rate



Almost all MS experience small wage increases over the considered period compared to the baseline. Exceptions are Germany, Italy and the United Kingdom, where wages slightly decrease, and Poland where wages initially increase and decrease after 2030 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. An increasing (decreasing) wage is related to an increasing (falling) “relative” demand for labour in the whole production system and thus cannot be traced back to a single reason. But the observed developments can be traced back to basically two effects. On the one hand, introducing the (for the most part) cheaper hydrogen technology into the market leads to a wealth effect that raises GDP and wages. On the other hand, a strong increase in efficiency in the transport sector by the introduction of hydrogen cars as in Germany, Italy, Poland and the United Kingdom shifts consumer’s demand from the labour-intensive consumption good sector to the less labour-intensive transport sector. This leads to lower demand for labour and thus reduced wages.

To conclude, the introduction of hydrogen in the transport sector has very different effects in the MS depending on the development of fossil fuel prices and the costs of hydrogen as well as conventional cars. The qualitative developments of the changes are very similar across the MS whereas the quantitative effects are not. This becomes obvious when comparing the levels of changes in macroeconomic variables between the single MS. These differences can be explained inter alia by diverse hydrogen production costs and penetration rates in the considered regions.

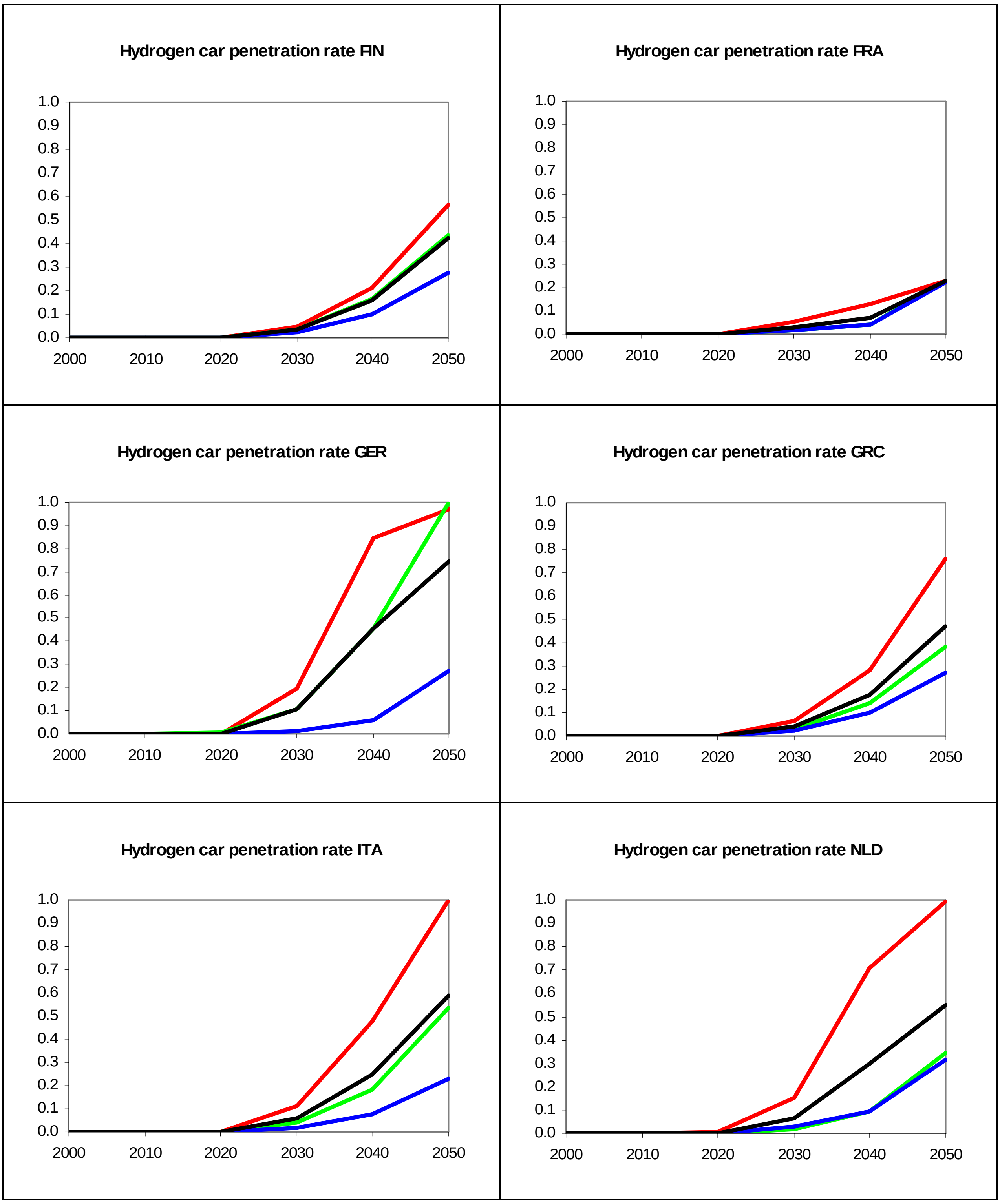
4.2 Low hydrogen penetration (L2L)

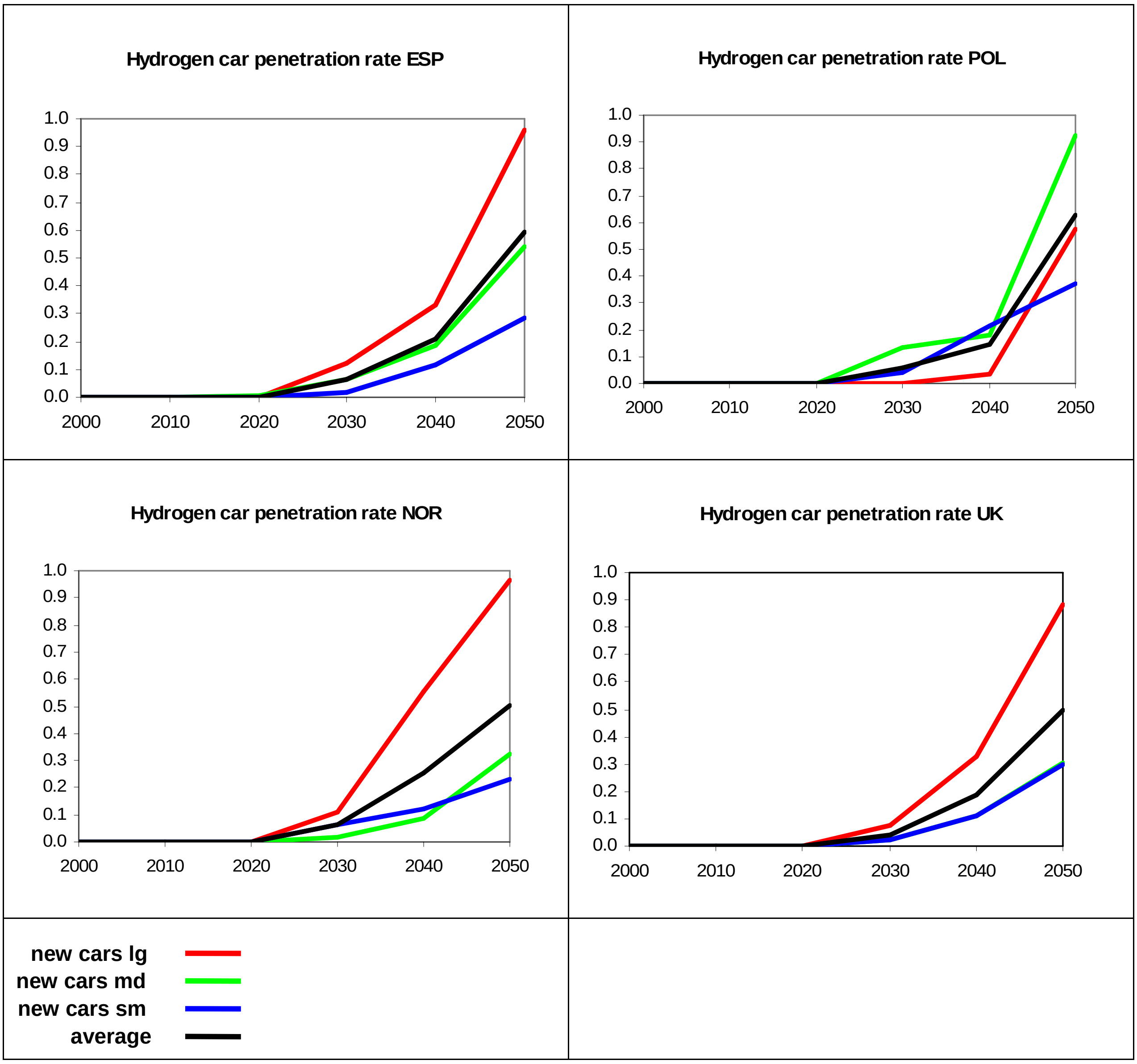
Now we turn to a scenario where we assume low hydrogen penetration rates and low technological progress (L2L). The difference to the analysis of the high penetration rate scenario in section 4.1 is the implementation of lower penetration rates and the assumptions of a smaller cost decrease of hydrogen fuelled cars.

4.2.1 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 L2L 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

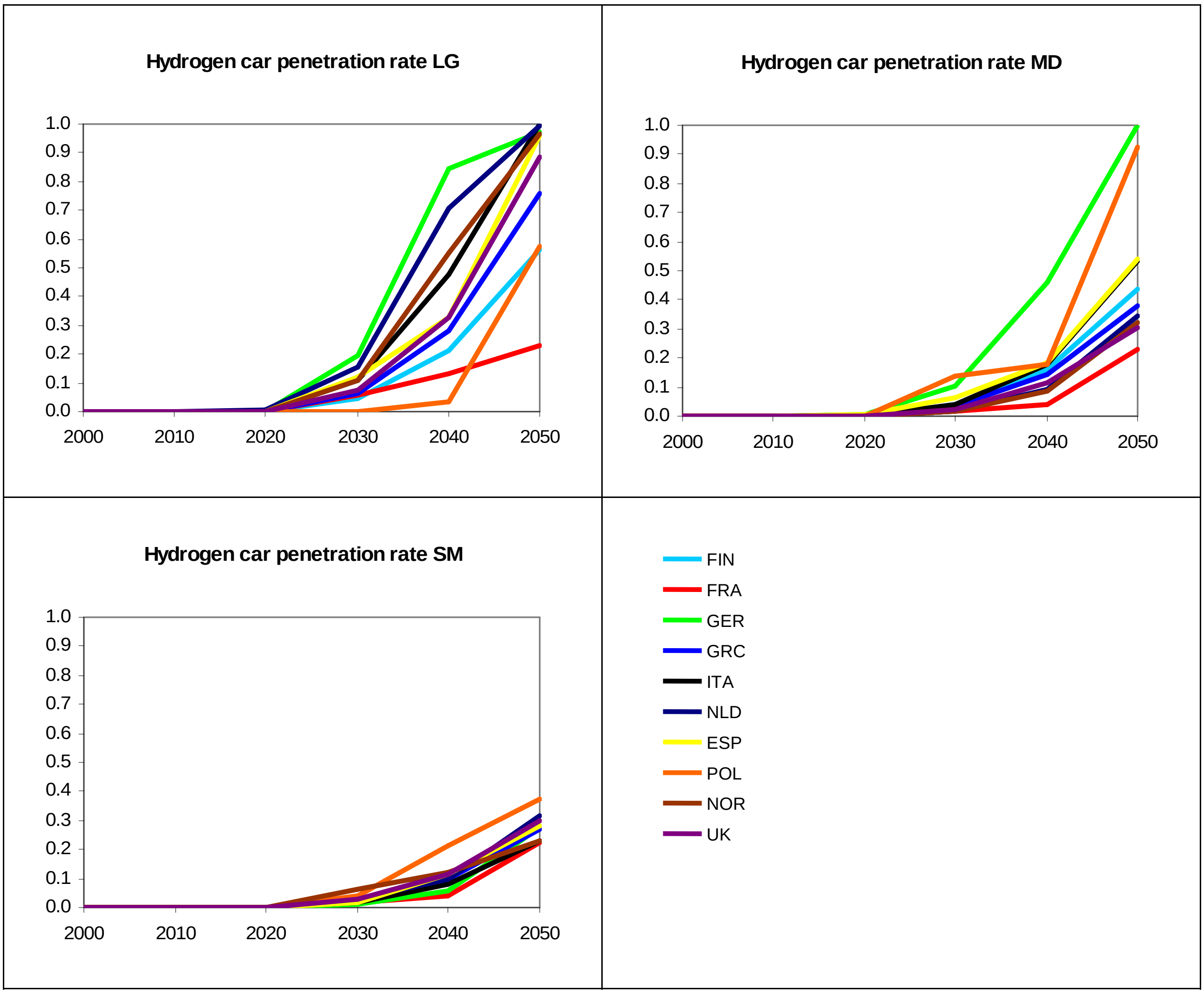




As the name of the considered scenario already indicates, penetration rates are now lower than in the H2H scenario. Stated differently, compared to the H2H scenario the same levels of hydrogen penetration are reached in later periods: Hydrogen cars start to penetrate the car markets from 2020 onwards only. Comparing different MS we observe large differences in penetration: The average share of H2 cars in 2050 varies from 19% in France to 71% in Germany. 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. By 2050 they reach around 20 % in all countries except Poland, where their share climbs to 28 %. Penetration rates for large cars are – with the exception of France - much higher: In most countries they go up to over 50% in 2050, in Germany, Italy, Spain, Norway and the Netherlands they reach around 100%. Poland is an exception in that here middle sized H2 cars are more successful than large cars – everywhere else penetration rates of middle-sized cars lie in between those of small and large cars.

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



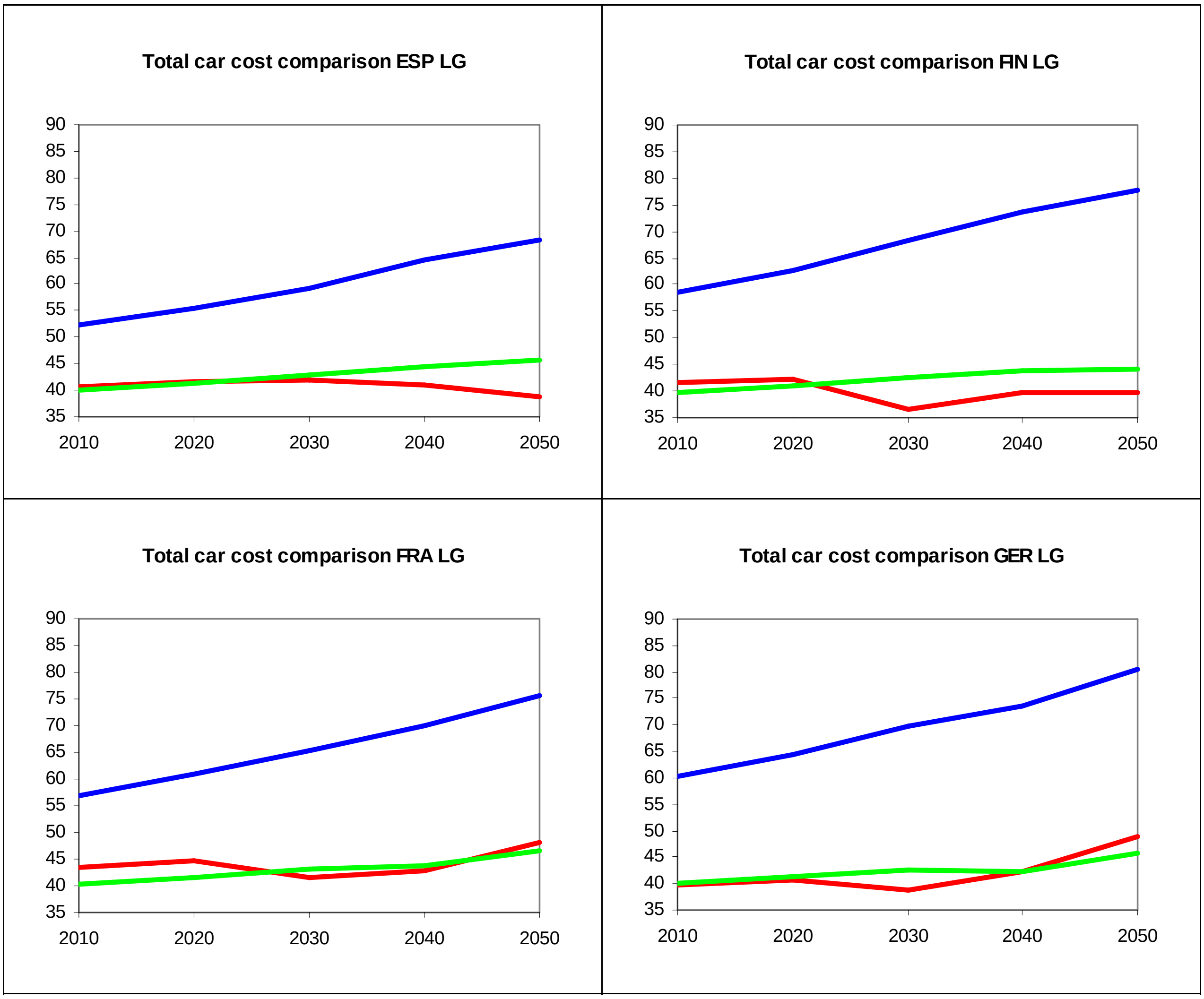
The comparison of penetration rates in MS by car category shows the large variation of penetration rates for large and middle-sized cars (between roughly 20% and 100%), whereas the variation in the case of small cars is moderate. Again we see that France is the country with the lowest penetration rates by far in all size categories. Germany and Poland are the only countries that reach full penetration for middle-sized cars in 2050, in most countries the rate lies between one third and half of all cars.

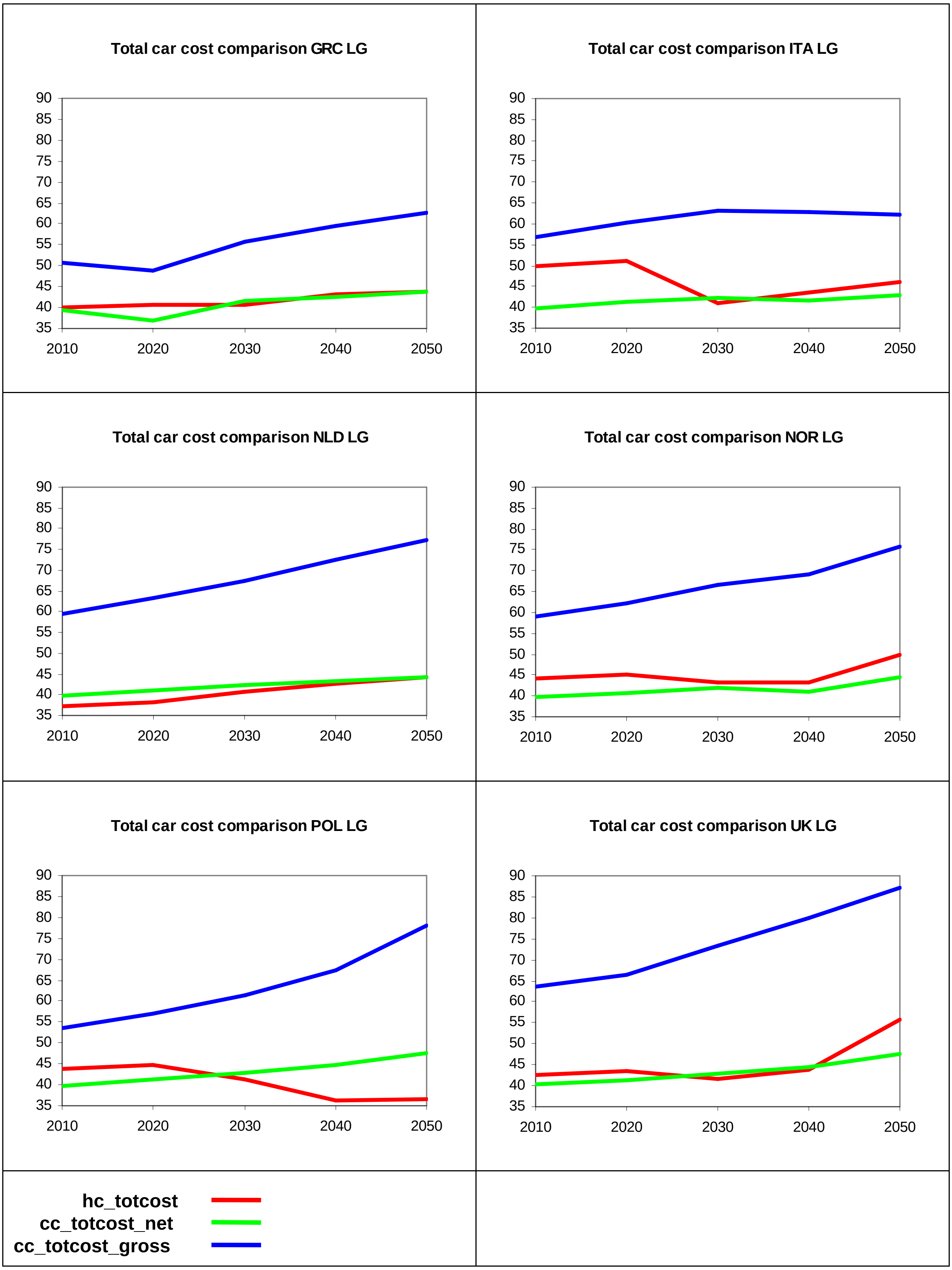
4.2.2 Cost comparison

The costs of the different conventional car categories are equal in both the H2H and the L2L scenario. However, hydrogen car prices in the L2L scenario deviate from the H2H scenario. As explained in Section 5.2, both a lower learning curve and lower penetration rates lead to a slower cost reduction of hydrogen cars. Take for example the price of a large-sized hydrogen car in Spain in 2020. In the H2H scenario the producer price amounts to 22,450 Euro while it is still 26,500 Euro in the L2L scenario.

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 L2L scenario.

Figure 15: Cost comparison of large cars





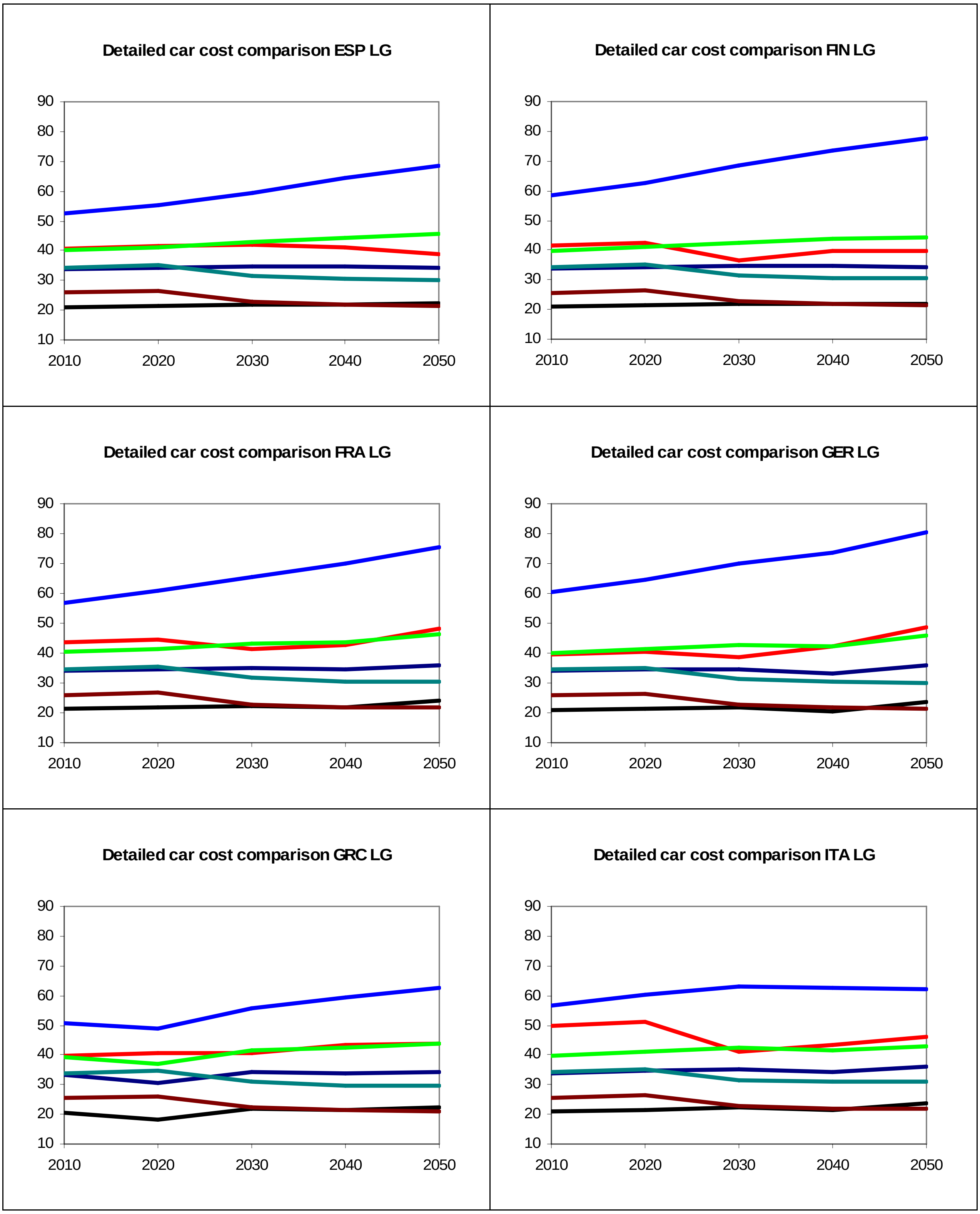
With low penetration rates, large hydrogen cars are cost competitive by 2030 (or before) on (hc_totcost is below the respective cc_totcost_net) in most countries, in Spain and Germany they reach this stage in 2020 already. The exception is Norway, where net costs of large hydrogen cars exceed that of conventional cars until 2050. In the UK and Italy hydrogen cars loose their competitiveness after 2040 – this reflects steeply increasing fuel costs for hydrogen. So slower technological learning and reduced production of hydrogen cars in advance (before hydrogen becomes competitive) still results in a cost decrease that is large enough to make the hydrogen technology become competitive quite in most countries by 2030. Generally cost differences between conventional and hydrogen cars are small after that year: They do not exceed 15%, being below 5% most of the time (with the exception of Poland, where large hydrogen cars are more than 20% cheaper than conventional cars in 2050). When the consumer chooses between a large hydrogen car and a large conventional one, 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.

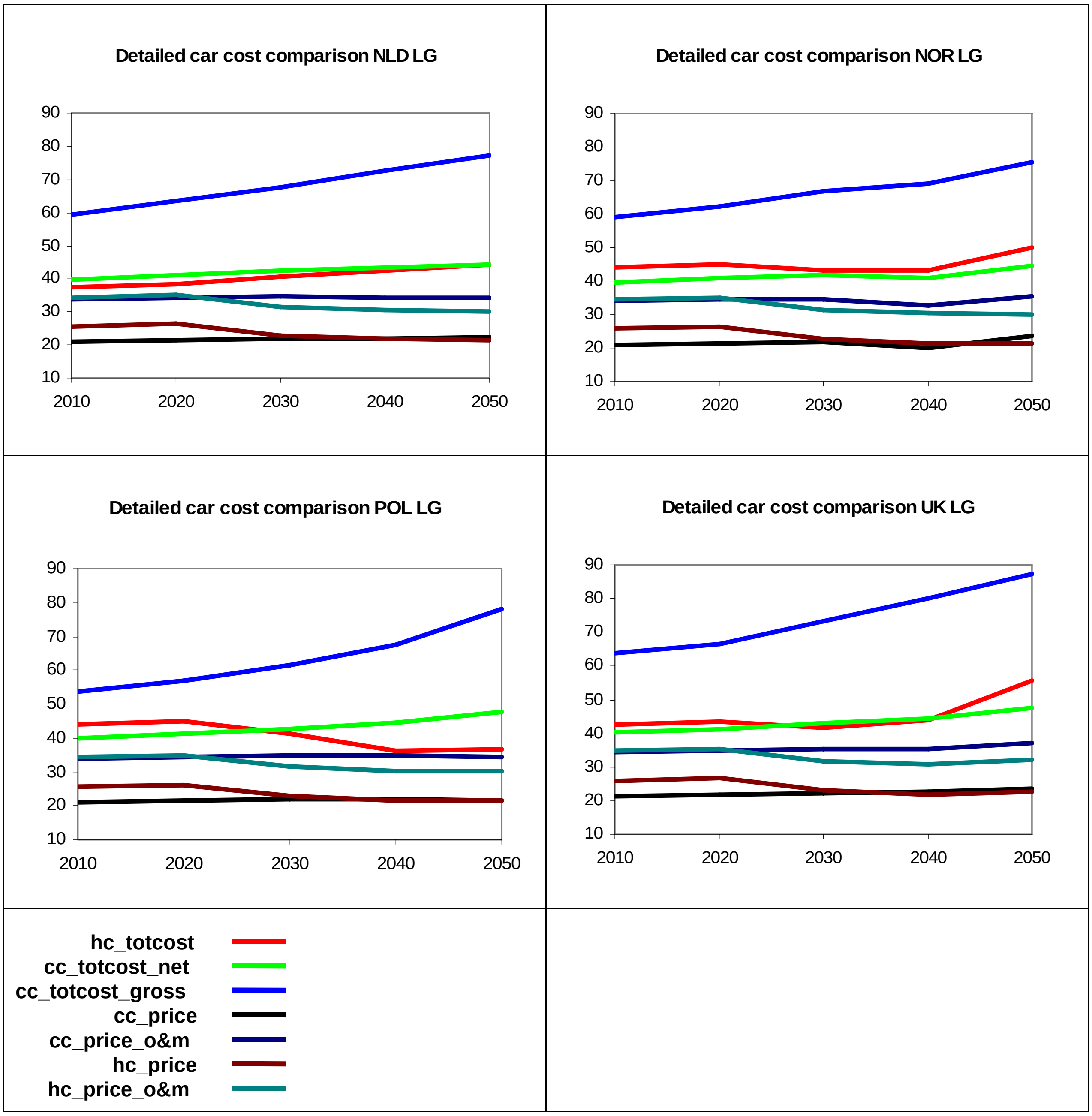
A more detailed comparison of the lifetime costs of large hydrogen and conventional cars is given in Figure 16.

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 in most countries from 2030 on. The decline of producer costs can be observed 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, and they may even increase over time. 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.

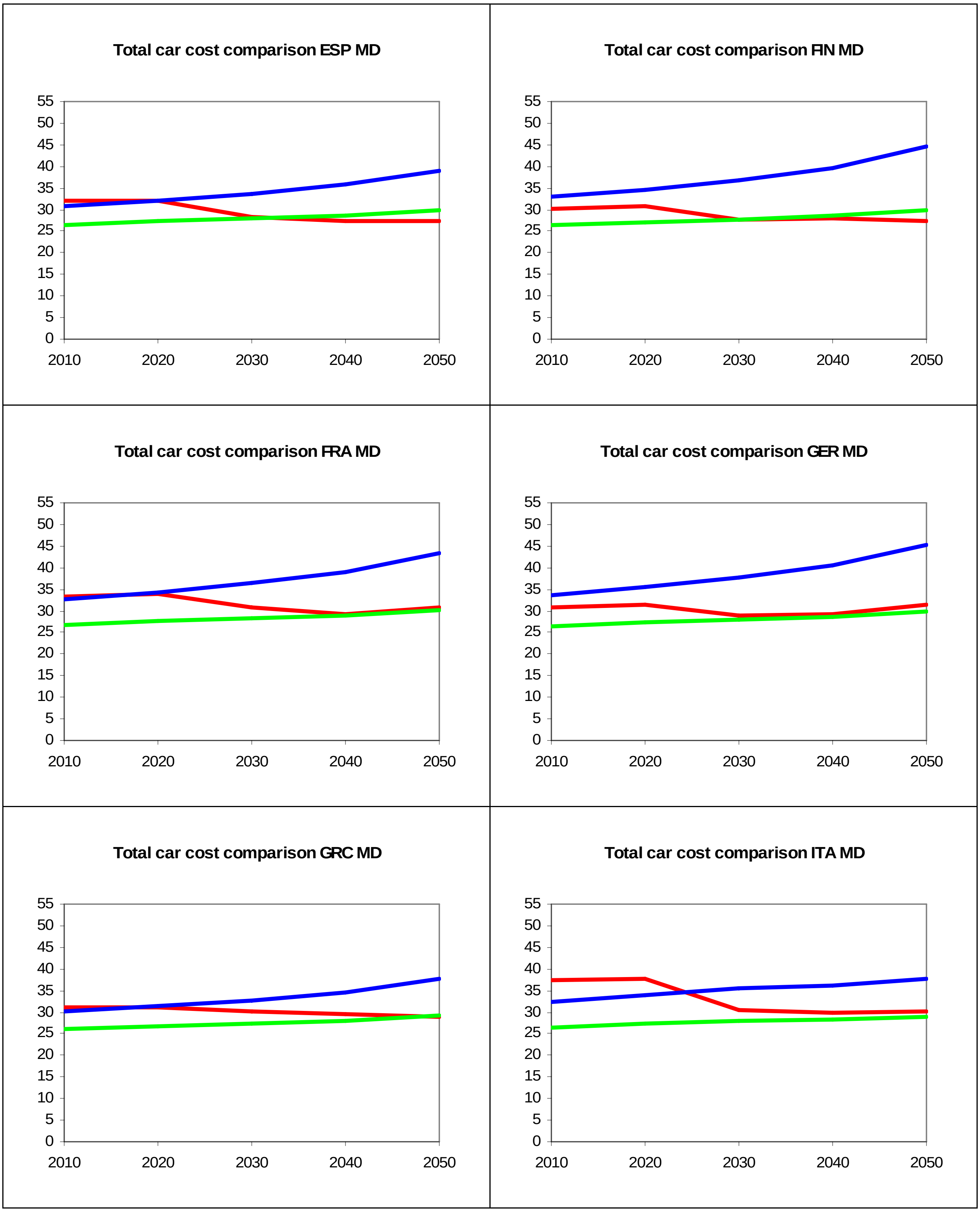
Figure 16: Detailed cost comparison of large cars

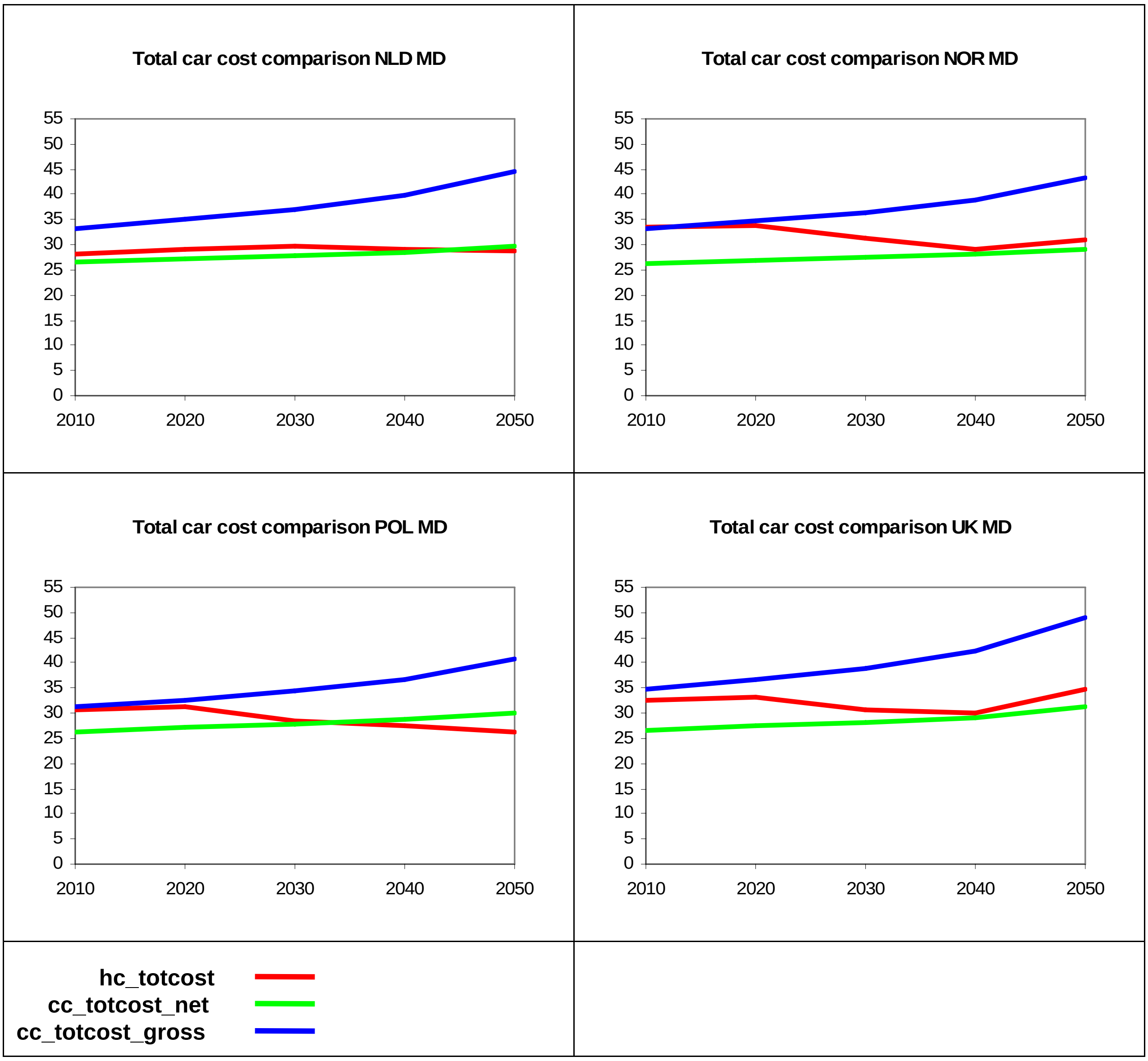




Now we turn to the cost comparison of medium-sized cars as provided in Figure 17.

Figure 17: Cost comparison of medium cars



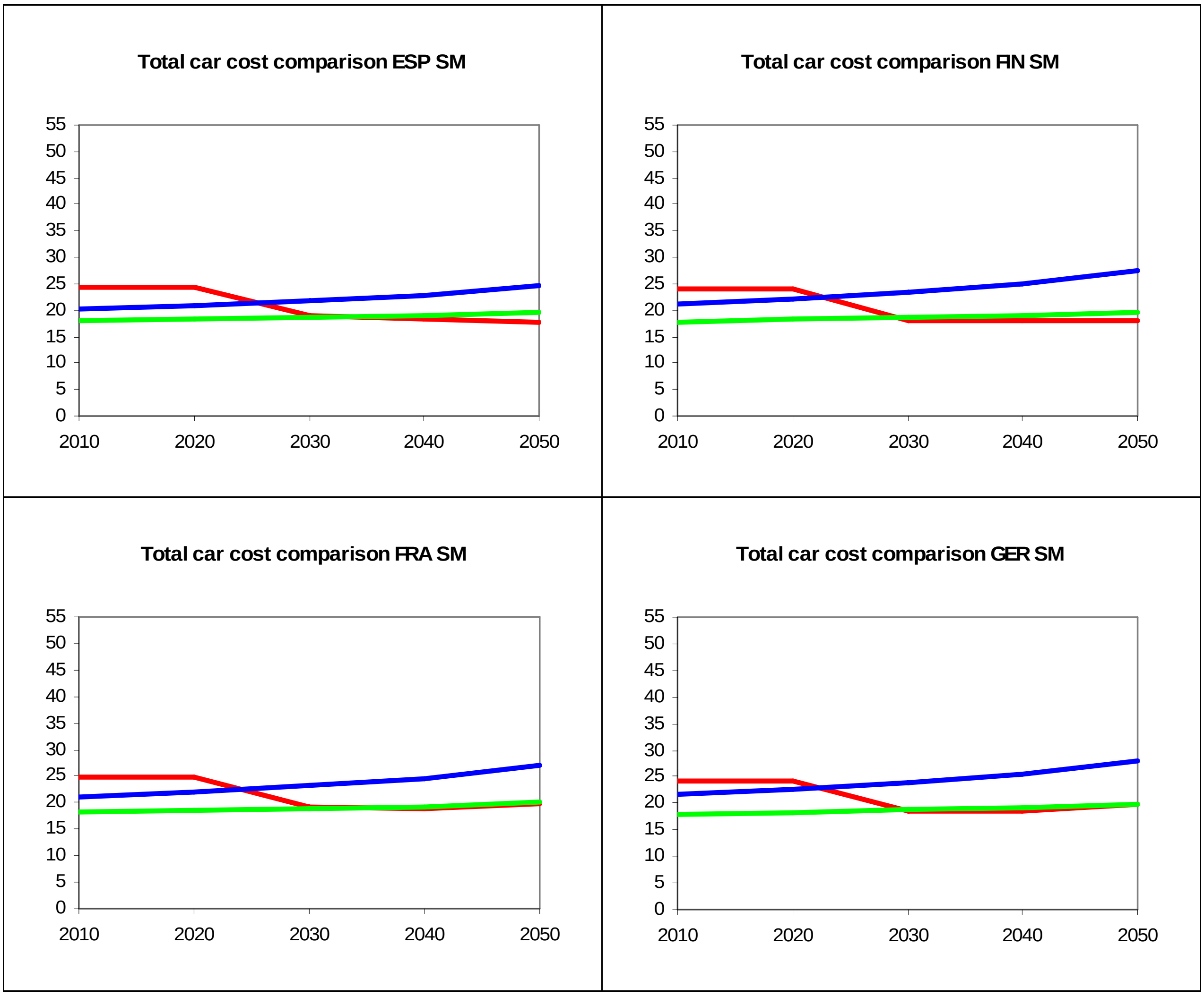


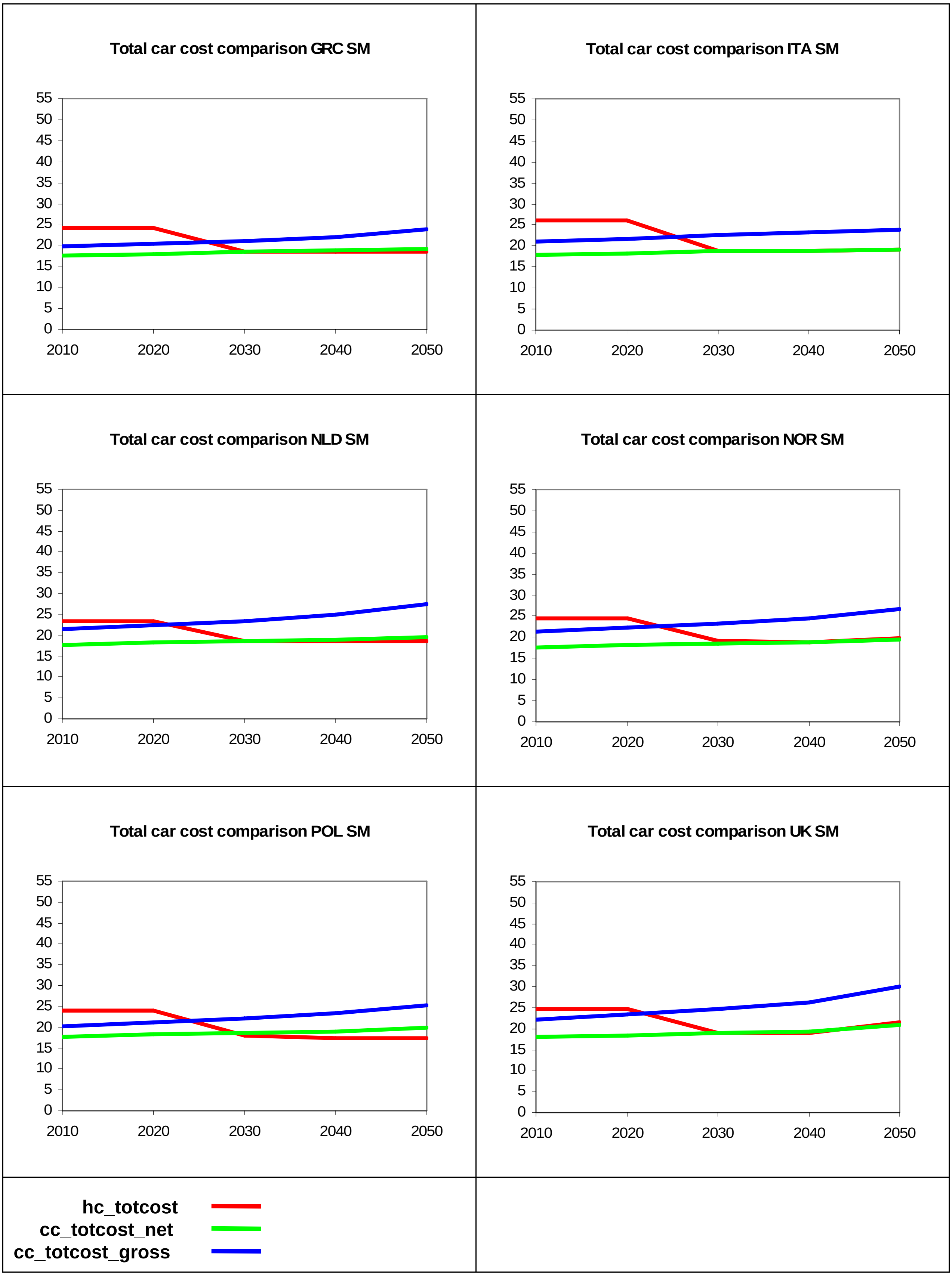
In Figure 17 we see that for medium sized cars the difference between the H2H and the L2L are significant: While in the H2H scenario medium-sized hydrogen cars become cost competitive from 2020 on, they do not become competitive before 2040 in any country, in France, Germany, Italy, Norway and the UK they do not become competitive at all. In Greece and the Netherlands they become competitive only in 2050. The reason is of course the slower decrease of producer costs for hydrogen cars due to a slower learning curve and the reduced penetration rates. The initial costs for medium hydrogen cars in 2010 are almost identical between the H2H and the L2L 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 and slower learning in the L2L scenario and thus a smaller cost decrease of hydrogen cars prevail. It should be noted, however, that differences of costs for hydrogen cars between the scenarios disappear over time: By 2050, lifetime costs for medium-sized hydrogen cars are slightly above 25.000 Euros in all countries and in both scenarios. The detailed cost comparison for medium cars is given in Figure 29 in Annex 7.2. 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 in the cases of large and medium-sized cars, small hydrogen cars also become competitive later than in the H2H scenario. In the L2L scenario, the total lifetime costs of small hydrogen cars (hc_totcost) are below or equal the respective costs of conventional cars net of taxes (cc_totcost_net) from 2030 on (the exception is Norway). From 2010 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





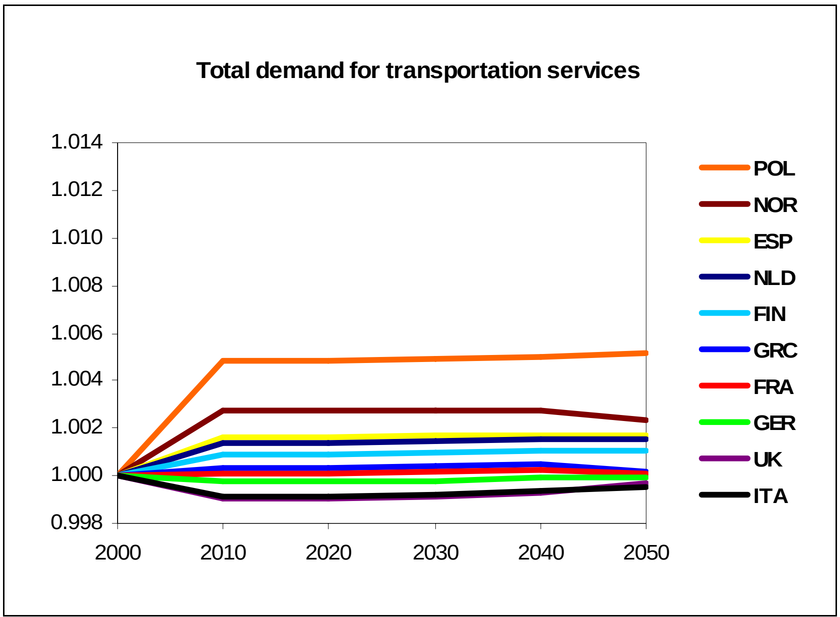
The detailed cost comparison of small cars is shown in Figure 30 in Annex 7.2.

These explanations should suffice to highlight the differences between the H2H and the L2L scenario. We now turn to the impact of lower penetration rates on transport demand, real consumption, welfare, GDP, and the wage rate.

4.2.3 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

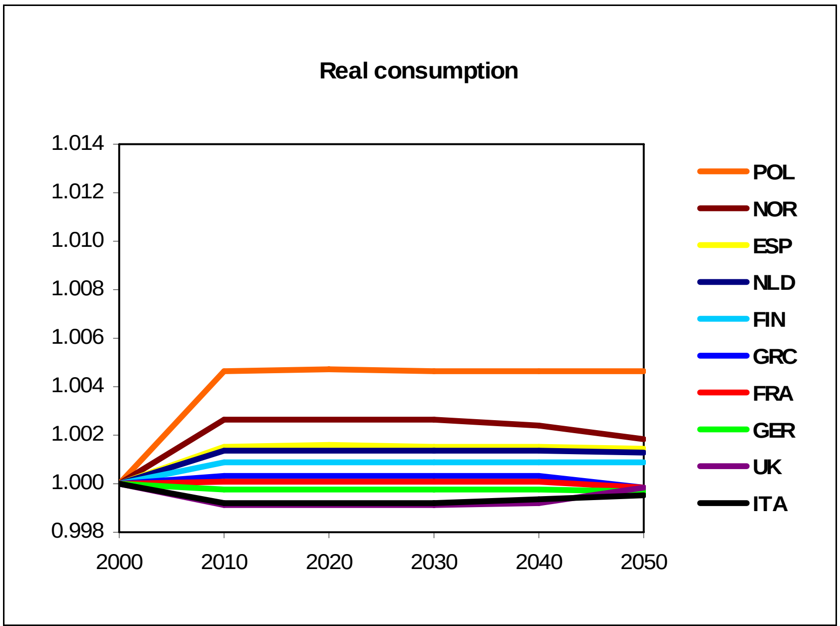


Comparable to the H2H scenario, transport demand increases in most countries with respect to the baseline –albeit to a lesser extend - (Poland, Norway, Spain, Netherlands, Finland) or remains (almost) flat (Greece, France, Germany, UK, Italy). In the latter countries temporary demand losses can be observed on the transition path. The mechanism behind this development is exactly the same as in the H2H scenario: In countries with increases in transport demand, constant transport prices together with an increasing budget of the representative consumer lead to a rise in transport demand. In contrast, temporary losses in some other countries reflect higher costs for hydrogen than for conventional technology (compare the previous paragraph). The penetration of hydrogen cars thus increases costs of transport services and thus reduces the consumer's budget. All changes in the L2L scenario are remarkably smaller than in the H2H case. The largest increase occurs in Poland where transport demand in 2050 exceeds the respective baseline values by approximately 0.5 percent. Norway, Spain and the Netherlands experience an increase of transport demand of 0.2 percent, Finland of 0.1 percent. Temporary losses are worst in Italy, but never exceed 0.1 percent.

The development of transport demand in Poland 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 L2L scenario. This finding in Poland 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 (in Poland, Norway, Spain, Netherlands, Finland) is reflected by a higher budget of the representative consumer. This in turn increases real consumption compared to the baseline. On the other hand, temporary consumption losses (most notably in Italy) reflect increases in the penetration of costly hydrogen cars, reducing the consumer's budget. 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 most in Poland (0.4 percent). Norway, Spain, the Netherlands and Finland experience a modest increase (between 0.1 and 0.2 percent), while long-term changes in Greece, France, Germany, the UK and Italy are negligible. Only Italy experiences a noticeable temporary consumption loss of 0.1 percent.

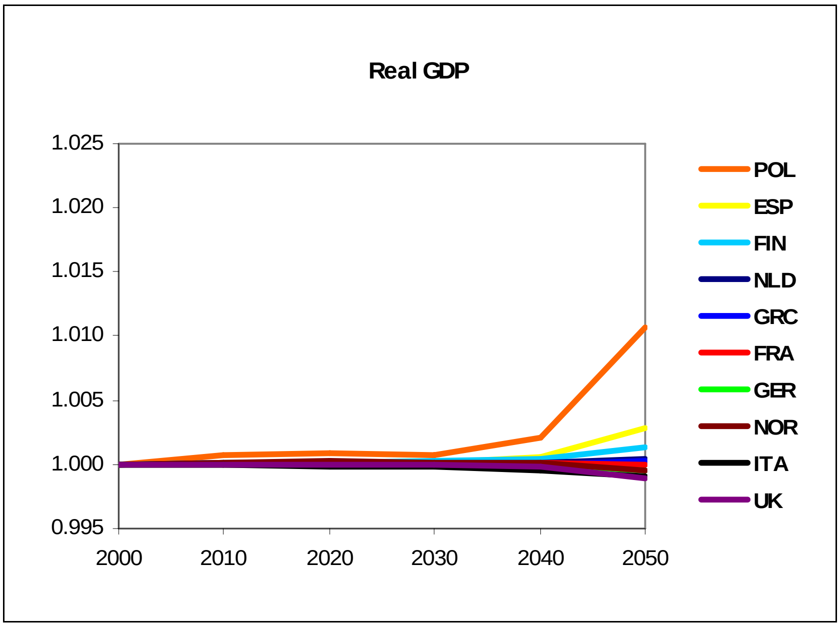
We now turn to the welfare effects of the H2L scenario as reported in Table 4. Again social welfare is calculated as a weighted average of real consumption. The results are no surprise and reflect the previous ones: Welfare effects are rather small for Poland, Norway, Spain, the Netherlands and Finland and negligible for Greece, France, Germany, the UK and Italy. According to the growth in real consumption, Poland experiences the largest welfare gains of 0.46 percent while the gains are smallest for France and Greece with 0.002 percent and 0.015 percent, respectively.

Table 2: Social welfare

Country	**Increase/Decrease in %**
Finland	0.085
France	-0.002
Germany	-0.029
Greece	0.015
Italy	-0.070
Netherlands	0.132
Norway	0.233
Spain	0.150
Poland	0.462
United Kingdom	-0.066

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

Figure 21: Real GDP



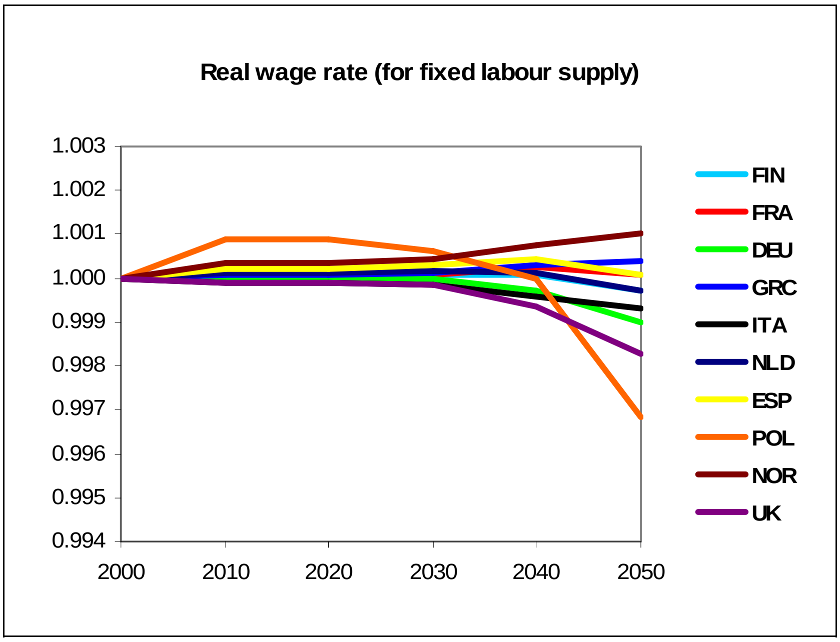
As expected, the development of GDP is again similar to the H2H scenario. The changes compared to the baseline are rather small. Until 2030, GDP develops almost the same as in the baseline in all ten MS. From 2040 on, GDP increases in Poland, Spain and Finland. The rise is by far the largest in Poland, where GDP in 2050 exceeds the baseline value by a remarkable 1.1 percent. In the Netherlands, Greece, France and Germany GDP remains roughly the same as in the baseline. In Norway, Italy and the UK it drops by 0.1 percent. Again, the two essential factors causing the increase in GDP are the introduction of hydrogen cars from 2030 on and the relative cost development of hydrogen and conventional cars.

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

As in the H2H scenario, the introduction of hydrogen technology has an impact on wages as well. We observe considerable losses with respect to the baseline case in Poland and the UK (0.3 and 0.2 percent by 2050) and some losses in Italy and Germany (0.1 percent by 2050). Norway experiences an increase in wages by 0.1 percent. Two effects occur: A wealth effect and a sectoral effect. As for the former, introducing expensive hydrogen technology into the market reduces the efficiency, leading to lower GDP and lower wages. As for the latter, a strong increase in efficiency in the transport sector by the introduction of hydrogen cars as in Poland shifts consumer's demand from the labour-intensive consumption good sector to the less labour-intensive transport sector, depressing the demand for labour and thus depressing wages.

To conclude, the effects of lower penetration rates on transport demand, real consumption, welfare, and GDP are slightly positive for half of the MS in our analysis (Poland, Norway, Spain, Netherlands, Finland) and negligible for the other half, at least in the long-run (Greece, France, Germany, UK, Italy). The development over time is 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 results presented above suggests, the effects in the H2L scenario are smaller than in the H2H scenario.

Figure 22: Real wage rate



4.3 Medium hydrogen penetration (H2M)

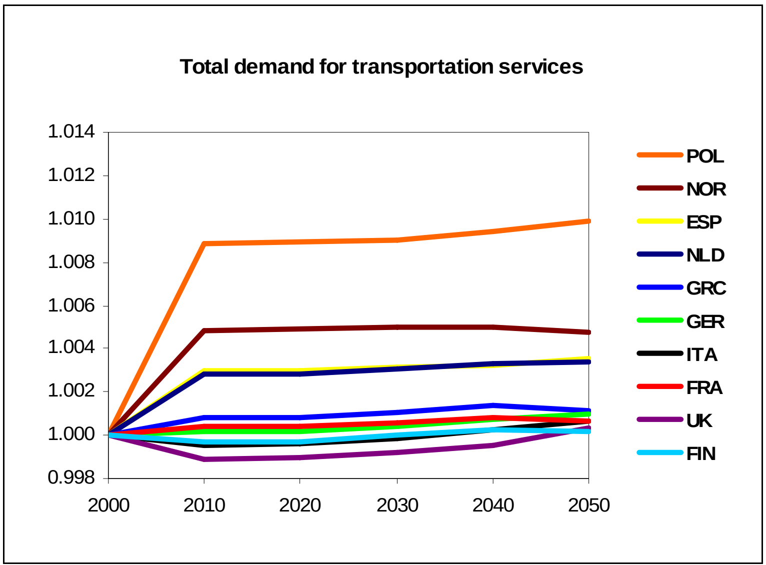
This section discusses a scenario which is in the middle between the two previous scenarios. While the H2H scenario assumed high penetration rates and a steep learning curve, hydrogen penetration in the L2L scenario is low and the learning curve is more moderate. The H2M scenario considered now implements the same steep learning curve as in the H2H scenario but slightly reduced hydrogen penetration rates. The paths and levels of hydrogen penetration rates in the H2M scenario are however very close to the H2H scenario. We therefore abstract from a the detailed discussion of the development of hydrogen penetration rates in the MS and the different size classes. The reader is referred to Figures 31 and 32 in the Annex 7.3.

As already stated above, even when assuming the same steep leaning curve as in the H2H scenario, the cost decrease for hydrogen cars in the H2M scenario is slower since lower hydrogen penetration rates lead to slower cost reductions of hydrogen cars. As a consequence, the lifetime costs of hydrogen cars are always slightly above those in the H2H scenario. Smaller deviations are due to changes in hydrogen fuel costs. All in all, the development of car lifetime costs is very close to the H2H scenario and the explanations are straightforward to those in the two previous scenarios. Therefore, the cost developments are shown in Figures 33 to 38 in the Annex.

As before, we report the effects of the introduction of hydrogen cars on the macroeconomic variables transportation demand, real consumption, GDP, wage rates and welfare. From the explanations above it already is obvious that the macroeconomic results will range between those of the H2H scenario and the L2L scenario. However, due to the same assumptions on the learning curve and very similar hydrogen penetration rates, the results of the H2M scenario will be close to the H2H scenario with very similar explanations.

First, consider the development of transportation demand as shown in Figure 23.

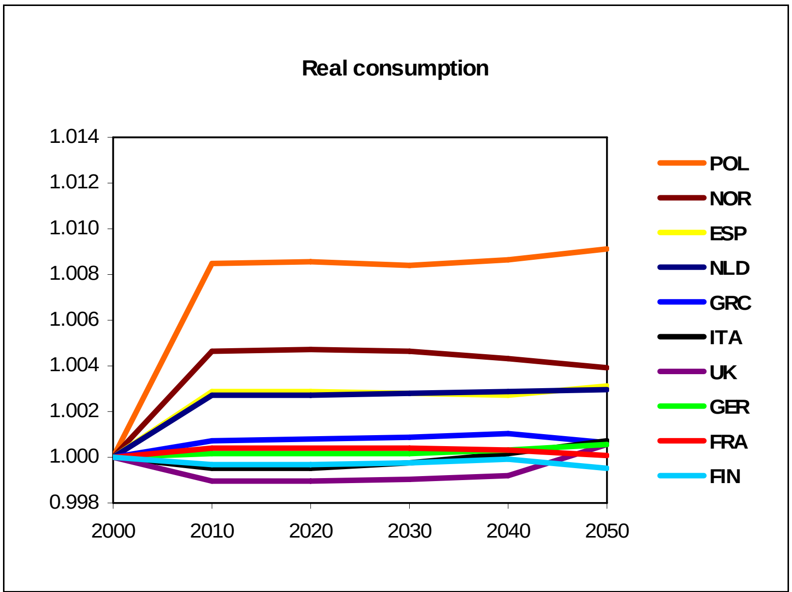
Figure 23: Transport demand



Obviously, the increase in transportation demand is dampened compared to the H2H scenario. The reason is the slower cost reductions of hydrogen cars associated with lower penetration rates and thus smaller changes in the representative consumer's budget. The ranking of countries slightly deviates due to the different developments of hydrogen penetration in the single MS and the specific changes in lifetime costs of hydrogen cars. Now transportation demand in Poland in 2050 is about 1 percent above the respective baseline value. The increases in Norway, the Netherlands and Spain range between 0.3 and 0.5 percent. Similar to the previous findings transportation demand in Greece, Germany and France are very close to the baseline values exceeding those by up to 0.1 percent. Finally, Finland, Italy and the United Kingdom experience temporary declines in transportation demand but in all three countries transportation demand in 2050 is slightly above their baseline values.

The findings for real consumption (see Figure 24) are also not surprising. Similar to the demand for transportation services the deviations from the baseline are dampened compared to the H2H scenario. As a consequence, the year-2050 value for real consumption in Poland in the H2M scenario is 0.9 percent above the baseline value instead of 1.2 percent in the H2H scenario. Consumption demand in Norway is now raised by 0.4 percent and by 0.3 percent in the Netherlands and Spain. Changes in real consumption in France, Germany and Greece are negligible. As before, Italy and the United Kingdom experience temporary decreases in consumption demand. Finland is the only country where real consumption is slightly below the respective baseline values during the whole considered period.

Figure 24: Real consumption



The changes in real consumption are directly reflected in the developments of social welfare as reported in Table 3.

Table 3: Social welfare

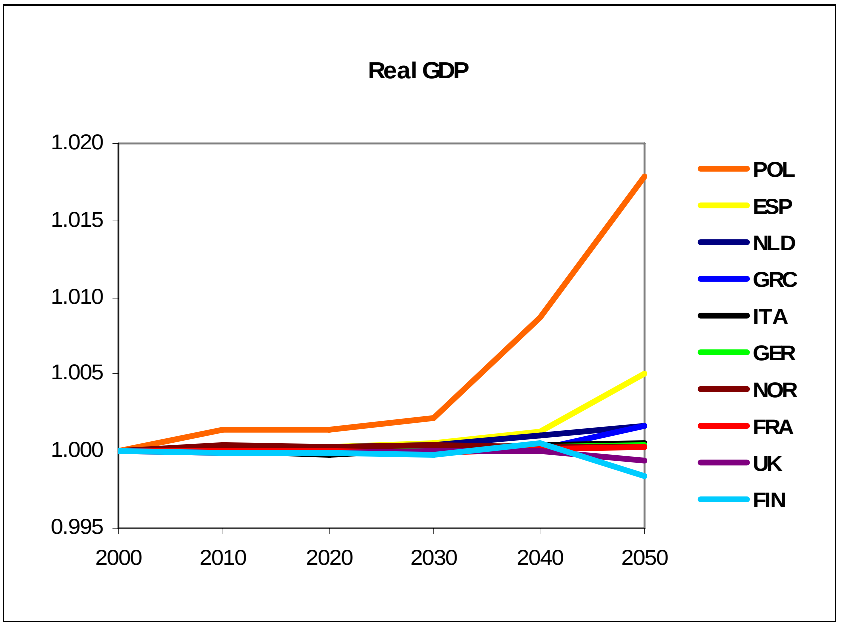
Country	Increase/Decrease in %
Finland	-0.035
France	0.020
Germany	0.029
Greece	0.074

Italy	0.003
Netherlands	0.282
Norway	0.436
Spain	0.289
Poland	0.870
United Kingdom	-0.046

If one looks at Tables 3, it becomes obvious that changes in social welfare are again very small. Most MS experience slightly lower welfare gains compared to scenario H2H. Due to the slower cost decrease of hydrogen cars Finland and the United Kingdom even experience small losses in social welfare. It is also worth mentioning that social welfare in Norway is slightly increased compared to the H2H scenario. This can be explained by substitution and income effects mostly due to the higher equilibrium oil price and hydrogen car costs.

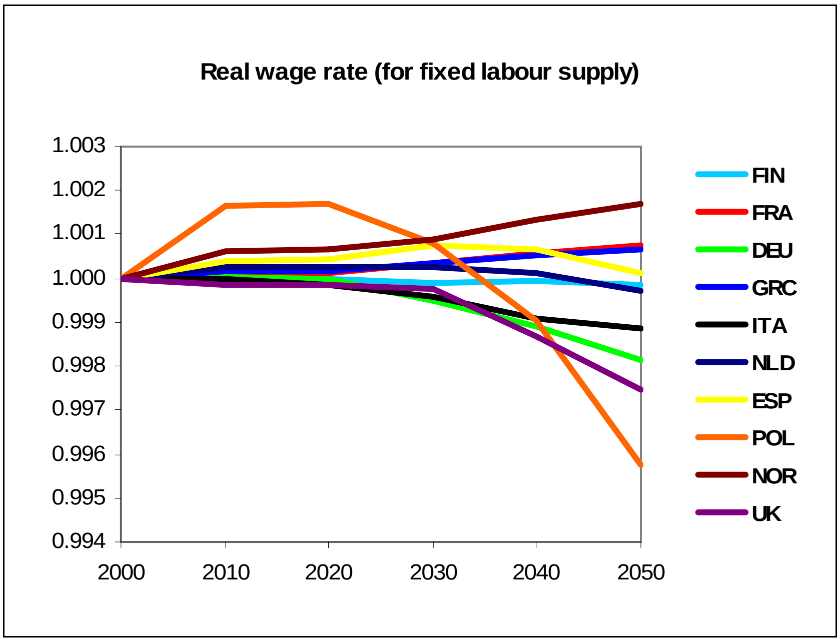
The development of GDP in scenario H2M is shown in Figure 25. From the previous explanations it is already clear that the effects are again rather low. The exception is again Poland due to its cheap hydrogen fuel costs. Thus, GDP in 2050 is 1.8 percent above its baseline value. A sizeable rise in GDP is also observed in Spain where the year-2050 is raised by 0.5 percent. In most other MS, GDP increases between 0 and 0.2 percent. Again, Finland and the United Kingdom experience temporary reductions in GDP.

Figure 25: Real GDP



Finally, Figure 26 shows the development of real wages in the MS. The effects are again very similar to the H2H scenario and can be explained identically. All in all, the deviations from the baseline are a somewhat less pronounced.

Figure 26: Real wage rate



5 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 – or their additional costs. Cost savings occur where the cost decline for hydrogen cars will be high in the future. Whereas in the long run no country loses by the introduction of hydrogen cars, some may experience losses on the transition. Second, the penetration rates determine how much of the cost savings potential will become active in the MS – or how much additional costs occur when hydrogen cars are introduced before their market maturity. It has to be emphasized, though, that additional costs only occur in some MS and only in the L2L scenario. Altogether these factors 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. In contrast to hydrogen cars, the production of hydrogen fuel may become more expensive over time. The difference between lifetime costs of conventional and hydrogen cars determines the level of the cost savings potential (resp. cost increases) 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.

6 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:

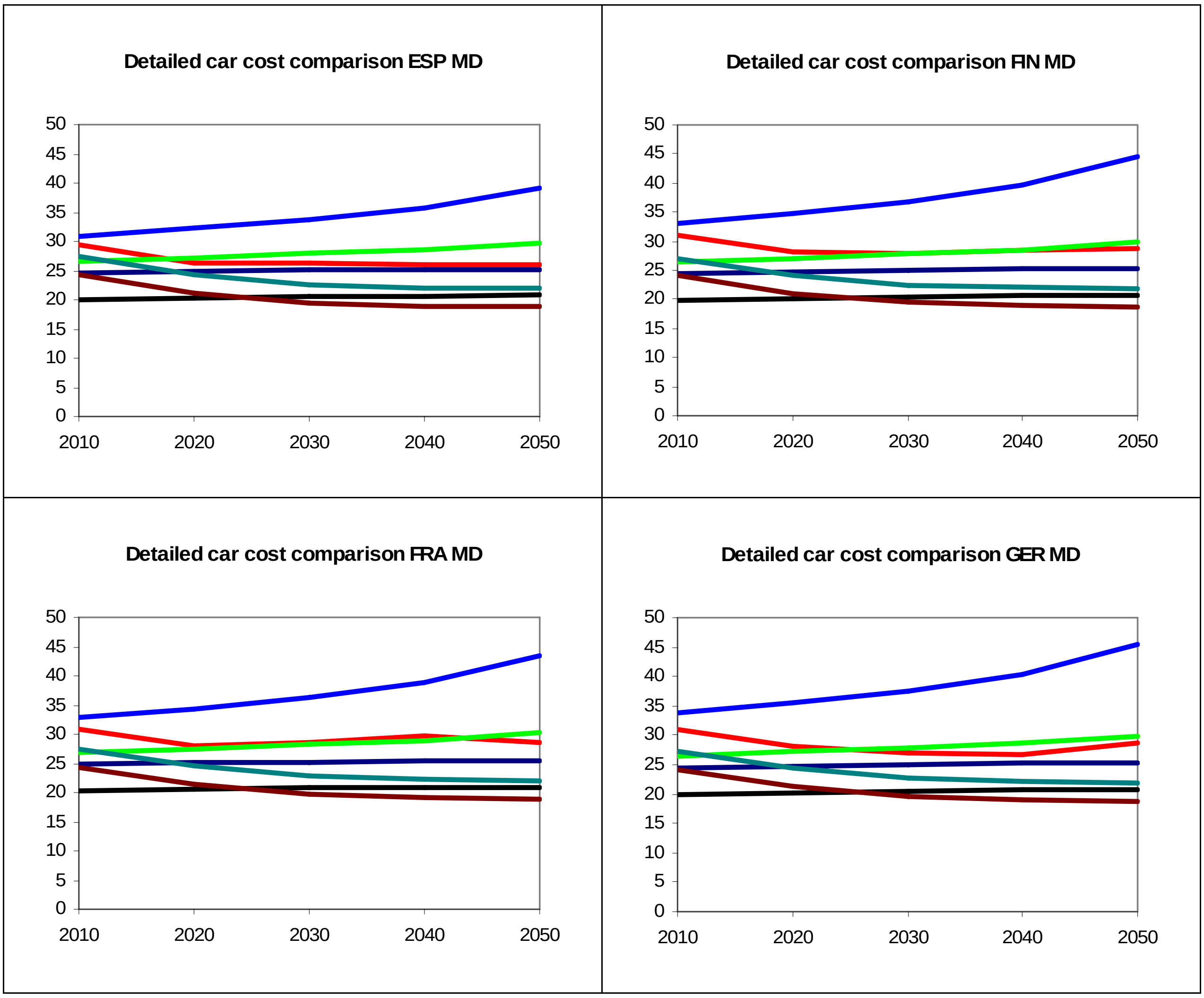
- Transport demand increases in most MS, with considerable differences in the levels. Some MS may – under unfavourable assumptions - experience a temporary and small drop of transport demand that will disappear in the long run.
- In line with transport demand, real consumption is expected to rise in the most MS (with clear differences in levels), while some MS will see a temporary, small drop in consumption, made up for after some periods. A drop, however, occurs only under assumptions of low penetration rates and a sluggish cost decrease.
- Welfare effects are positive for a number of MS and negligible for the others.
- GDP is also expected to increase in most MS. Temporary drops in some other countries are negligible in scope.
- From a global, macroeconomic viewpoint, the extent of welfare, transport demand, real consumption, and GDP changes is 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 rather point into one direction (higher transport demand, higher consumption, higher welfare), there are considerable differences in the details across the scenarios. Under unfavourable assumptions some MS may very well experience temporary losses in the key economic variables. However, these are generally small. Not surprisingly, the simulation results suggest that, given the same cost decrease for hydrogen cars, the effects with a low penetration rate are smaller than with a high penetration rate. 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 ten MS. Turned the other way round, low penetration rates and at the same time a smaller cost decrease affect the economic outcome in the ten MS the least.

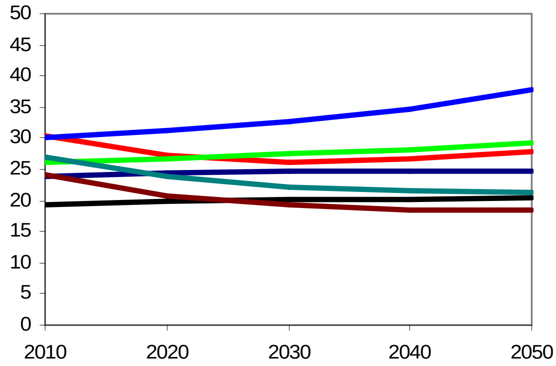
7 Annexes

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

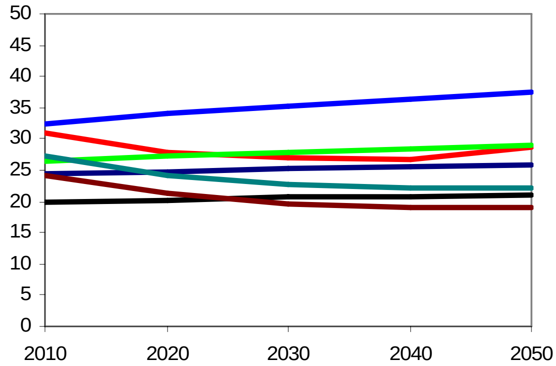
Figure 27: Detailed cost comparison of medium cars



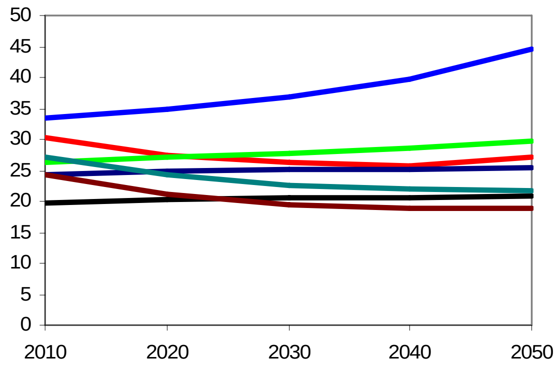
Detailed car cost comparison GRC MD



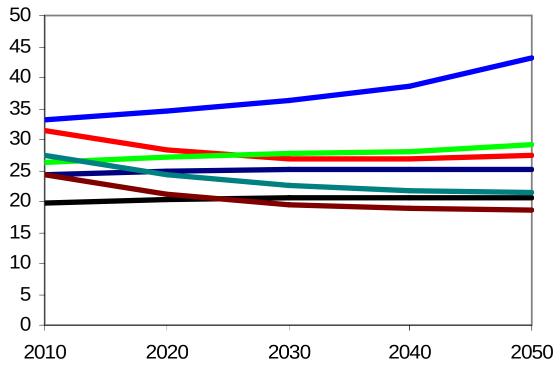
Detailed car cost comparison ITA MD



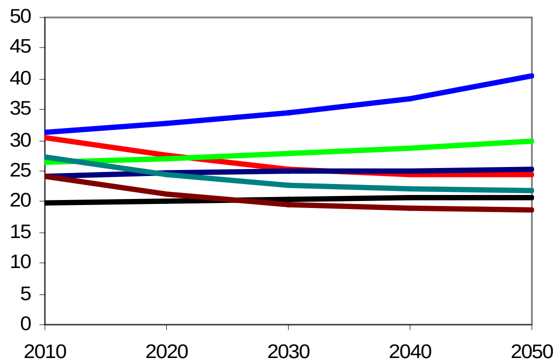
Detailed car cost comparison NLD MD



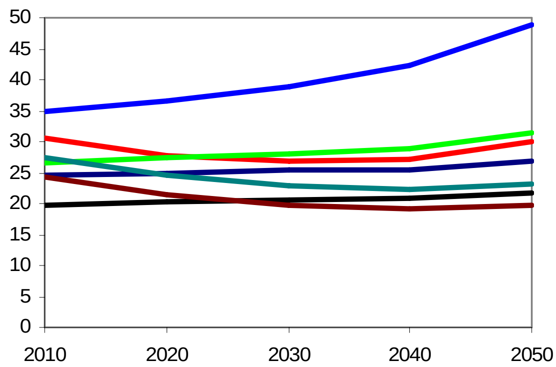
Detailed car cost comparison NOR MD



Detailed car cost comparison POL MD



Detailed car cost comparison UK MD



hc_totcost
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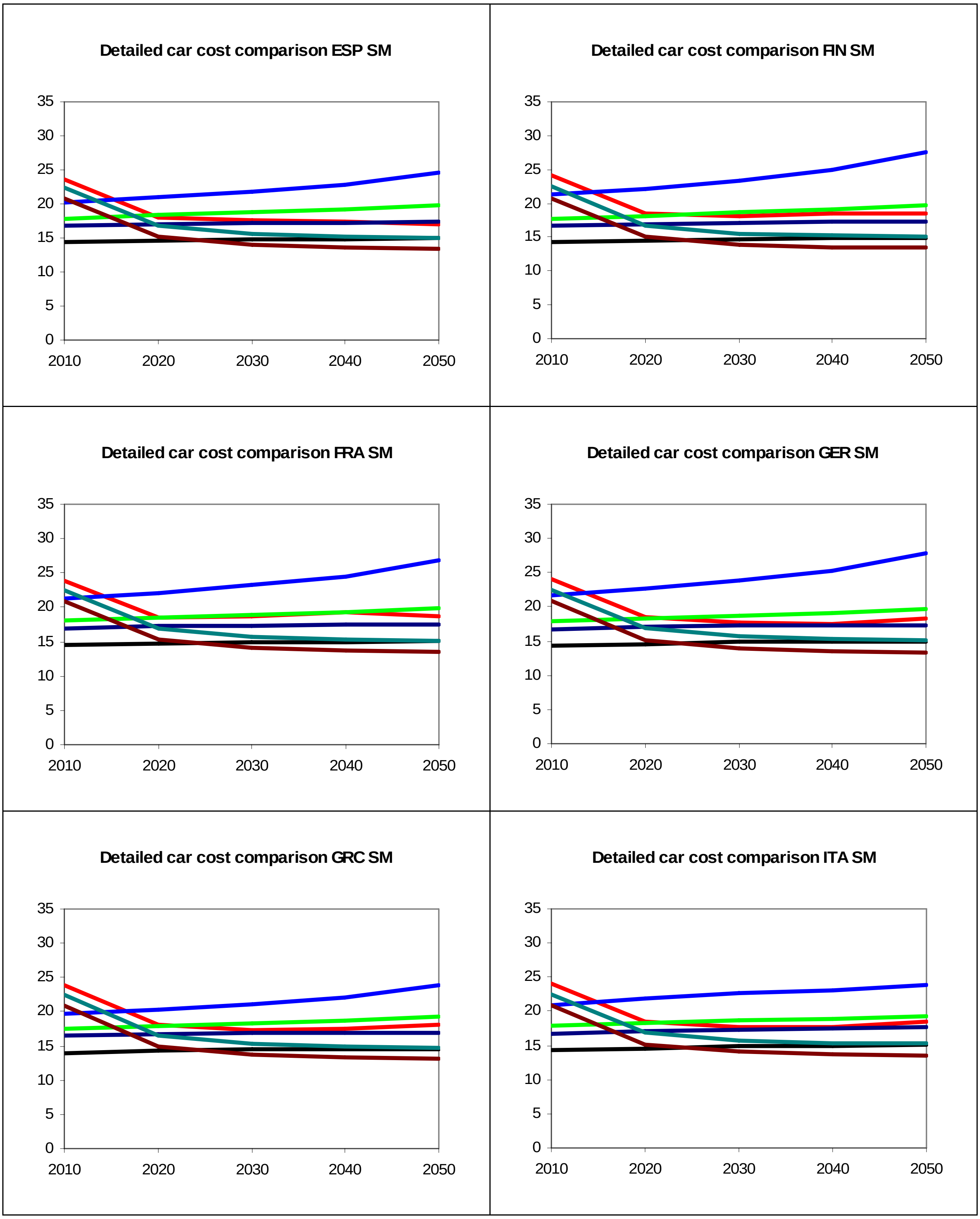
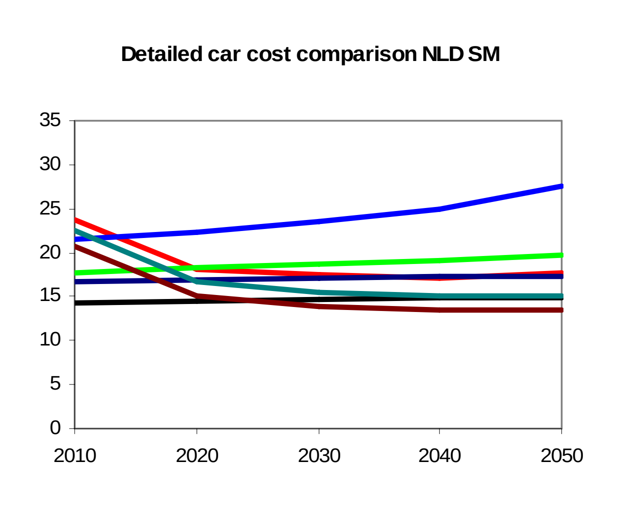
cc_price_o&m
hc_price
hc_price_o&m

Figure 28: Detailed cost comparison of small cars




Detailed car cost comparison NLD SM
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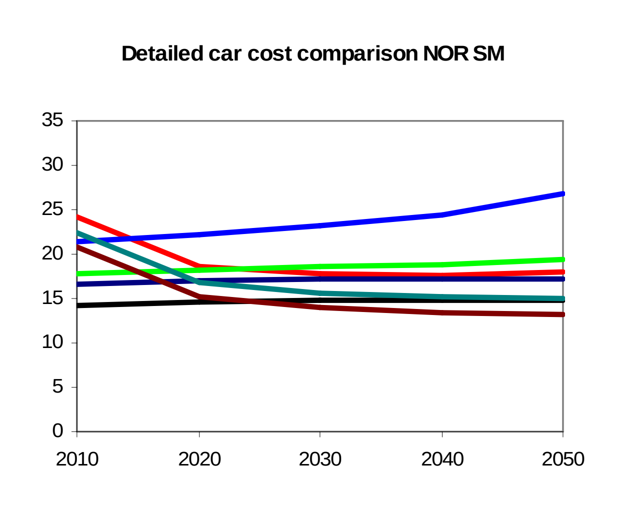
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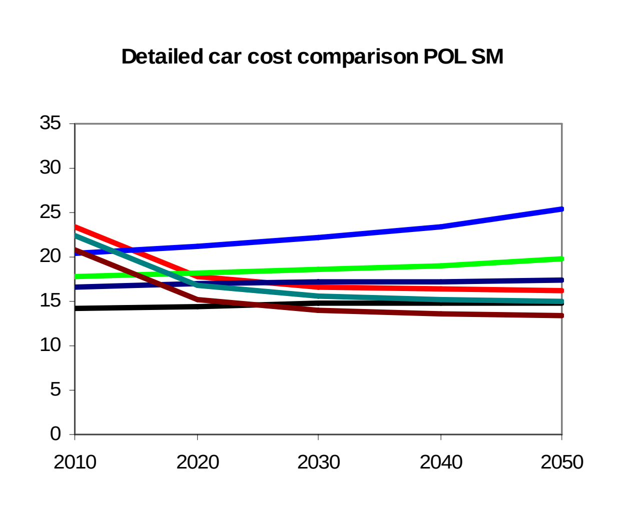
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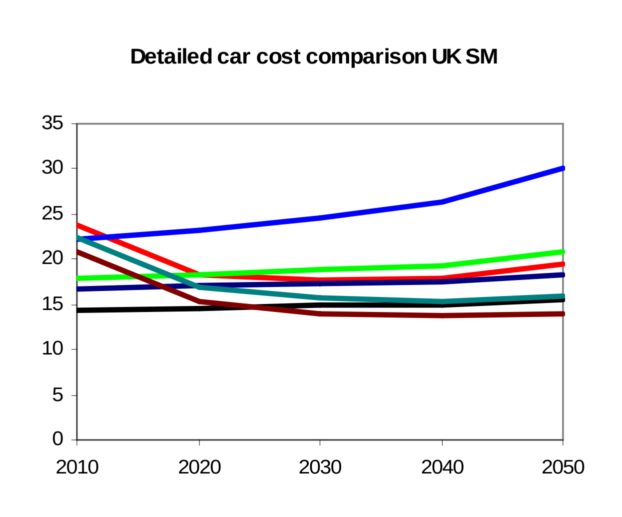
Detailed car cost comparison UK SM
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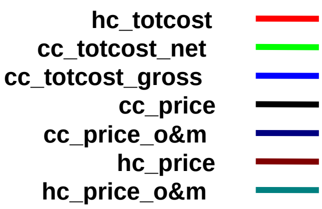
hc_totcost
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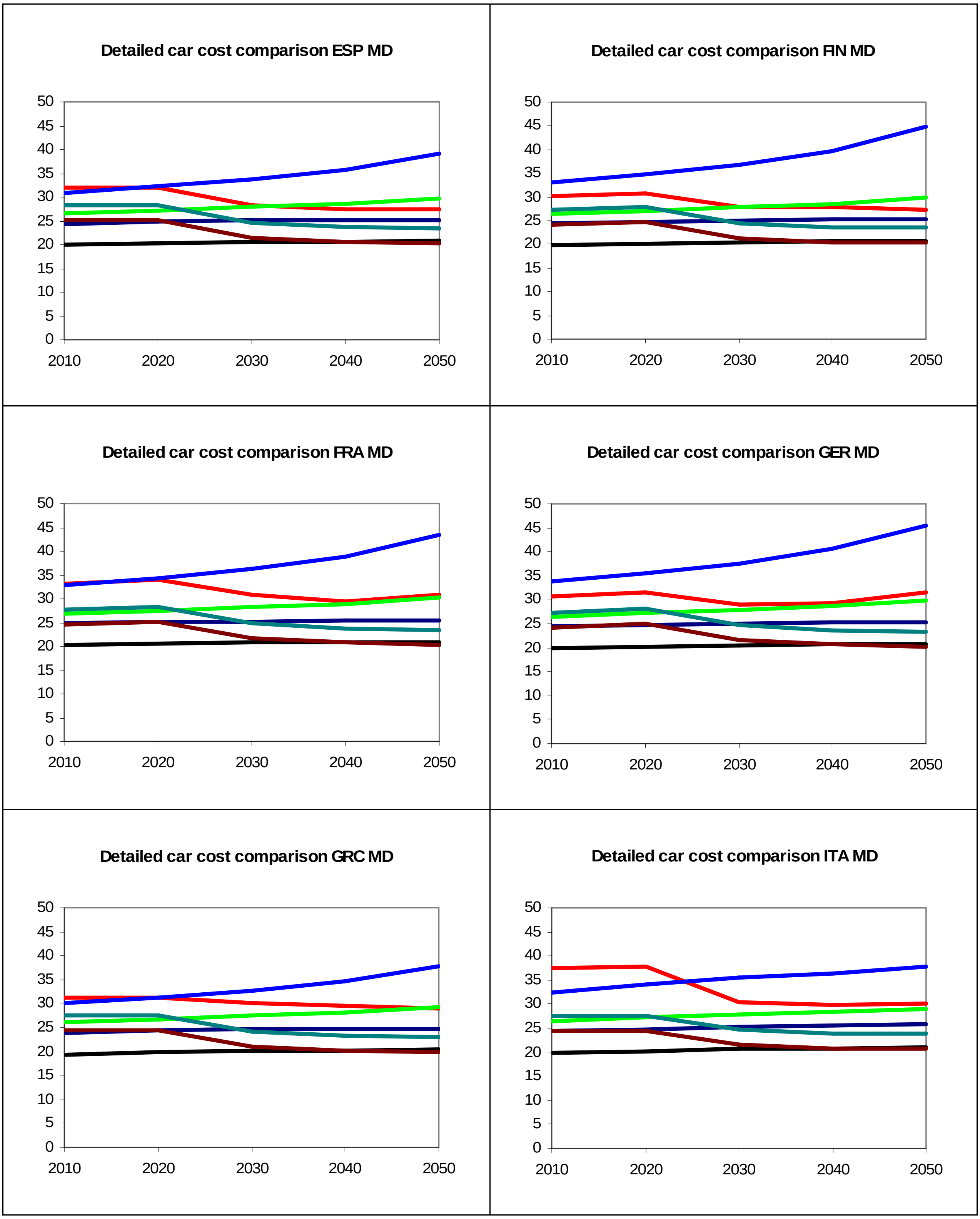
7.2 Low hydrogen penetration (L2L) – Detailed cost comparison of cars

Figure 29: Detailed cost comparison of medium cars



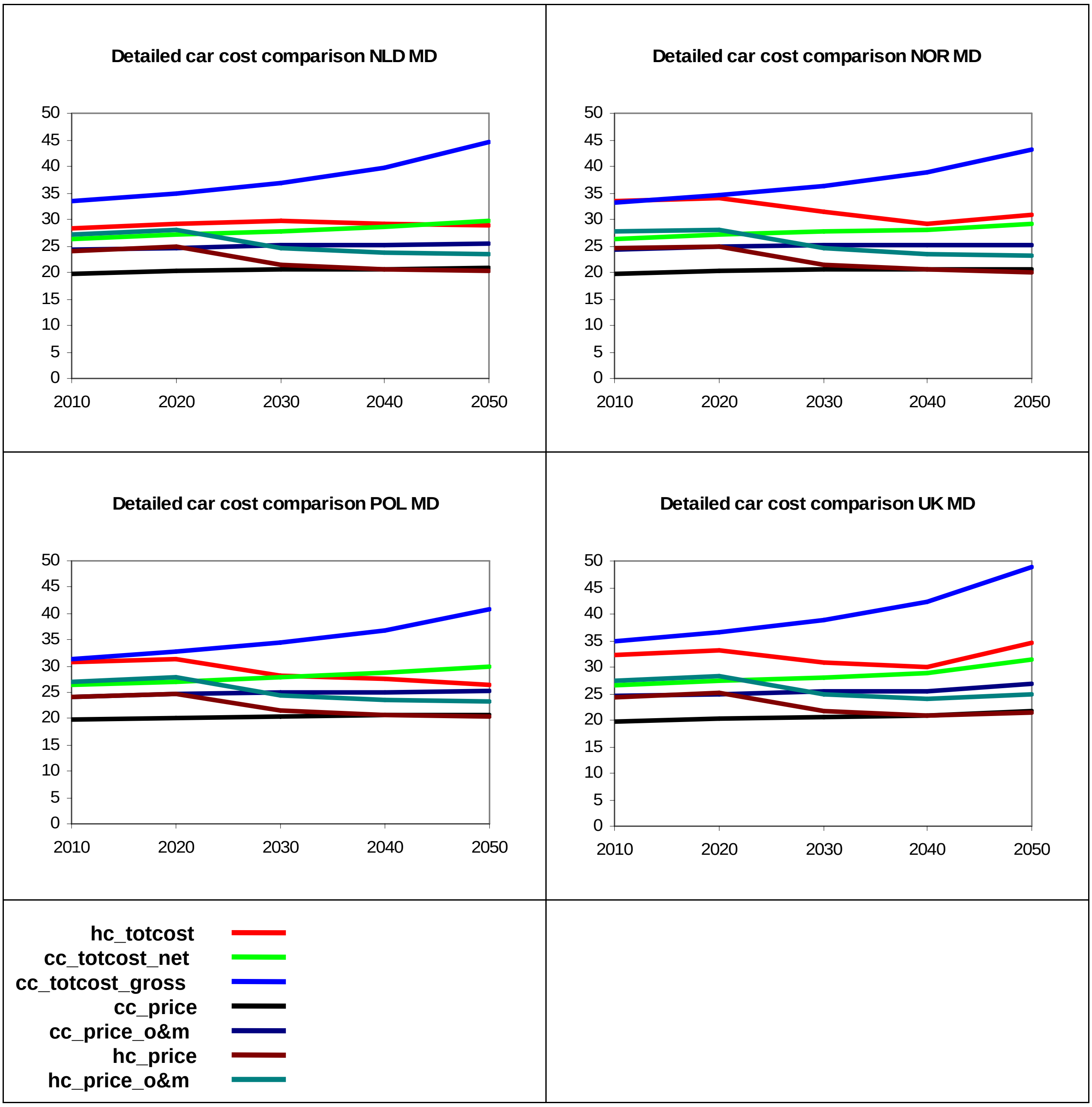

Detailed car cost comparison NLD MD
Detailed car cost comparison NOR MD
Detailed car cost comparison POL MD
Detailed car cost comparison UK MD
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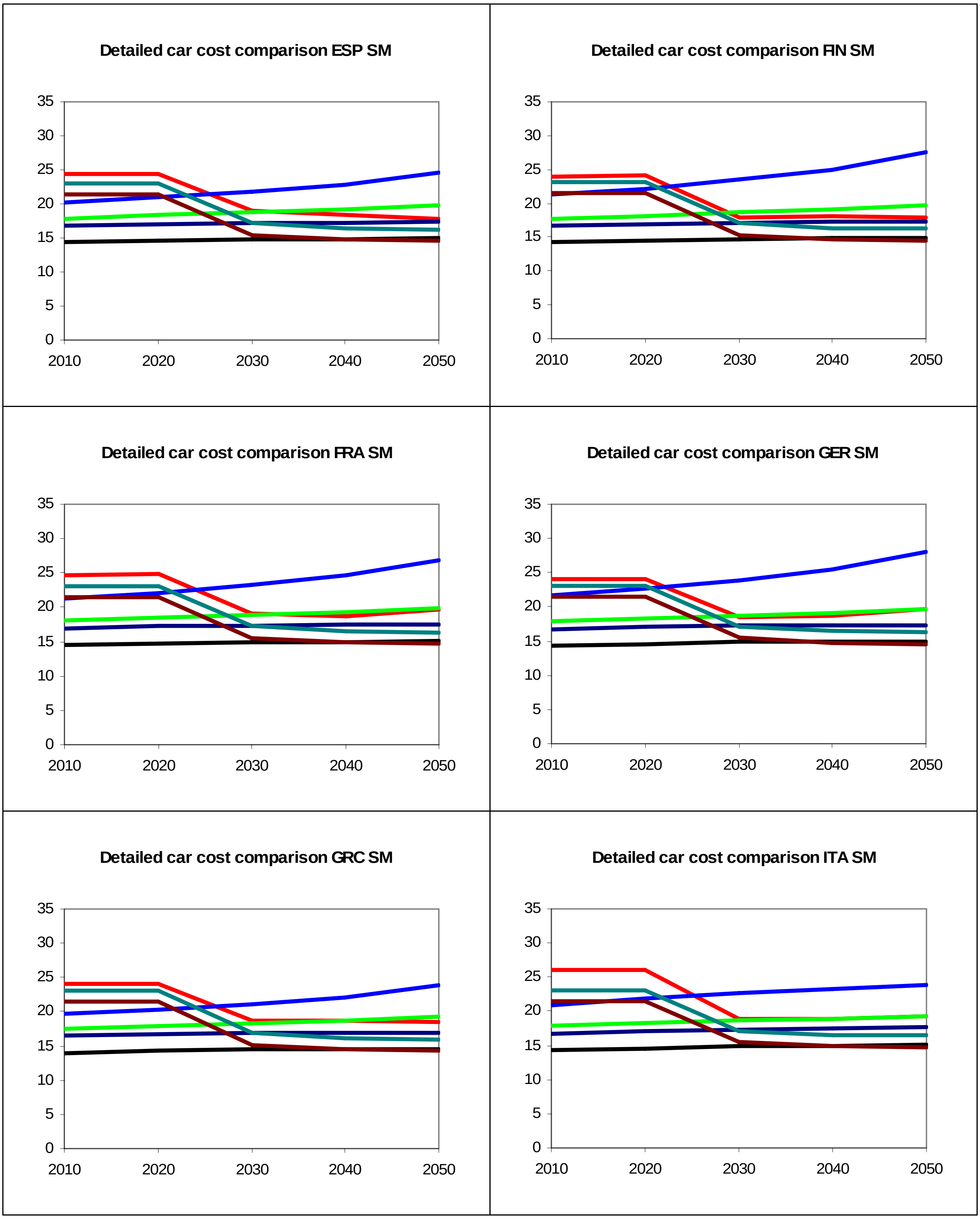
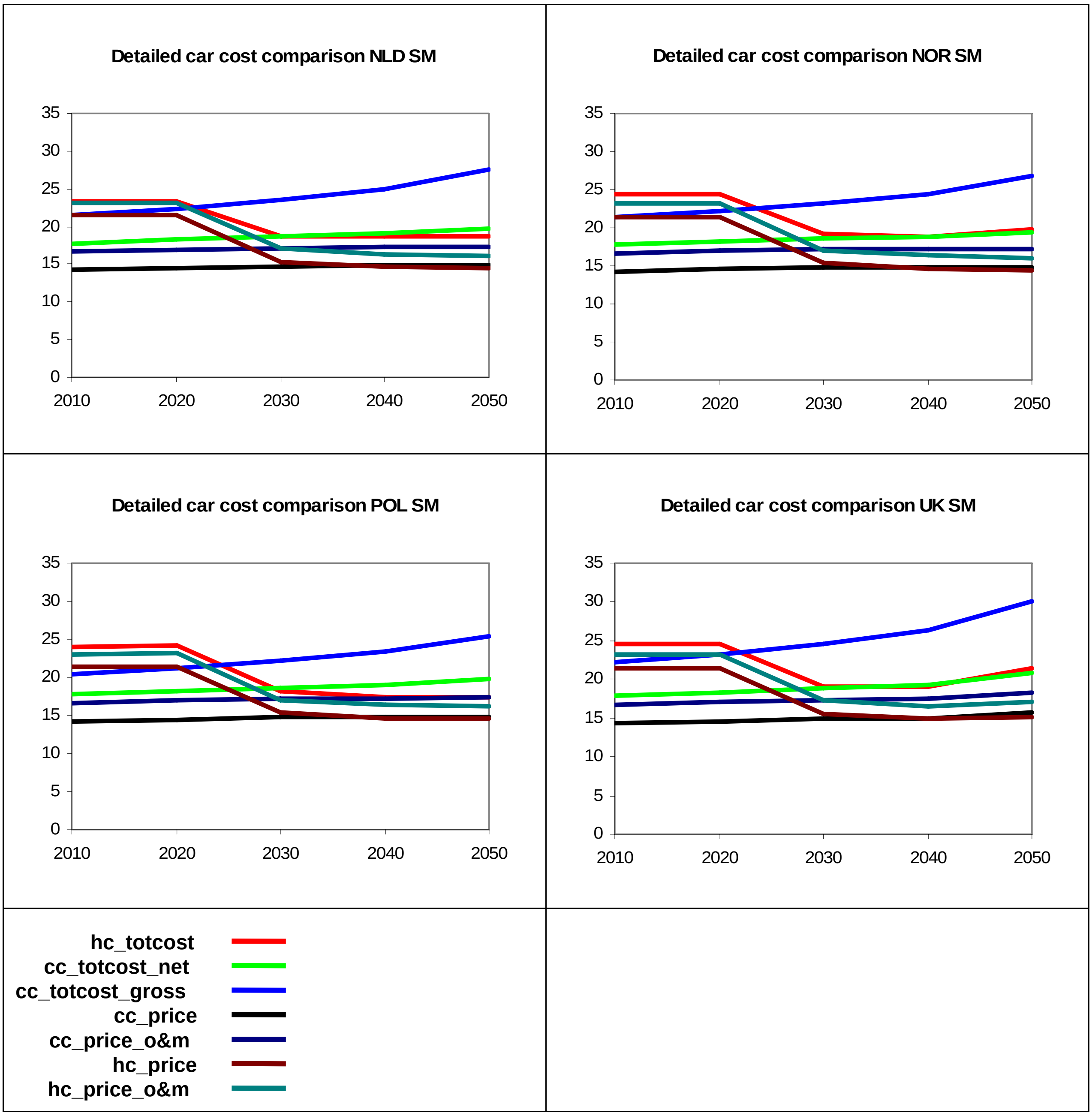
Figure 30: Detailed cost comparison of small cars




Detailed car cost comparison NLD SM
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Detailed car cost comparison POL SM
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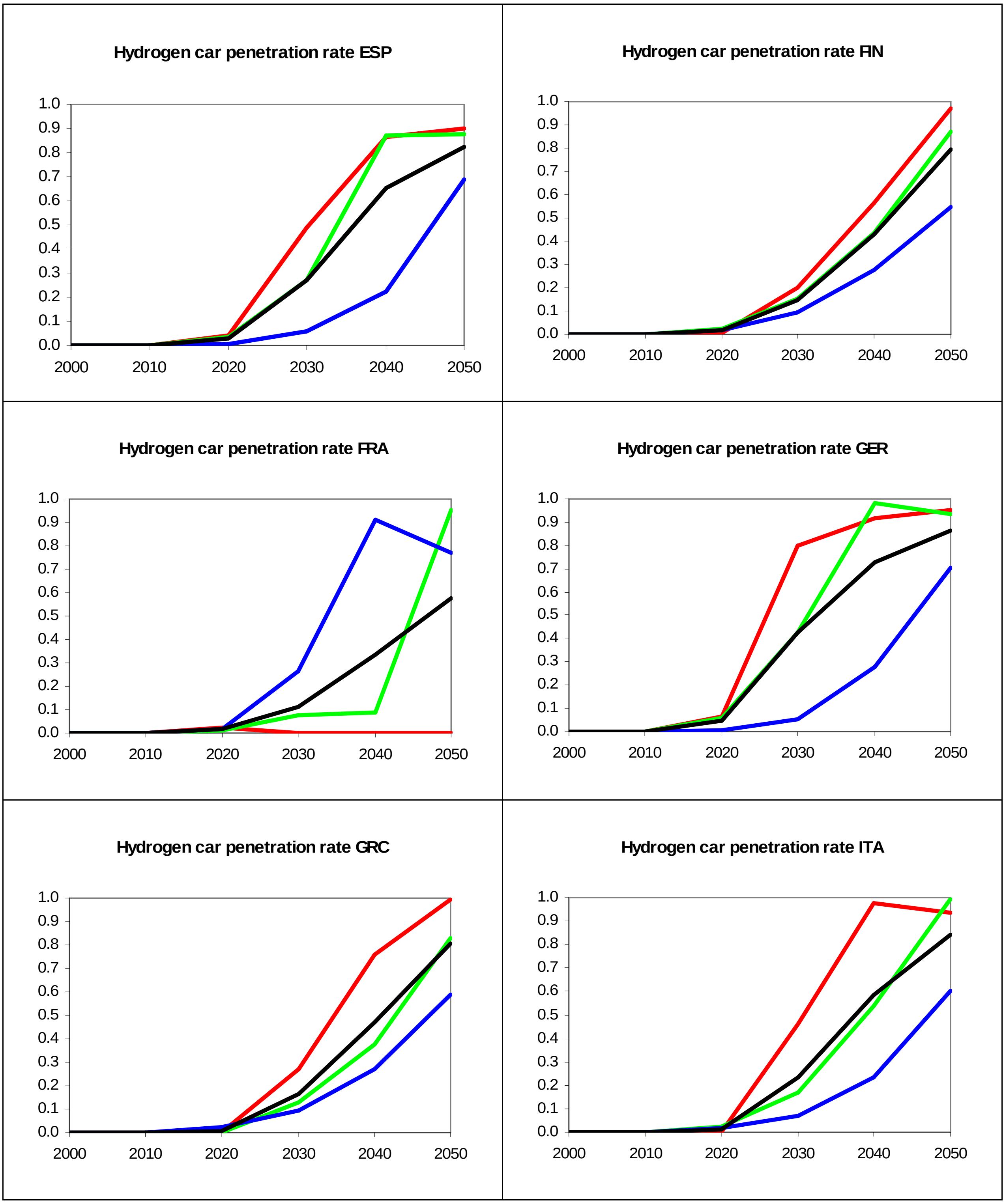
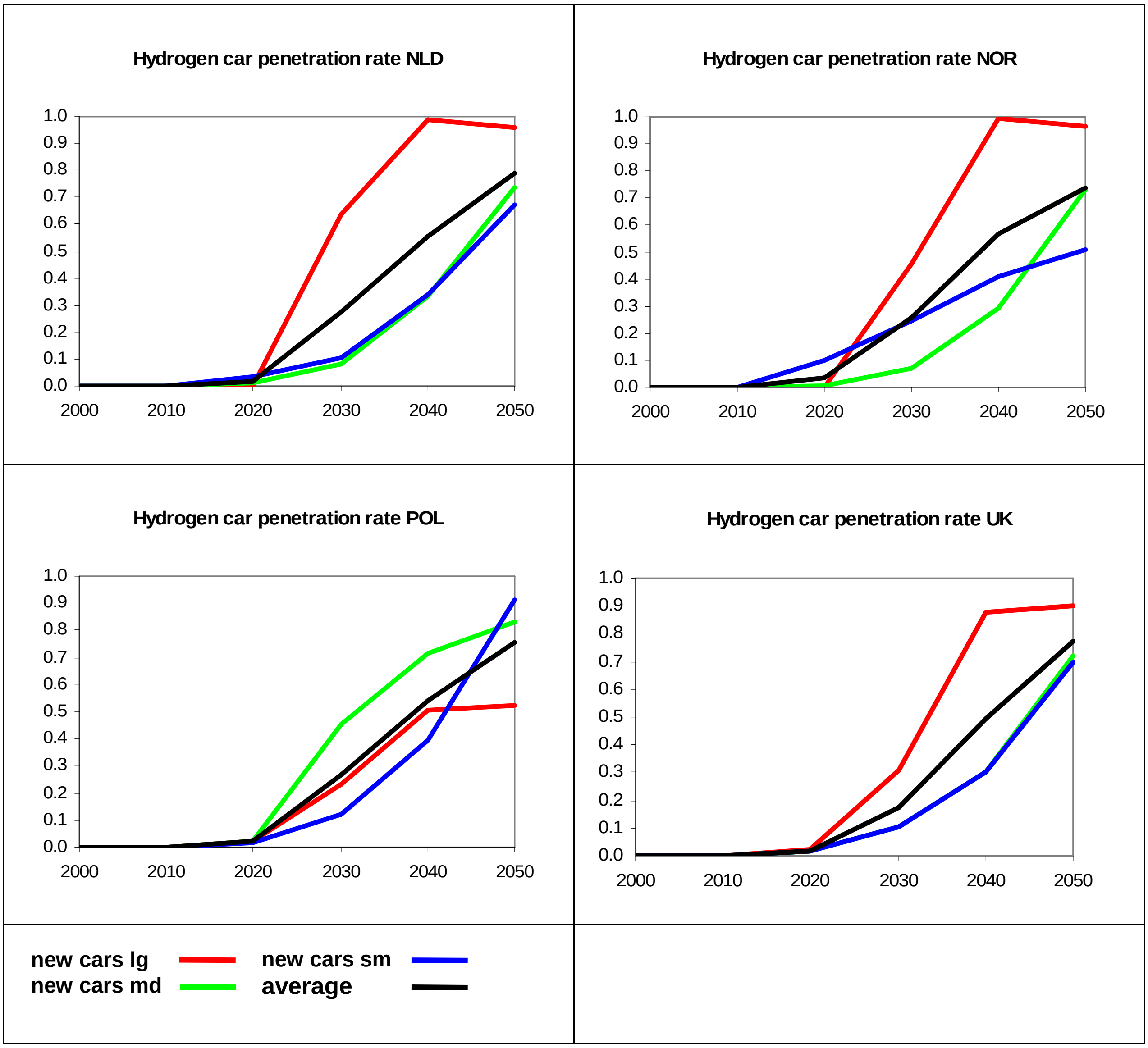
7.3 Medium hydrogen penetration (H2M) – Detailed cost comparison of cars

Figure 31: Hydrogen penetration rates for new cars in different countries




Hydrogen car penetration rate NLD
Hydrogen car penetration rate NOR
Hydrogen car penetration rate POL
Hydrogen car penetration rate UK
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new cars md
new cars sm
average

Figure 32: Hydrogen penetration rates for new cars in different size classes

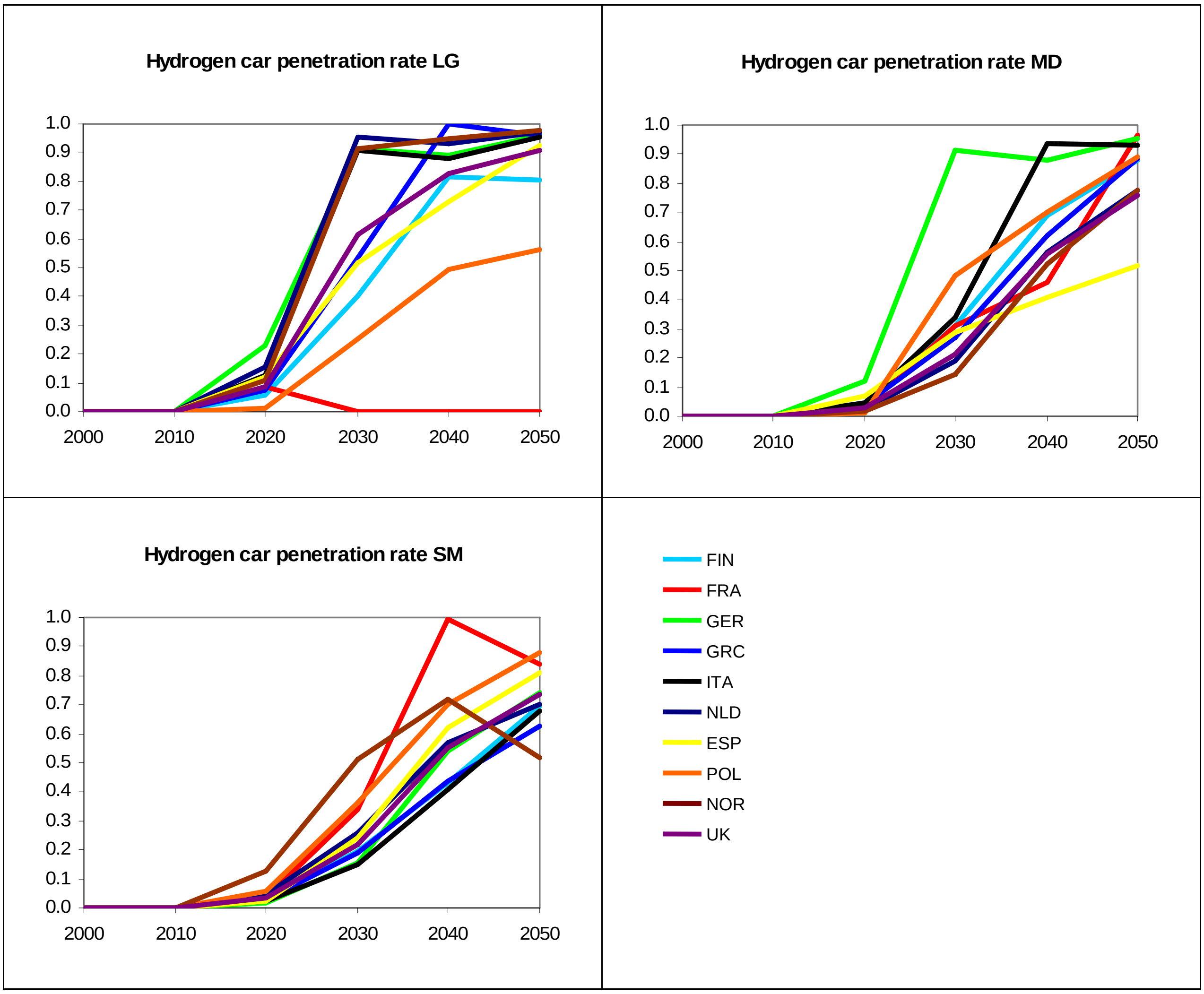
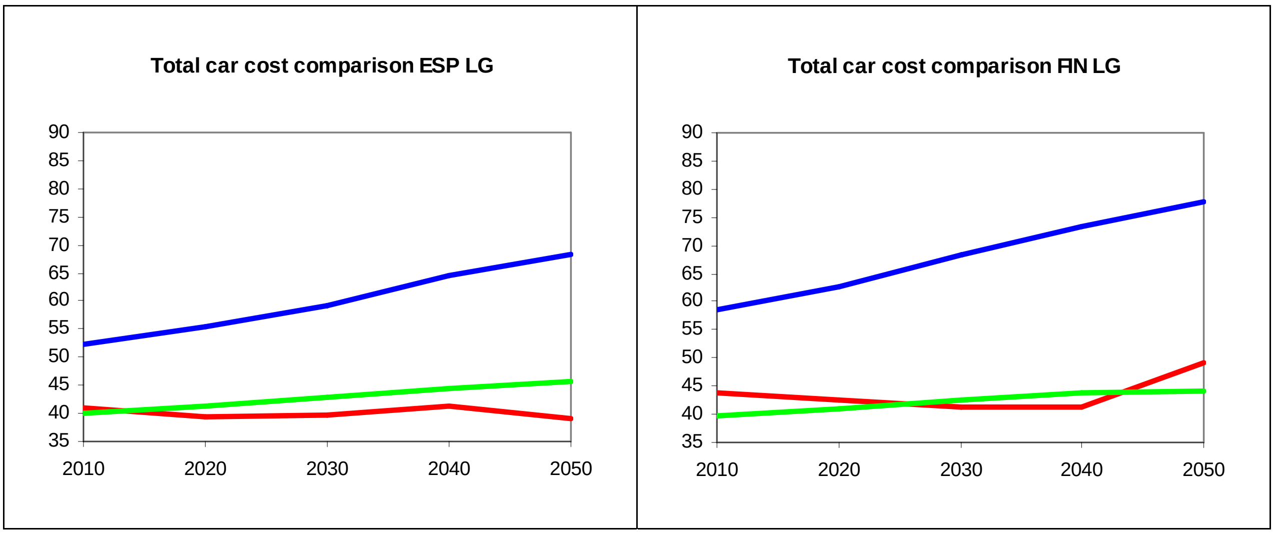
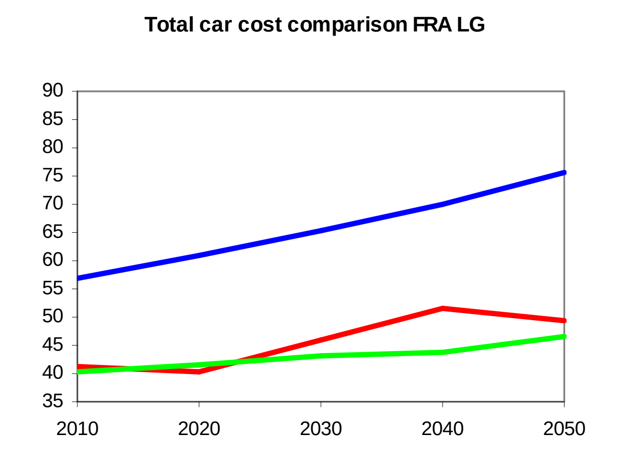


Figure 33: Cost comparison of large cars




Total car cost comparison FRA LG
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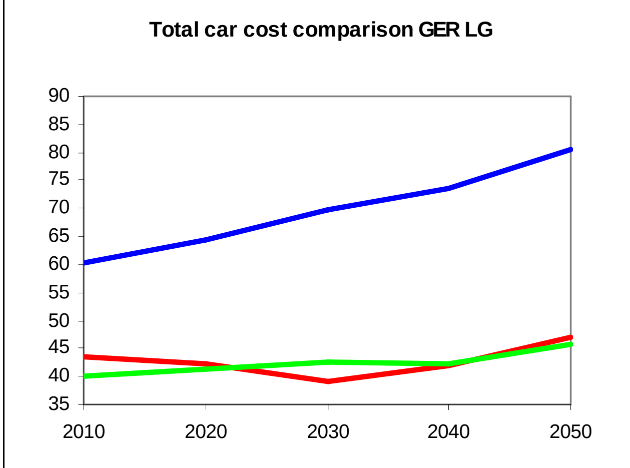
Total car cost comparison GER LG
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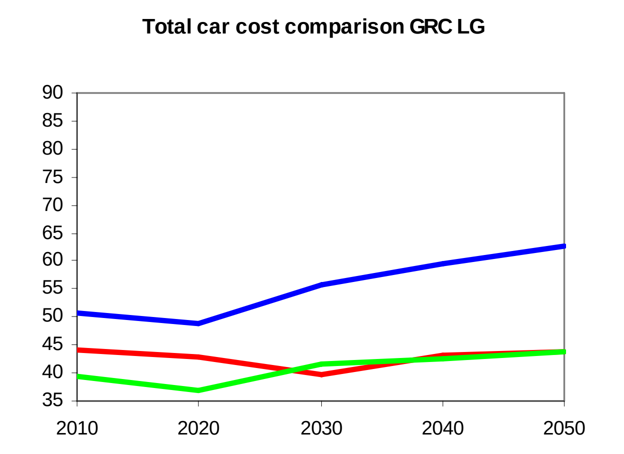
Total car cost comparison GRC LG
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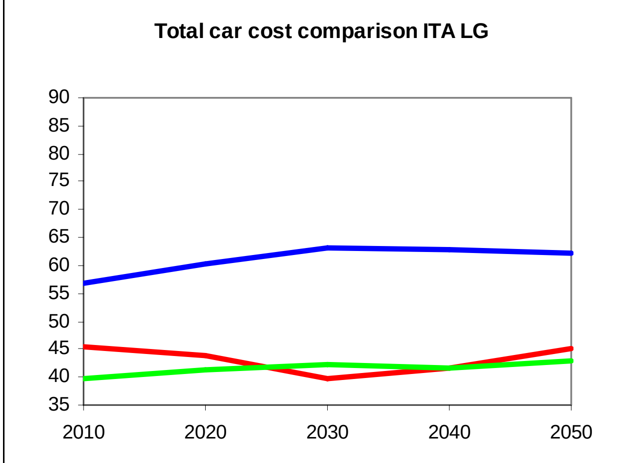
Total car cost comparison ITA LG
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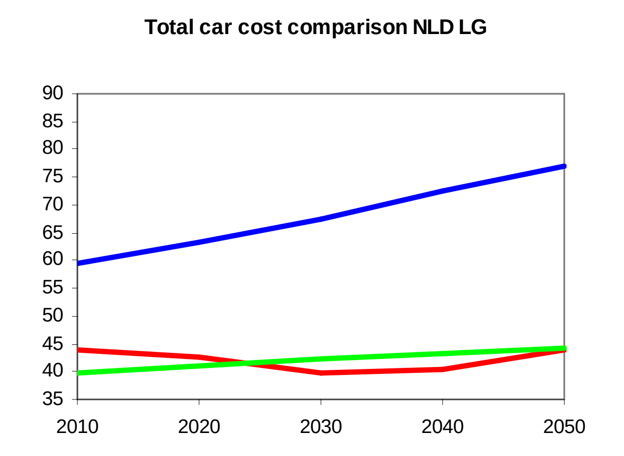
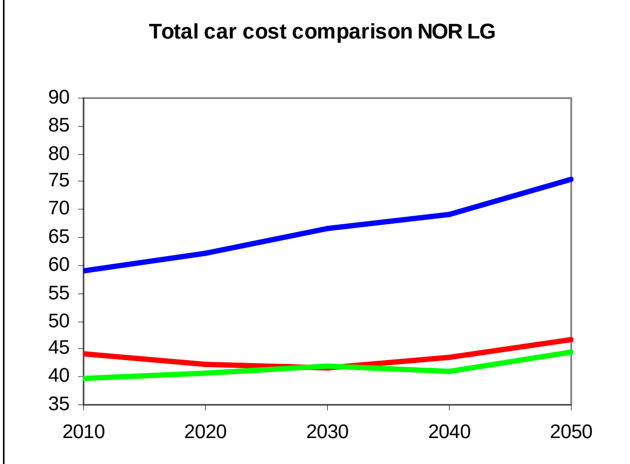

Total car cost comparison NLD LG
90
85
80
75
70
65
60
55
50
45
40
35
2010
2020
2030
2040
2050


Total car cost comparison NOR LG
90
85
80
75
70
65
60
55
50
45
40
35
2010
2020
2030
2040
2050

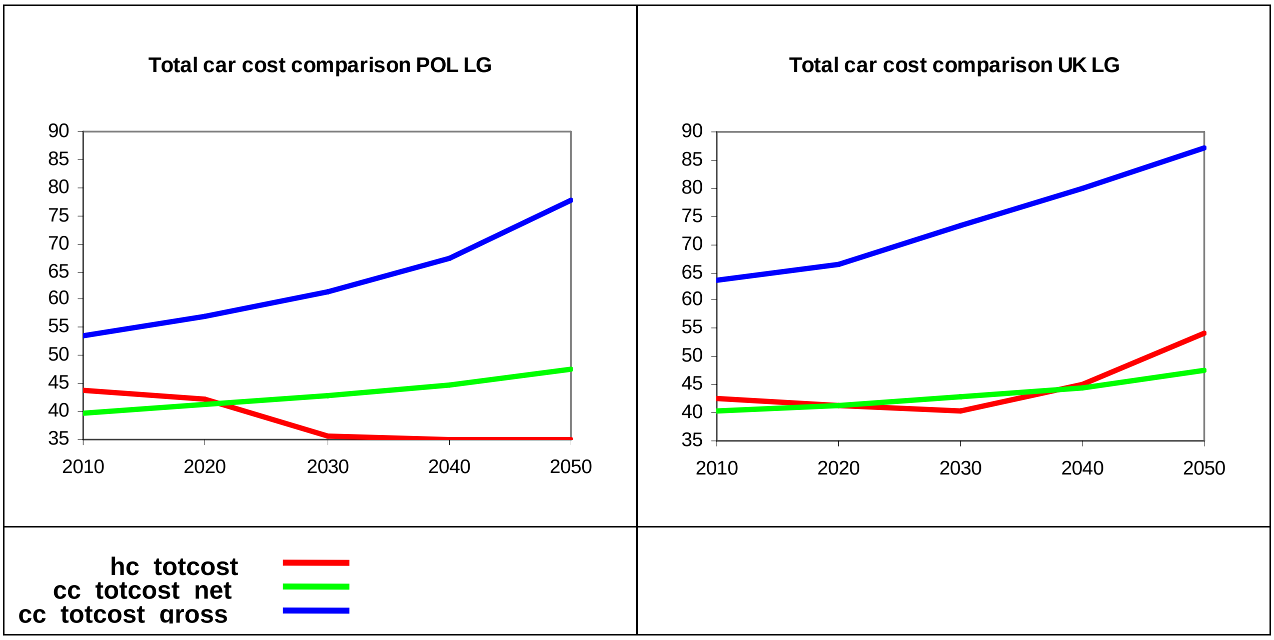
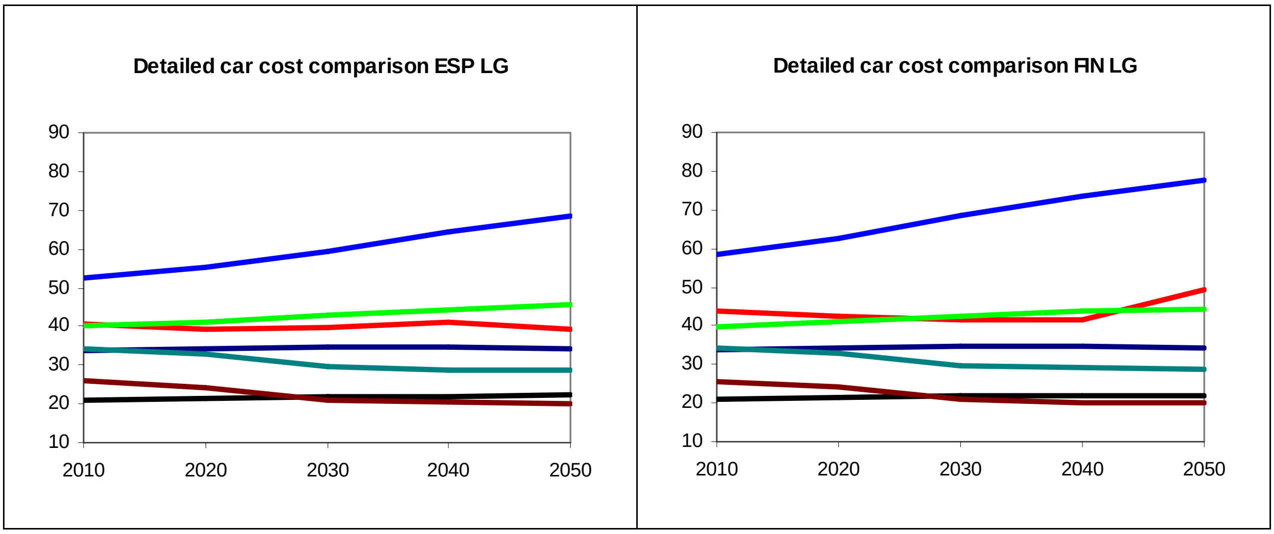
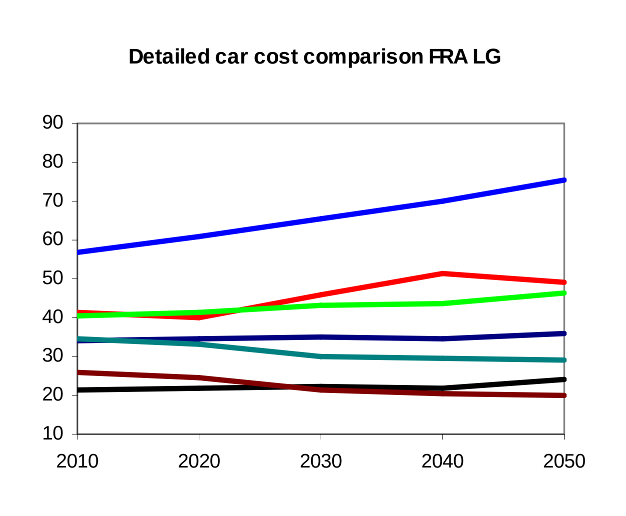
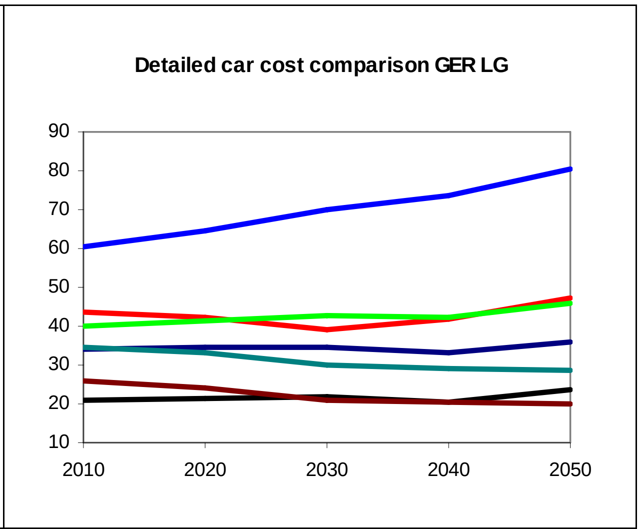
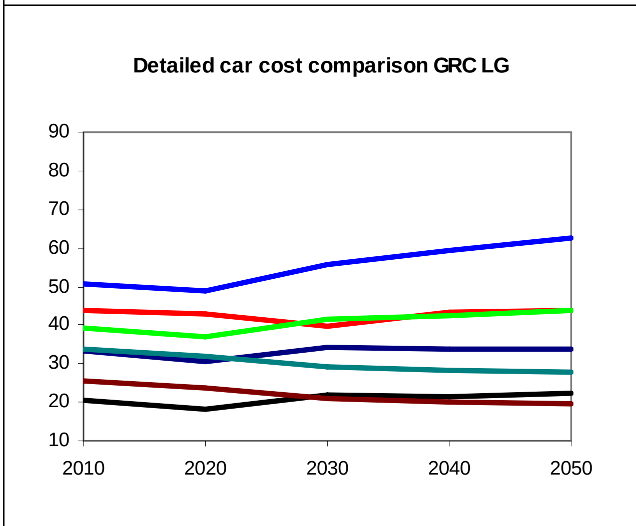


Figure 34: Detailed cost comparison of large cars




Detailed car cost comparison FRA LG
90
80
70
60
50
40
30
20
10
2010
2020
2030
2040
2050


Detailed car cost comparison GER LG
90
80
70
60
50
40
30
20
10
2010
2020
2030
2040
2050


Detailed car cost comparison GRC LG
90
80
70
60
50
40
30
20
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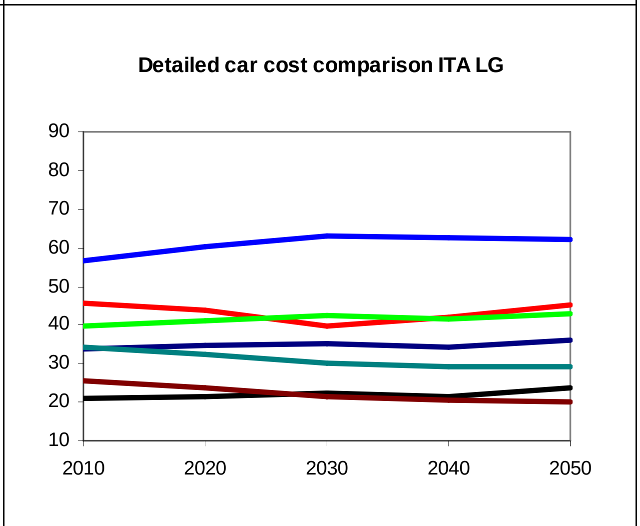
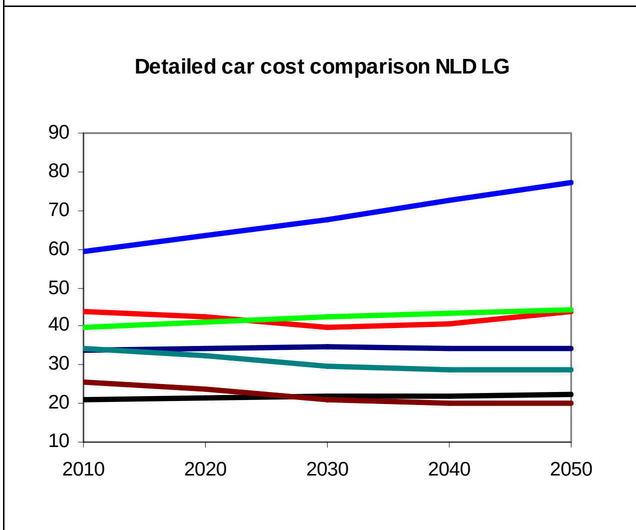
2010
2020
2030
2040
2050


Detailed car cost comparison ITA LG
90
80
70
60
50
40
30
20
10
2010
2020
2030
2040
2050


Detailed car cost comparison NLD LG
90
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40
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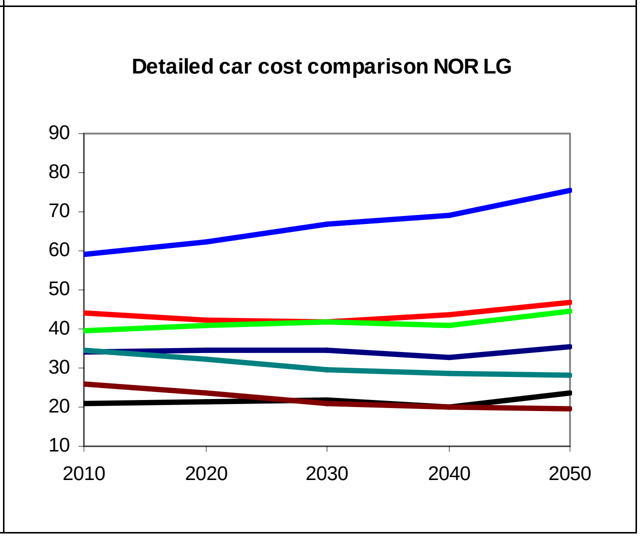
Detailed car cost comparison NOR LG
90
80
70
60
50
40
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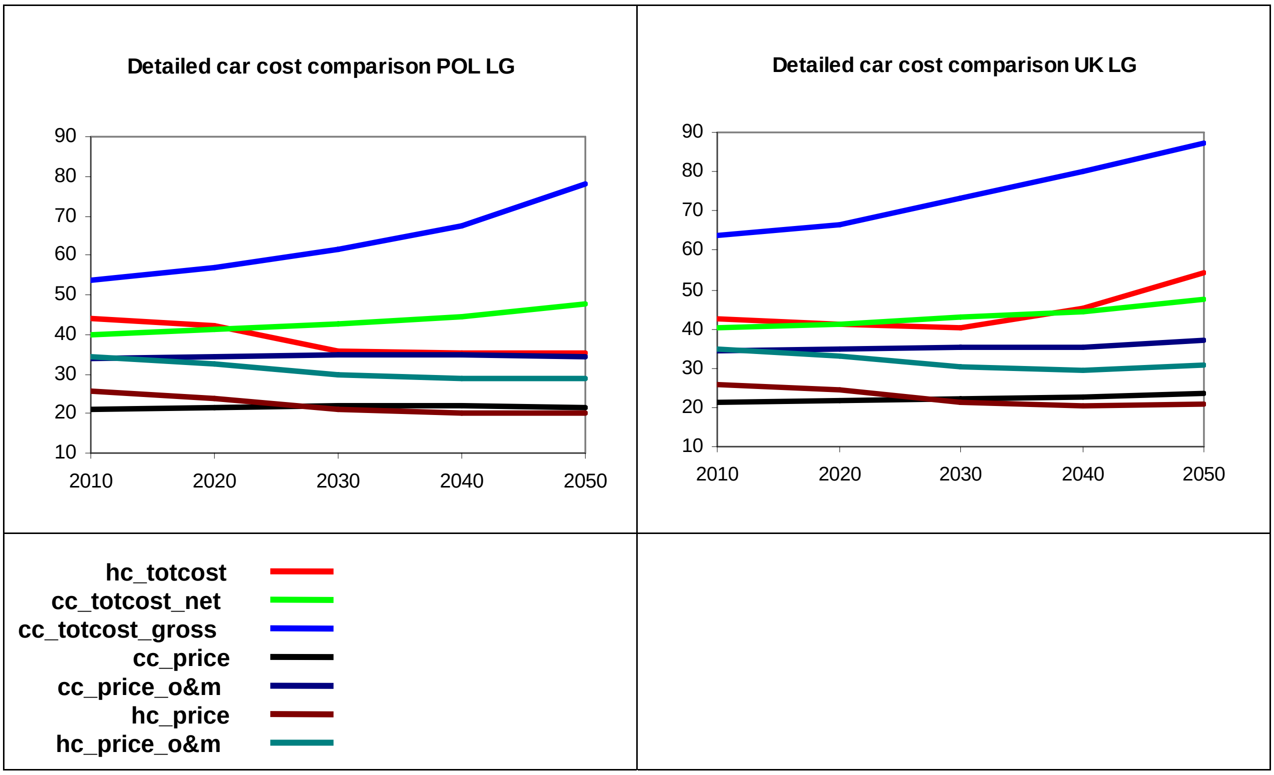
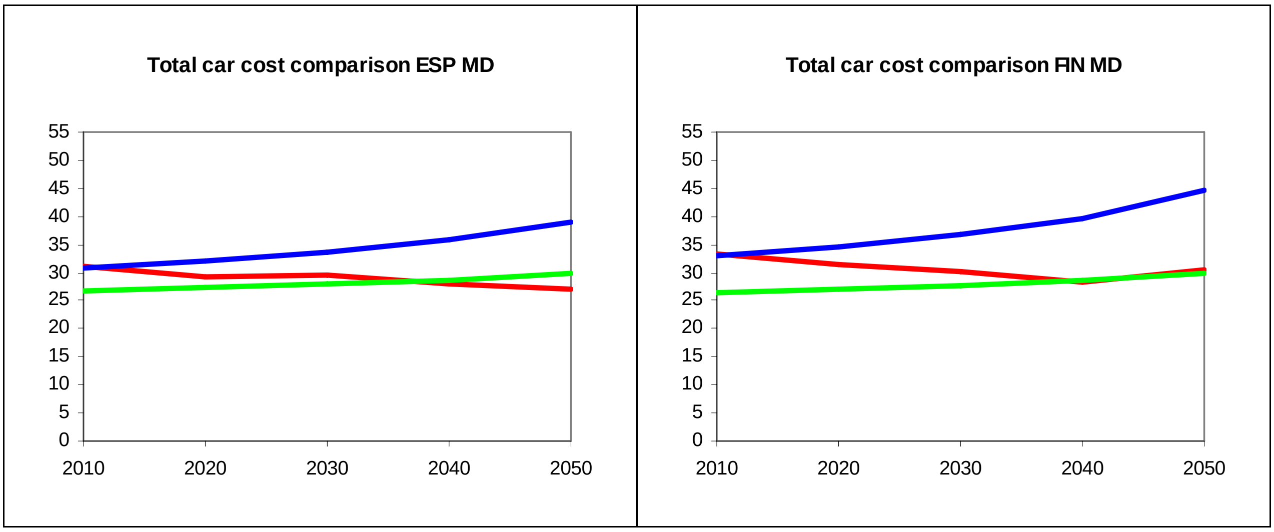
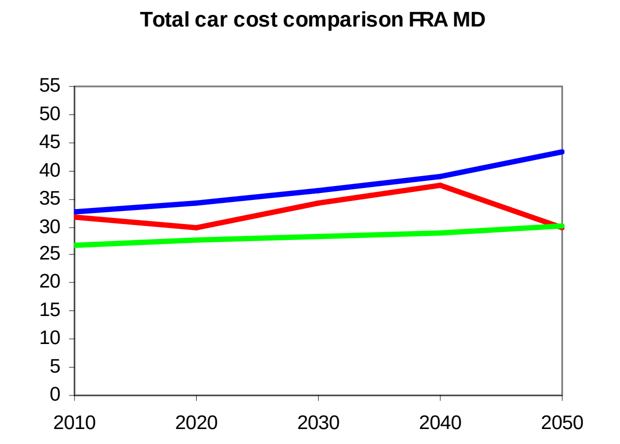
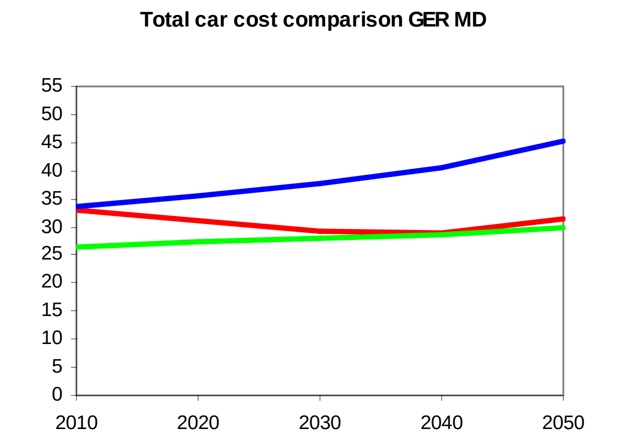


Figure 35: Cost comparison of medium cars




Total car cost comparison FRA MD
55
50
45
40
35
30
25
20
15
10
5
0
2010
2020
2030
2040
2050


Total car cost comparison GER MD
55
50
45
40
35
30
25
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15
10
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0
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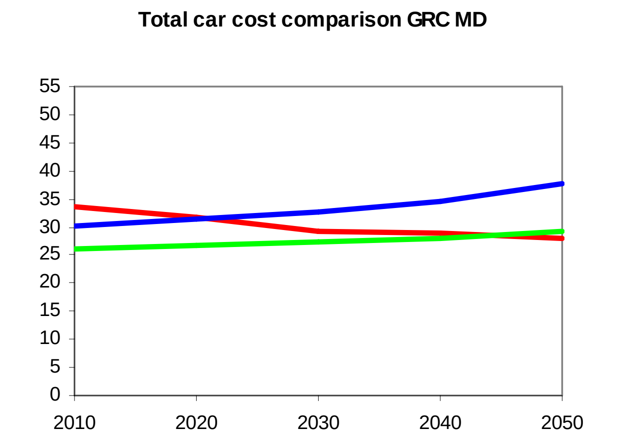
2050


Total car cost comparison GRC MD
55
50
45
40
35
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25
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15
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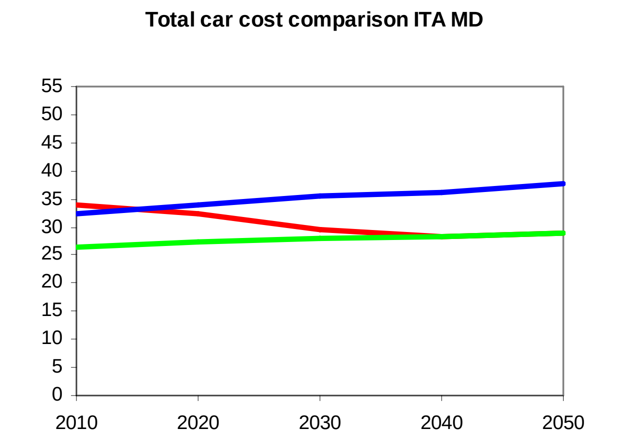
2050


Total car cost comparison ITA MD
55
50
45
40
35
30
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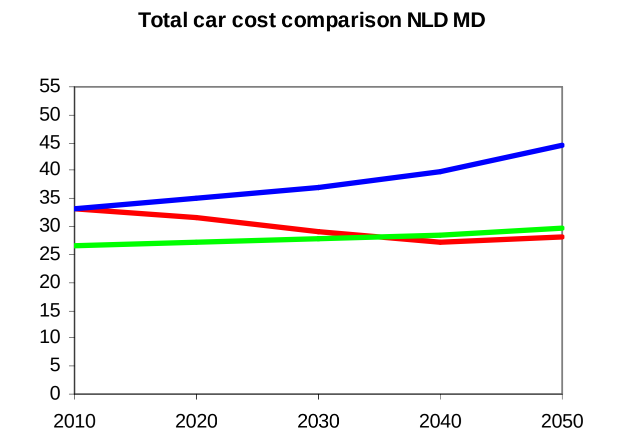
Total car cost comparison NLD MD
55
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45
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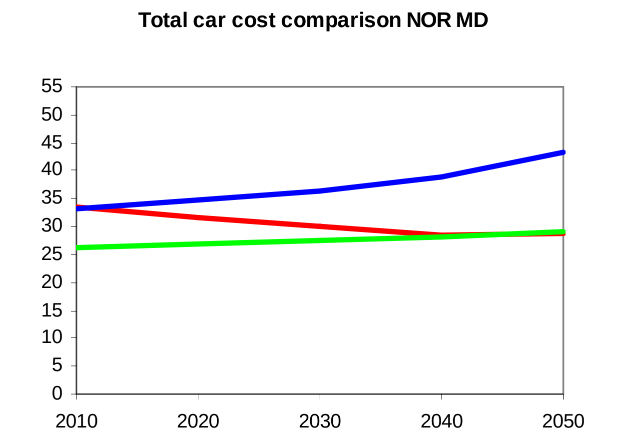
Total car cost comparison NOR MD
55
50
45
40
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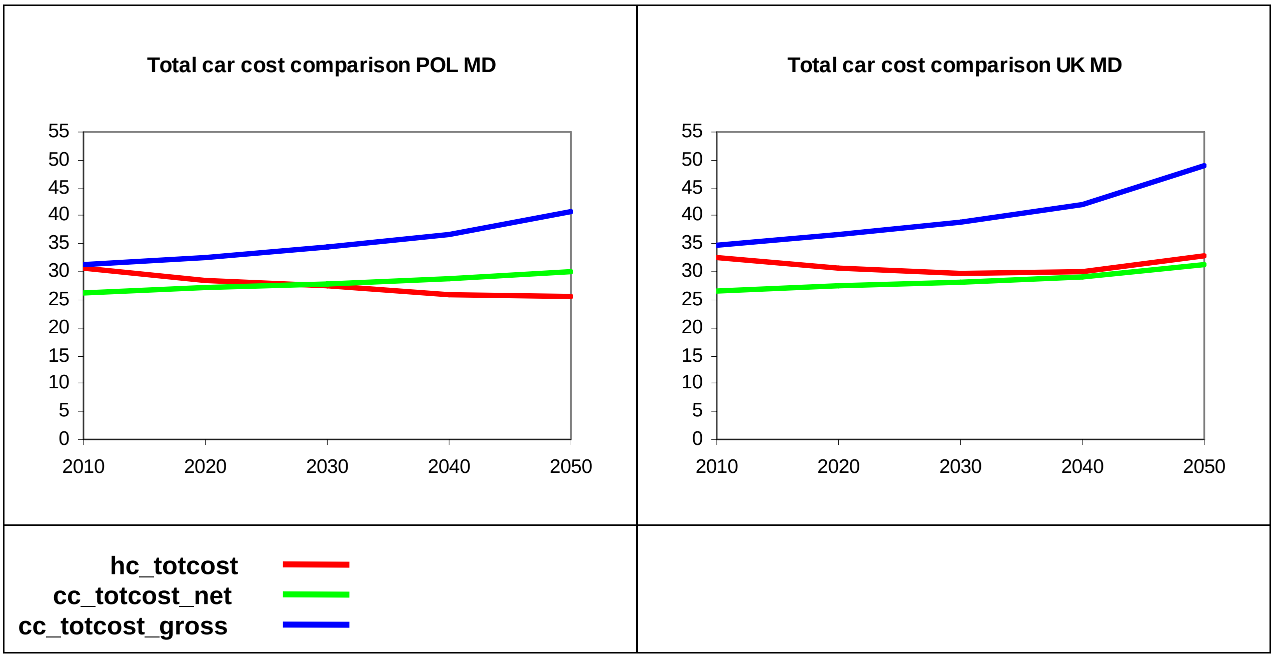
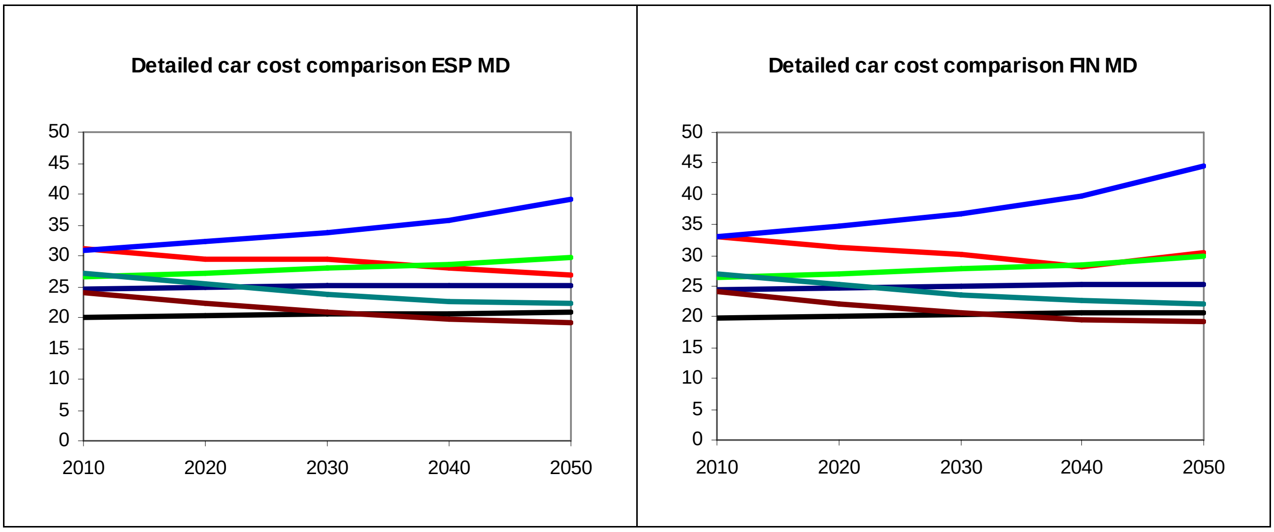
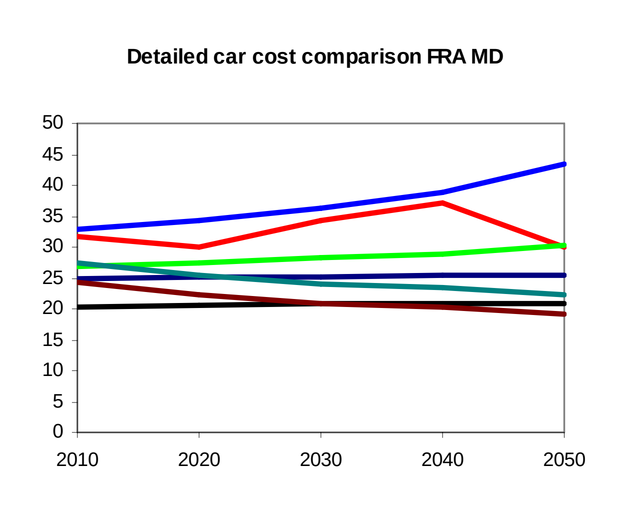


Figure 36: Detailed cost comparison of medium cars




Detailed car cost comparison FRA MD
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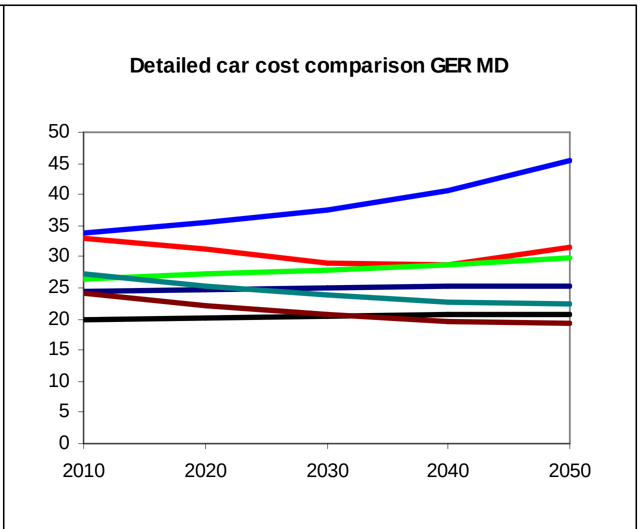
Detailed car cost comparison GER MD
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45
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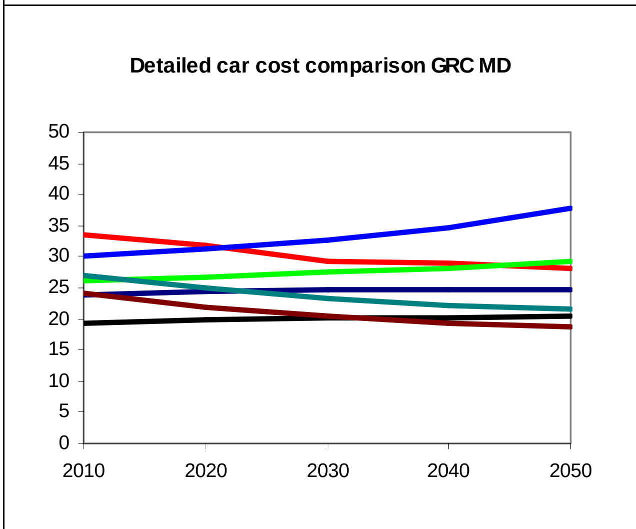
Detailed car cost comparison GRC MD
50
45
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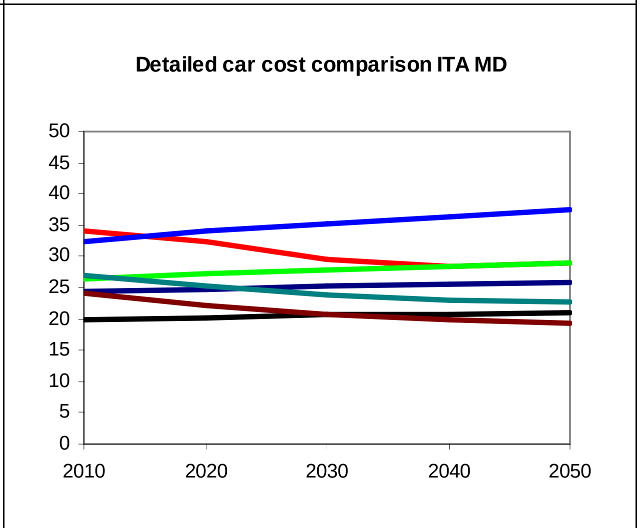
Detailed car cost comparison ITA MD
50
45
40
35
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2010
2020
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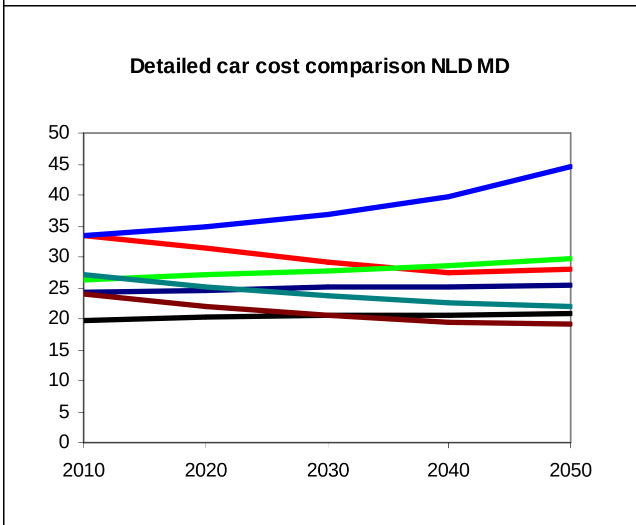
2040
2050


Detailed car cost comparison NLD MD
50
45
40
35
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25
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0
2010
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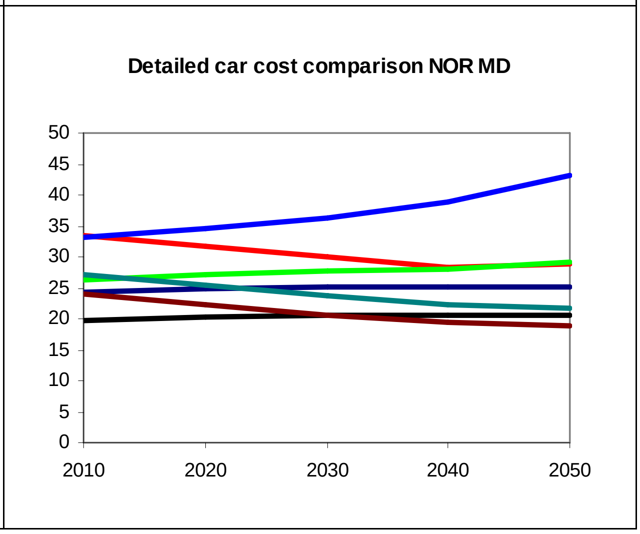
2050


Detailed car cost comparison NOR MD
50
45
40
35
30
25
20
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5
0
2010
2020
2030
2040
2050

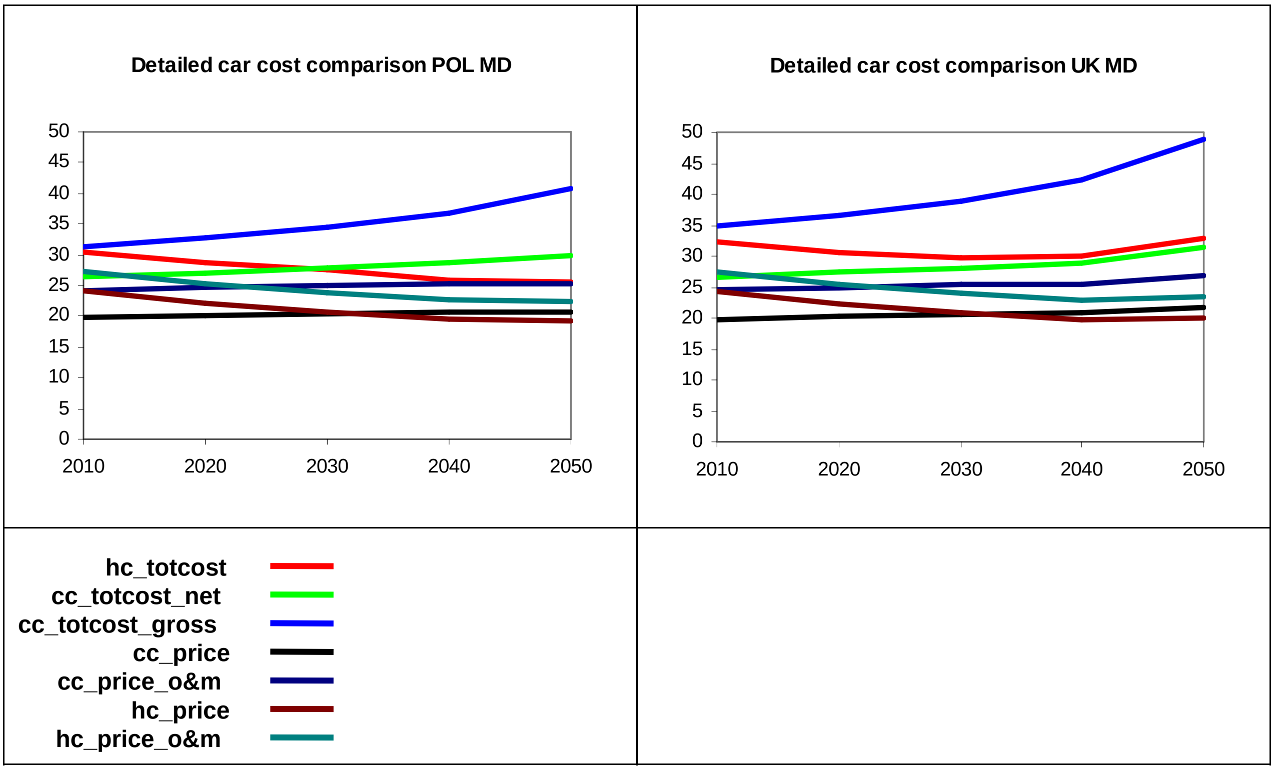
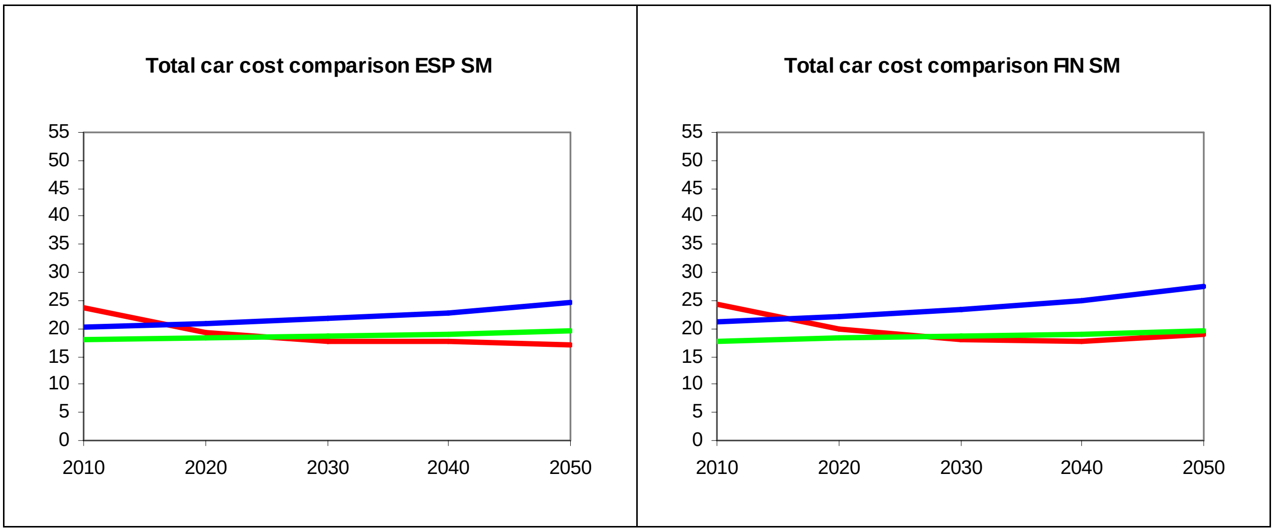
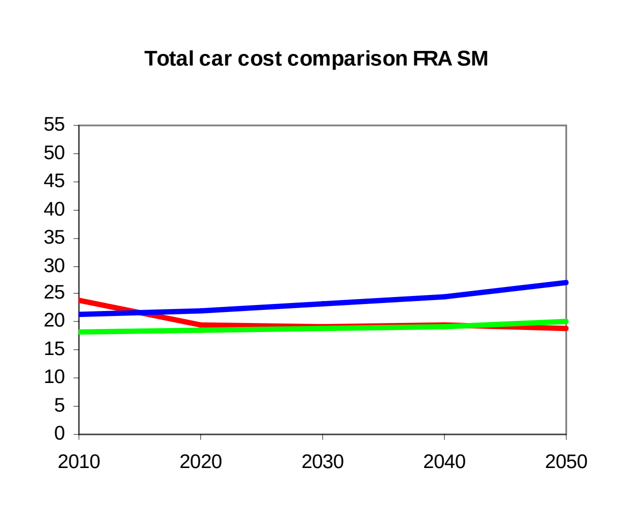
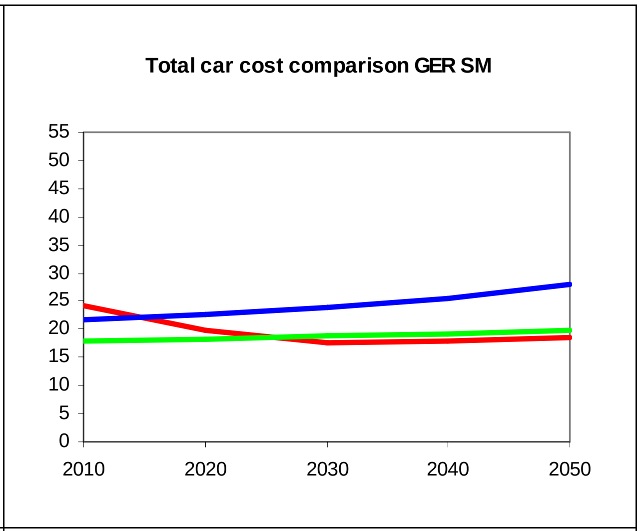
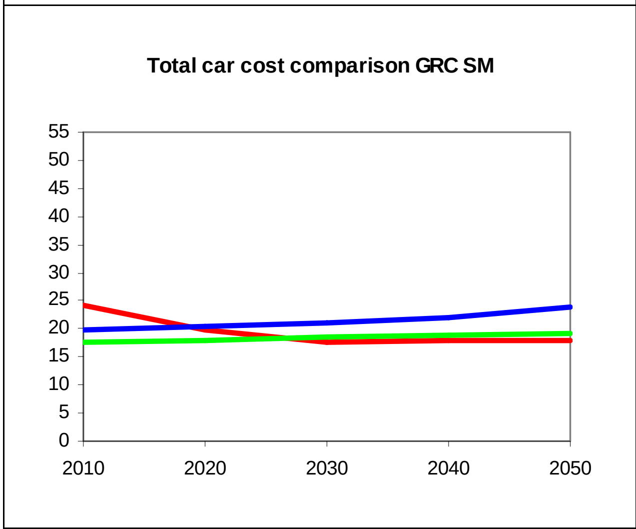


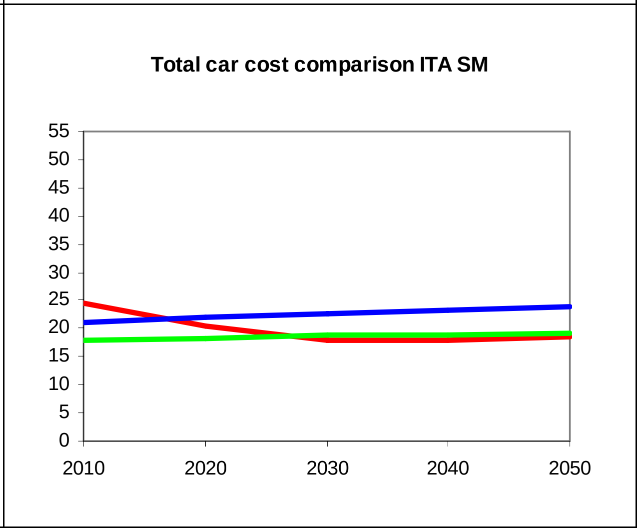
Figure 37: Cost comparison of small cars

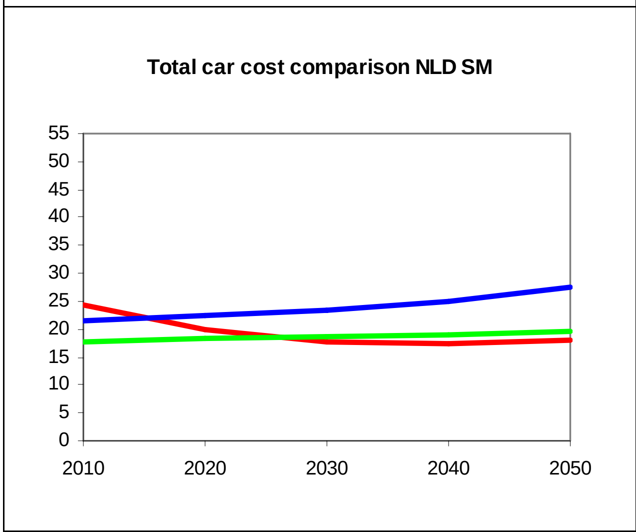


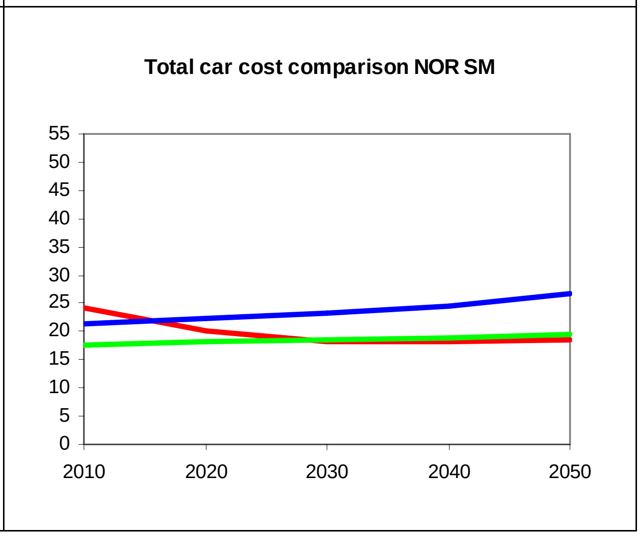

Total car cost comparison FRA SM
0 5 10 15 20 25 30 35 40 45 50 55
2010 2020 2030 2040 2050


Total car cost comparison GER SM
0 5 10 15 20 25 30 35 40 45 50 55
2010 2020 2030 2040 2050


Total car cost comparison GRC SM
0 5 10 15 20 25 30 35 40 45 50 55
2010 2020 2030 2040 2050


Total car cost comparison ITA SM
0 5 10 15 20 25 30 35 40 45 50 55
2010 2020 2030 2040 2050


Total car cost comparison NLD SM
0 5 10 15 20 25 30 35 40 45 50 55
2010 2020 2030 2040 2050


Total car cost comparison NOR SM
0 5 10 15 20 25 30 35 40 45 50 55
2010 2020 2030 2040 2050

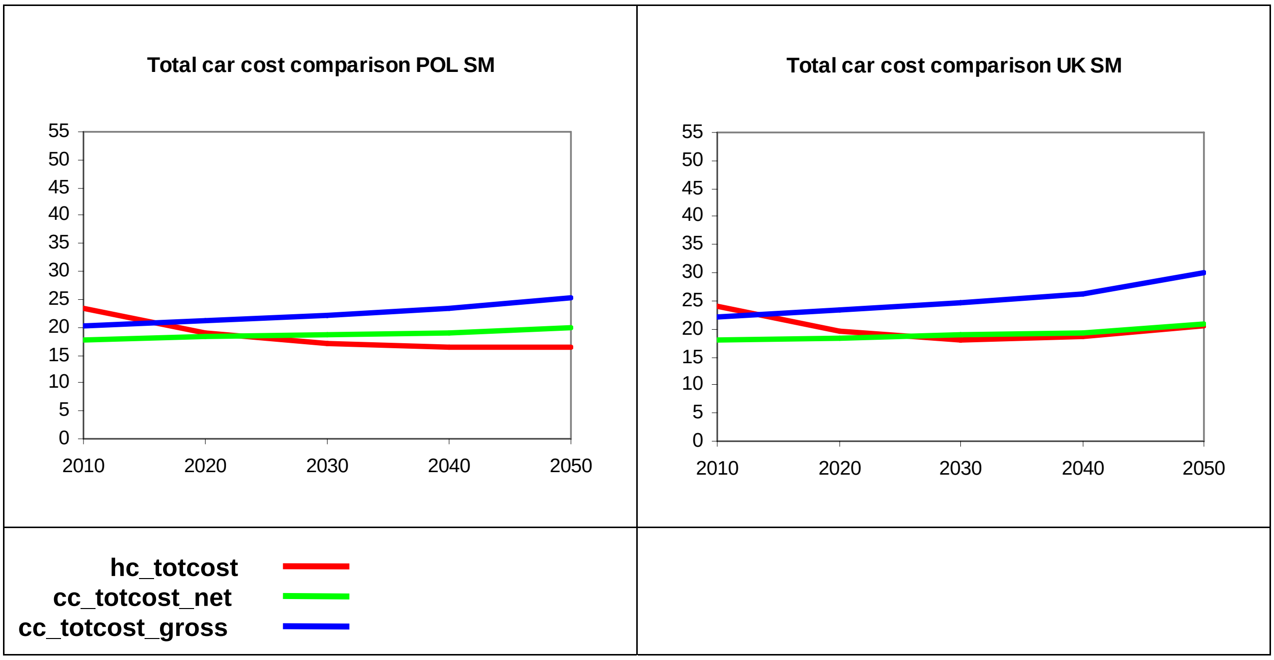
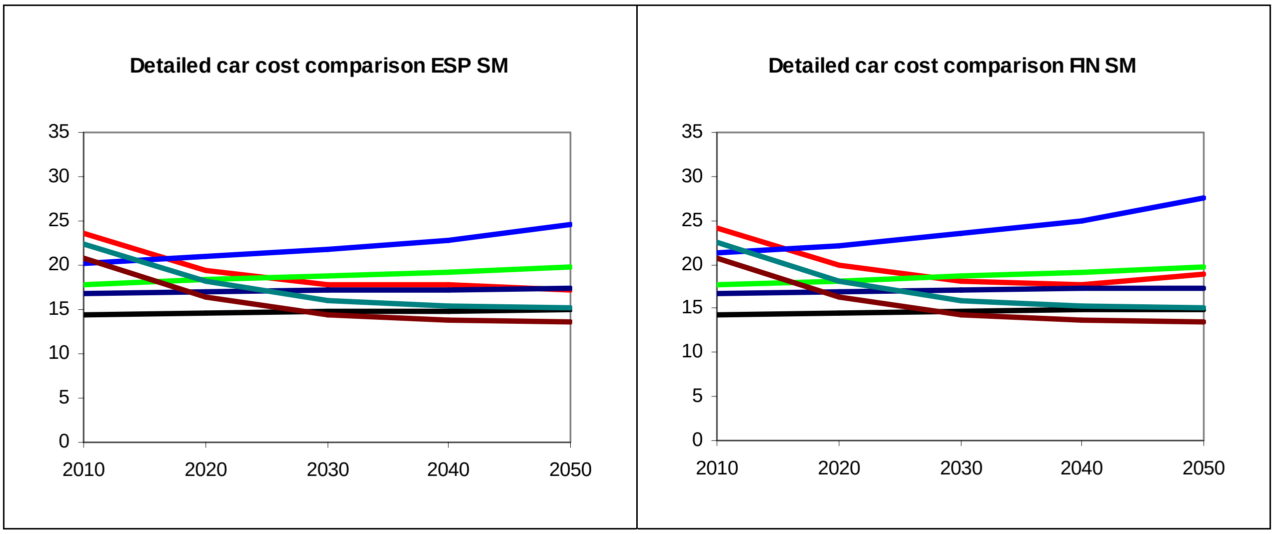
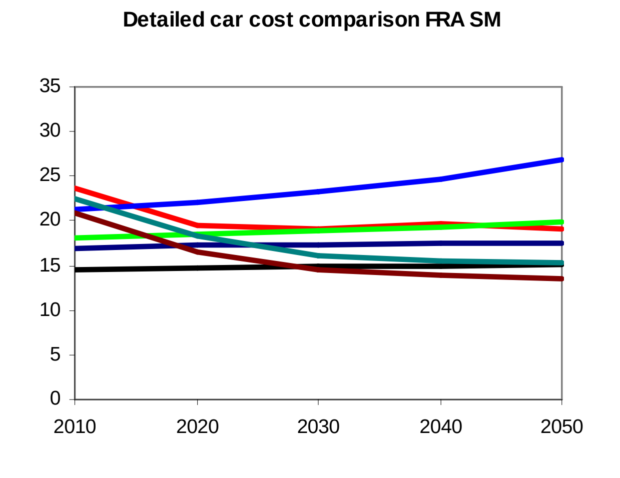


Figure 38: Detailed cost comparison of small cars




Detailed car cost comparison FRA SM
35
30
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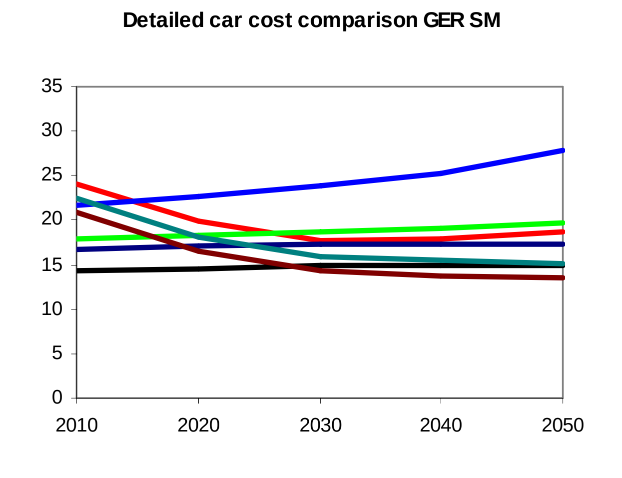
Detailed car cost comparison GER SM
35
30
25
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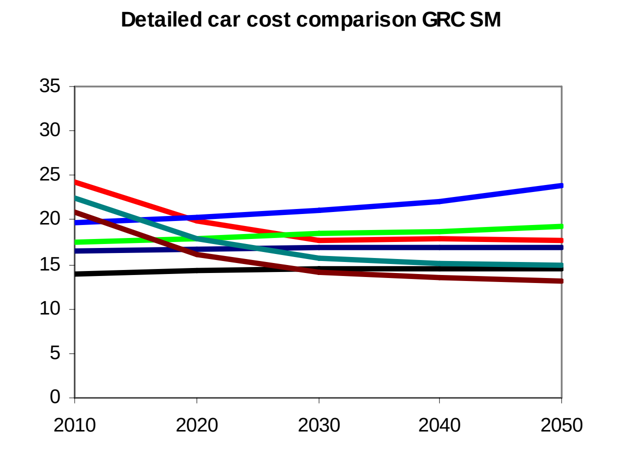
2050


Detailed car cost comparison GRC SM
35
30
25
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2010
2020
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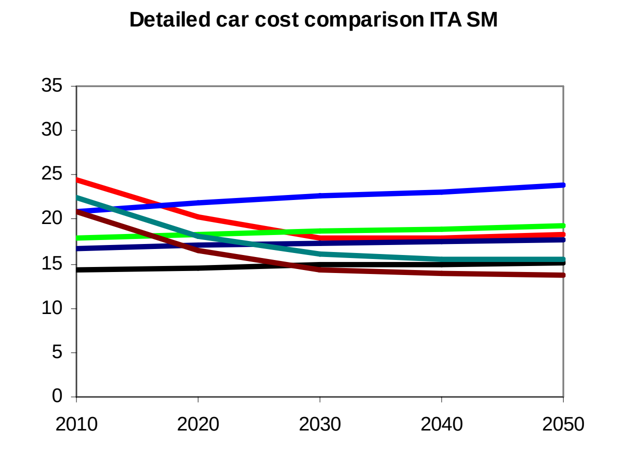
2040
2050


Detailed car cost comparison ITA SM
35
30
25
20
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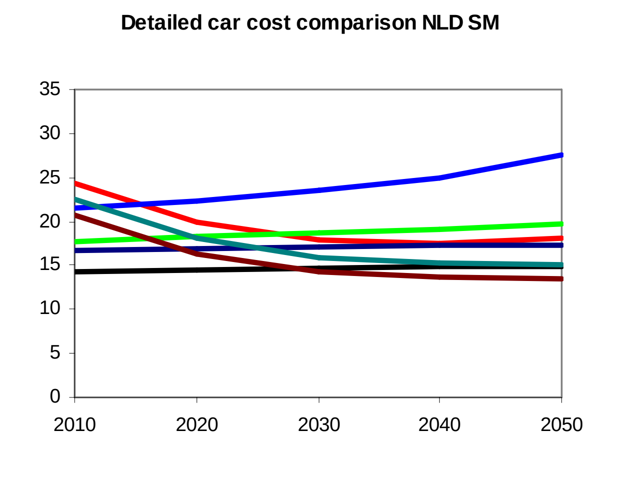
10
5
0
2010
2020
2030
2040
2050


Detailed car cost comparison NLD SM
35
30
25
20
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5
0
2010
2020
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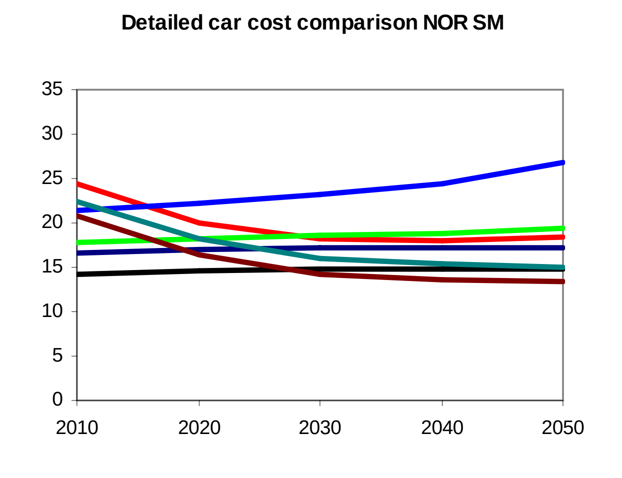
2050


Detailed car cost comparison NOR SM
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30
25
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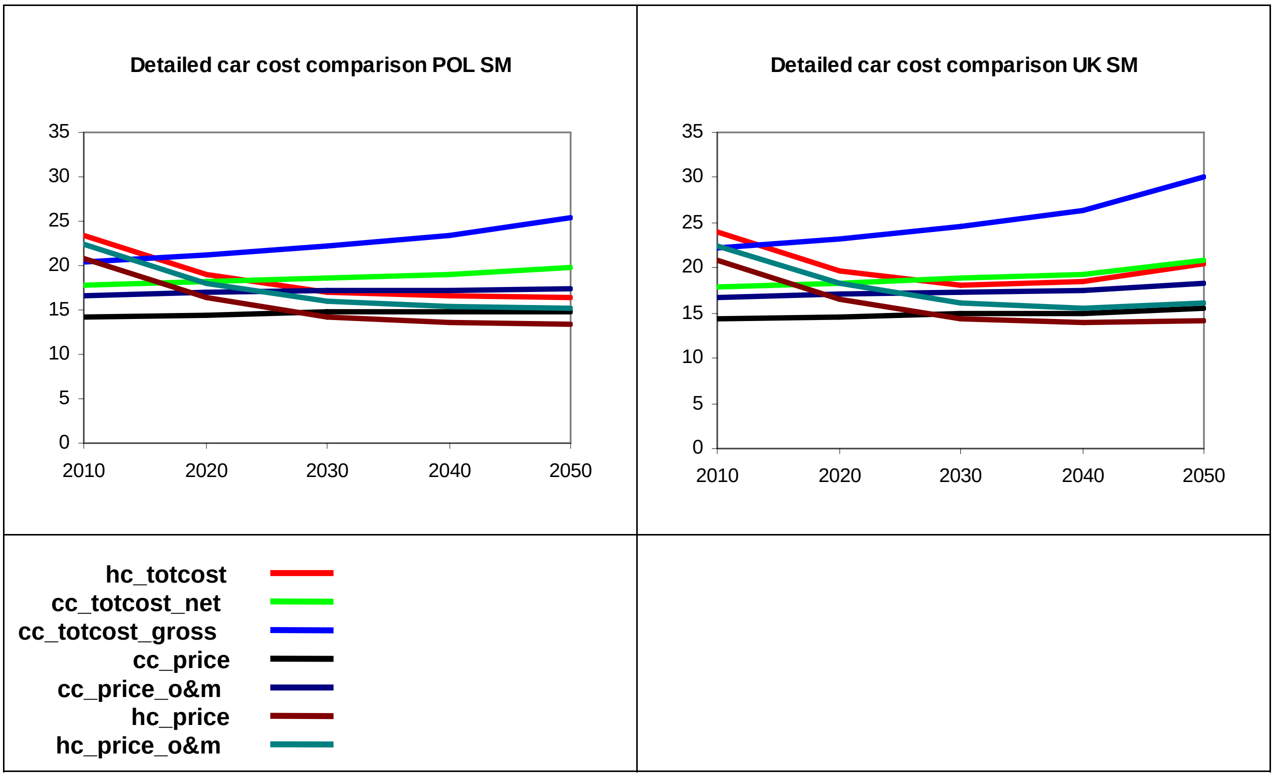
15
10
5
0
2010
2020
2030
2040
2050


Detailed car cost comparison POL SM
Detailed car cost comparison UK SM
35
30
25
20
15
10
5
0
2010
2020
2030
2040
2050
hc_totcost
cc_totcost_net
cc_totcost_gross
cc_price
cc_price_o&m
hc_price
hc_price_o&m