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Energy system aspects of hydrogen as an alternative fuel in transport

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Abstract

Considering the enormous ecological and economic importance of the transport sector the introduction of alternative fuels—together with drastic energy efficiency gains—will be a key to sustainable mobility, nationally as well as globally. However, the future role of alternative fuels cannot be examined from the isolated perspective of the transport sector. Interactions with the energy system as a whole have to be taken into account. This holds both for the issue of availability of energy sources as well as for allocation effects, resulting from the shift of renewable energy from the stationary sector to mobile applications. With emphasis on hydrogen as a transport fuel for private passenger cars, this paper discusses the energy systems impacts of various scenarios introducing hydrogen fueled vehicles in Germany. It identifies clear restrictions to an enhanced growth of clean hydrogen production from renewable energy sources (RES). Furthermore, it points at systems interdependencies that call for a priority use of RES electricity in stationary applications. Whereas hydrogen can play an increasing role in transport after 2030 the most important challenge is to exploit short–mid-term potentials of boosting car efficiency.

Keywords: Hydrogen; Alternative fuels; Energy systems analysis

1. Alternative fuels—the key to mitigating the environmental impacts of transport

What kind of fuel will we use for our cars tomorrow? Considering the enormous ecological and economic importance of the transport sector this question touches upon a core element of sustainable development. The introduction of alternative fuels—together with drastic energy efficiency gains—will be a key to sustainable mobility, nationally as well as globally.

In all western economies vigorous activities aim at mitigating the environmental impacts of transport while reducing the risks of a geopolitical dependence on oil. The European Commission's White Paper *A European Transport Policy for 2010* (2001b), for instance, predicts a growth of European CO_2 emissions in transport by 50% up to some 1.1 billion tons for the period between 1990 and 2010. The White Paper comes to the conclusion that a viable way of reducing greenhouse gas emissions is the introduction of cleaner alternative fuels. This would also lower the present dependence of the European transport sector on oil, which is currently at 98%. The EU Commission has specified first political targets for the sector of road traffic, laying down that by the year 2020, alternative fuels should replace 20% of conventional fuels (European Commission 2001a, b, c).

Natural gas and biofuels are seen as the most important short-term options for meeting these goals, whereas in the long run, a substantial contribution is expected to be delivered by hydrogen (H_2) and the fuel cell technology. The basic assumption here, that hydrogen is a clean energy carrier that under certain conditions is abundantly available, is gaining more and more political impetus, as growing budgets for related research show. The US government, for example, recently announced planned investments of some 1.7 billion US$ in the FreedomCAR and hydrogen fuel initiative set up to develop fuel cell cars powered by hydrogen and to establish the related H_2-infrastructure. Comparable activities can be found in Japan, and the EU is also intensifying efforts to prepare for the future hydrogen technology markets (European Commission, 2003a).

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However, the future role of alternative fuels cannot be examined from the isolated perspective of the transport sector. Interactions with the energy system as a whole have to be taken into account. This holds both for the issue of availability of energy sources as well as for allocation effects, resulting from the shift of renewable energy from the stationary sector to mobile applications.

Key questions that often remain open are how to deliver the hydrogen in a sustainable manner and in sufficient quantities, and how to integrate the new H_2 option into tomorrow's changing energy and transport infrastructures. From an environmental point of view, the abatement of local emissions related to transport, such as NO_x, VOC, particles, noise, etc., is not the only reason for promoting hydrogen (European Commission, 2003b). An equally important challenge is the transformation of a transport system based on exhaustible resources to a system relying on renewable energy sources (RES), and, moreover, achieving a drastic reduction of transport-related GHG emissions.

For that reason, in the long run any sustainable hydrogen economy can only rely on clean primary energy sources—commonly seen as RES. In addition, on the international scale a wide range of options is under debate including nuclear power and the use of coal in combination with carbon capture and sequestration (European Commission, 2003a; DOE, 2003).

These primary energy options, however, need to be discussed independently from the energy carrier hydrogen. Regardless of any fuel cell application it is often questioned whether nuclear energy will become ever a sustainable option as it involves certain inherent technology risks. The problem of nuclear waste disposal still remains unsolved, and few societies fully accept nuclear energy. The large-scale use of fossil fuels in combination with carbon sequestration (e.g. via coal gasification), where manifold technical, economic and ecological aspects remain unclear, is a doubtful option, too. Even putative technological breakthroughs cannot extend the future potential of carbon sequestration beyond the limits of the availability of suitable reservoirs and the economic obstacles to large-scale carbon management. In both cases, normative decisions need to be taken by energy policy and society whether in principle to accept these routes for any final energy use or not.

Different to this controversy there is a broad consensus that in any case RES will have to play a central role for any future hydrogen energy system (green hydrogen, solar hydrogen). For that reason, in the following sections the focus will be put on the energy system's interdependencies between hydrogen production and the availability of RES.

2. The introduction of hydrogen as a new fuel

A common perception is that the vision of a solar hydrogen economy should be realised in the course of the 21st century. Divergent views, however, can be found once it comes to the short to mid-term strategies. Worldwide, a common approach to market introduction is still lacking. In any case, it will take time to extend the capacity of clean primary energy sources for hydrogen production and establish an appropriate infrastructure. For the period of transition, therefore, bridging solutions with low environmental impacts and risks have to be found that allow using exhaustible resources more efficiently.

The introduction of alternative fuels will require significant, long-term investments for setting up and expanding infrastructures. This is especially true in the case of a hydrogen economy based on renewables. Today's decisions, therefore, should be oriented toward robust options with stable prospects even under changing future framework conditions. Long-term scenarios are one tool for finding robust options because they allow outlining future developments of energy systems in relation to a variety of framework conditions and policy settings. These scenarios refer to the total energy system so as to provide a complete balance of energy consumption and GHG emissions, and to take shifts between different sectors into account. A scenario analysis is needed because depending on how fast the share of H_2 vehicles grows, the impacts on final energy consumption, the energy demand for hydrogen, and the resulting GHG emissions will differ.

This paper builds on a recent study (Ramesohl et al., 2003) that is based on the long-term scenario assembled by the German Federal Environmental Agency (Umweltbundesamt UBA; Fischedick et al., 2002). Its analysis of the energy system provides the basis for our more detailed investigation of the transport sector. The motorised individual transport sector has been chosen as matter of investigation, because there are far more choices for different alternative fuels and power train technologies than in any other transport sector. Its high relevance to the fuel problem makes this sector of private passenger cars, i.e. vehicles of up to 2.8 t weight, an ideal example for discussing the impacts of different strategies of introducing alternative fuels. Comparable analyses are possible for all remaining sectors and can be extended to a European perspective.

Three pathways have been outlined for the analysis of the impacts that the introduction of hydrogen has on the energy system (Table 1). They vary in terms of the share of H_2 vehicles over time:

- A forced introduction pathway is based on the assumption that 100% coverage of hydrogen vehicles will be realised between 2010 and 2035. This path reflects an extreme case with politics and industry pushing ahead the H_2 strategy at top speed.
- The stretched introduction describes a slower, but nevertheless complete introduction of hydrogen between 2010 and 2050.
- The moderate introduction leads to a share of 50% of hydrogen vehicles by 2050 (beginning in 2010), which is considered to provide a sufficient foundation for

Table 1
Assumptions on introduction pathways for hydrogen vehicles in Germany (private passenger cars only)

	2000	2010	2020	2030	2040	2050
Total car stock in Germany [Mio. cars]	42.4	48.9	50.2	50.1	47.8	43.7
Stock share H2-cars						
Forced introduction	0%	0%	20%	82%	100%	100%
Stretched introduction	0%	0%	2%	12%	59%	100%
Moderate introduction	0%	0%	2%	10%	22%	49%

Source: Ramesohl et al., 2003.

achieving a hydrogen economy some time after 2050.

These three pathways illustrate very different approaches to a hydrogen system. They are no prognoses or market studies. On the contrary, their purpose is to outline possible futures and provide a basis for a discussion of the impacts that different modes of hydrogen production and use have on the energy system and the ecosystem. As an observation, until 2030 the stretched and the moderate introduction follow the same path, i.e. for a certain time the same strategy will keep the flexibility to end up at two quite different levels.

3. Background and methodology

3.1. Specific GHG emissions of fuel chains

A full assessment of the energy and ecological aspects of the various fuel paths requires an evaluation of conversion efficiencies and specific emissions along the entire fuel process chain. First, this concerns fuel processing from the primary energy source to the vehicle, i.e. the specific GHG emissions per unit of final energy [g CO_2eqv/MJ]. The specific emission factors used in the study for the selected fuel pathways are depicted in Table 2. In the case of renewable energy paths it has to be kept in mind that these values are seen from the perspective of the transport sector only and do not take systemic effects into account.

Second, the total emissions of a fuel pathway are strongly affected by the propulsion technology that converts fuel to motion on board the vehicle. The efficiencies of the Otto engine, the diesel engine, the hydrogen internal combustion engine or the hydrogen fuel cell can differ quite significantly. The values for conversion efficiency [MJ/km] of the selected propulsion technologies are depicted in Table 3.

3.2. Specification of the specific fuel consumption of car fleet

Regardless of any alternative fuel, energy demand and GHG emissions of the whole vehicle fleet will change. Important driving factors are overall car use (kilometres per person and year), progress in vehicle technology and a changing mix of vehicle types in the total fleet. Independently from the discussion on alternative fuels, therefore, two lines of development of the average energy consumption of cars between 2000 and 2050 are defined:

- Consistent with current trends it is possible to assume that average fleet consumption will drop by a range of 43% (diesel) and 57% (fuel cell vehicle) between 2000 and 2050. This trend projection builds on a foreseeable variety of improved technologies including aerodynamic improvements, lightweight construction, a demand shift toward smaller cars, etc[1]. Even without a significant replacement of gasoline and diesel with alternative fuels, these reductions in specific fleet consumption will induce significantly lower GHG emissions. This business-as-usual case (BAU) will lead to a decrease of emissions from 135 million tons CO_2eqv in the year 2000 to 78.3 million tons CO_2eqv in 2050.
- This, however, falls short of an ambitious sustainability target, i.e. a reduction to 30.4 million tons CO_2eqv by 2050 that is based on the German Federal Environmental Agency's sustainability scenario mentioned below, which calls for an 80% reduction of total GHG emissions between 1990 and 2050. Meeting this goal without any contribution from new fuel options would require a reduction of average fleet consumption by some 80% by 2050 compared to 2000—no doubt an enormous challenge. A high-savings case was therefore outlined to describe an extreme development where a combination of all kinds of energy saving measures results in an average fleet consumption of around 2 l gasoline/100 km by 2050.

Starting point for the model calculations are the current long-term scenarios for the German Federal Environmental Agency (UBA), i.e. the reference (REF) and the sustainability (NH) case (Fischedick et al., 2002). As a basic assumption for the BAU-case of this exercise, a common development of transport demand has used according to the UBA-REF scenario, excluding any consumer behaviour related traffic reductions (Table 4). As point of departure, a base case relying on a mix of conventional fuels (2/3 gasoline and 1/3 diesel) without any

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[1] LBST, 2002b, Dauensteiner, 2002, Petersen and Diaz-Bone, 1998.

Table 2
Selected emission factors of hydrogen fuel chains compared to gasoline and diesel

Specific GHG-emissions	Fuel chain ($g\,CO_2eqv/MJ$)	Vehicle emissions ($g\,CO_2eqv/MJ$)[a]	Local CH_4 and N_2O emissions ($g\,CO_2eqv/MJ$)[b]	Total ($g\,CO_2eqv/MJ$)
Gasoline	12.5	73.4	2.4	88.3
Diesel	14.2	72.8	1.7	88.7
CGH_2 700 bar (EU gas mix, decentral. MSR)	104.6	0.0		**104.6**
CGH_2 700 bar (waste wood gasification)	10.7	0.0		**10.7**
CGH_2 700 bar (wind power, decentral. electrolysis)	0.0	0.0		**0.0**
LH_2 (MSR)	124.0	0.0		**124.0**
LH_2 (wind power, central electrolysis)	2.0	0.0		**2.0**

Source: CONCAWE, EUCAR, JRC, 2003, LH_2 paths are taken from LBST (2002a).
Renewable energy paths are seen from the transport sector and do not reflect systemic effects.
CGH_2: compressed hydrogen; LH_2:liquefied hydrogen; MSR:methane steam reforming

[a] CO_2 content of fuel.

[b] Conventional drive trains.

Table 3
Assumptions on the development of specific fuel consumption of selected power trains

Trend (BAU)	2000 (MJ/Pkm)	2010 (MJ/Pkm)	2020 (MJ/Pkm)	2030 (MJ/Pkm)	2040 (MJ/Pkm)	2050 (MJ/Pkm)	2000–2050 (%)
Gasoline	2.10	1.74	1.50	1.37	1.26	1.16	−45
Diesel	1.92	1.53	1.38	1.28	1.19	1.10	−43
Hydrogen ICE	2.10	1.56	1.35	1.23	1.15	0.95	−55
Hydrogen FC	2.10	1.25	1.20	1.10	1.00	0.90	−57
High-Saving (HS)							
Gasoline	2.10	1.67	1.33	1.05	0.86	0.45	−79
Diesel	1.92	1.59	1.25	1.00	0.81	0.43	−78
Hydrogen ICE	2.10	1.51	1.19	0.94	0.63	0.41	−80
Hydrogen FC	2.10	1.25	1.05	0.90	0.60	0.39	−81

ICE: internal combustion engine; FC: fuel cell; Pkm: person-kilometre.*Source*: Ramesohl et al., 2003.

Table 4
Set of key parameters used for scenario calculation (drivers for vehicle use and conversion efficiencies)

Parameter	Unit	Year					
		2000	2010	2020	2030	2040	2050
Traffic intensity	Bil. Pkm	744.3	864.4	899.2	897.1	856.8	783.7
Car passenger number	Persons	1.41	1.42	1.44	1.44	1.44	1.44
Car stock	Mil. cars	42.4	48.9	50.2	50.1	47.8	43.7
Car driving distance	km/a	12.442					
Conversion efficiencies							
Steam reforming (MSR)	%	66.3	68.5	70.0	70.0	70.0	70.0
Electrolysis	%	73.8	76.0	77.0	80.0	80.0	80.0
H_2-liquefaction	%	72.4	74.7	77.1	77.1	77.1	77.1
H_2-compression up to 80 Mpa[a]	%	81.4	81.4	82.2	83.0	83.9	84.7
Share of H_2-generation in Mix-path							
RES-electrolysis, MIX-path	%	0	0	5	20	40	65
MSR, MIX-path	%	100	100	95	80	60	35
Full load hours wind power	h/a	2.000					

Pkm: person-kilometre; MSR: methane steam reforming; RES: renewable energy sources.
Source: Ramesohl et al., 2003

[a] Value for CGH2-refueling station

alternative fuel has been defined. Against this background the impact of the selected fuel paths was studied by increasing the share of the specific fuel option while decreasing the share of conventional fuels homogeneously to the debit of gasoline and diesel. The total car stock in the year 2000 has been linearly extrapolated until 2050 in correspondence to the development of the transport demand[2] and the average car passenger number. With respect to the average yearly driving distance however it has been assumed that it will remain constant over the time horizon (i.e. unchanged mobility behaviour). The analysed time horizon covers the decades between the year 2000 and 2050.

4. The key question: where does the hydrogen come from?

The use of hydrogen as a fuel has the advantage that hydrogen-driven vehicles will produce hardly any emissions but vapour. The energy inputs and major ecological impacts of hydrogen production, transport and distribution are to be found in the fuel chain, which therefore needs to be submitted to closer scrutiny.

Conventional hydrogen production through methane steam reforming (MSR) causes specific emissions of 103 g CO_2 eqv/MJ, i.e. some 18% higher than the gasoline/diesel fuel chain. As the fuel cell propulsion system promises to be some 30–40% more efficient than the conventional ICE, an overall (well-to-wheel) reduction of GHG emissions takes place. In the case of stretched introduction in combination with improvements in fuel cell vehicle efficiency consistent with the trend line, the MSR path will lead to a decrease of GHG emissions by nearly 8% compared to the BAU case (72.6 million tons vs. 78.7 million tons by 2050). In a scenario that ignores the issue of resource availability in the phase of transition, the use of natural gas as a feedstock for hydrogen production will induce slightly positive effects without substantially contributing to the ambitious targets for climate change mitigation.

In the long run, however, hydrogen production based on fossil energies is not an option. For implementing a climate-friendly and sustainable hydrogen system it will be essential at what time and to what degree RES can cover transport-related energy demands. RES, however, cannot be examined from the isolated perspective of the transport system. Interactions with other areas need to be taken into account. A holistic energy system analysis reveals that the near future is rather less bright where hydrogen is concerned:

- Assuming progress in vehicle technology consistent with current trends, even the stretched introduction induces a demand for compressed hydrogen (CGH_2) of some 700 PJ in the year 2050. Taking into account the conversion losses for electrolysis and compression, the required amount of renewable electricity reaches 289 TWh (Fig. 1), which corresponds to more than 50% of total electricity generation in Germany in the year 2001 (534 TWh) and exceeds the current production from RES (36.3 TWh in 2001) by more than seven times. It will not be easy to deliver this amount. Comparable obstacles arise for the use of biomass as the primary energy source for hydrogen.

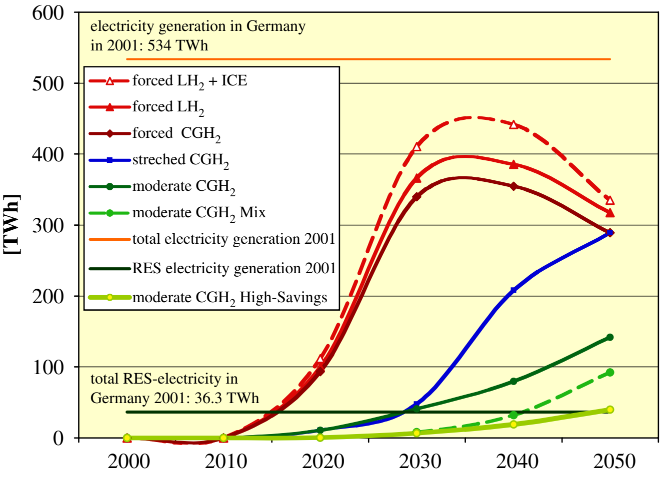

Fig. 1. Overview of hydrogen pathways and the resulting demand for RES electricity.

- In the forced introduction case, hydrogen will be needed much earlier to reach a 100% share in 2035. Several driving factors that diminish energy demand after 2030 such as declining population, more efficient cars, etc. do not yet come to bear at this point. Energy demand accordingly rises to an intermediate peak of 850 PJ H_2 and approx. 355 TWh RES electricity in 2040.
- The retarded moderate introduction represents a share of 50% in 2050 and thus leads to a lower energy demand for hydrogen (346 PJ H_2) and RES electricity (144 TWh) in 2050. Compared to today's level, however, even these figures require an increase in RES capacity by three or four.
- The demand for RES electricity decreases further if hydrogen is produced not only through electrolysis but in a generation mix. Assuming an initial 100% coverage by MSR followed by a growing share of RES electrolysis reaching 60% in 2050, the maximum demand for RES electricity is 90 TWh in 2050. If the high-savings path materialises, only 40 TWh will be needed. These figures are in a much more realistic range.
- Compared to compressed gas hydrogen (CGH_2), additional losses occur in the case of hydrogen liquefaction (LH_2), which induces an additional demand for RES electricity. In the forced introduction case, the maximum for LH_2 will be reached in the year 2035 (386 TWh, i.e. +23% compared to the CGH_2 path). Compared to the CGH_2 + fuel cell option, even more losses occur when using LH_2 in an internal combustion engine, raising the maximum to 440 TWh in 2035 and surpassing the CGH_2 case by 40%[3].

Theoretically, the potentials for producing the required amount of RES electricity do exist. But it is quite

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[2] Mainly triggered by the development of population.

[3] BMW announced a significant improvement of the hydrogen ICE (BMW, 2003).

unrealistic to suppose that they can be fully exploited. Even with a mix of different RES, it will hardly be possible to reach the required capacities in so little time, especially since other end-use sectors increasingly call for RES, too.

These limits to growth can be illustrated by the case of wind power, which is commonly regarded as the most promising and fast-growing RES option. Assuming a load factor of 2000 h/a, the demand of 290 TWh (stretched introduction) corresponds to a capacity enlargement by 145,000 MW. Consider, as a comparison, that in 2001 the complete power park in Germany added up to a total capacity of 102,000 MW. In the case of a moderate introduction and a hydrogen generation mix, in contrast, a demand of 90 TWh has to be met. This equals a wind energy capacity of 45,000 MW, a figure well in line with the current planning of off-shore wind parks in Germany.

It would be wrong to conclude, however, that the vision of a renewable hydrogen system will have to be abandoned. On the contrary, a first intermediate result is that the current expansion of RES needs to be pursued and accelerated. Special attention should be given to technologies with base load characteristics such as geothermal power (HDR) and the possibilities of importing RES electricity e.g. from solar thermal power plants in the south of Europe. At the same time, however, it becomes evident that only significant efficiency gains in all end-use sectors can reduce the demand for renewable energy to a realistic level. Taking these preconditions into account and applying a suitable long-term time frame, hydrogen is and will be an environmentally sound fuel option.

4.1. *The input of renewable energies has to be optimised*

In addition to the limits of capacity growth there is another short- to mid-term problem for RES input into hydrogen production: The various energy carriers can be used for different stationary and mobile applications. From the system perspective, therefore, the input of RES with limited availability has to be optimised as far as possible, i.e. each energy carrier has to be used in the way that most benefits both the environment and the total energy system.

Consider the following example: Under current conditions, 1 kWh of RES electricity can substitute enough public-grid generation to prevent specific emissions of some 590 g CO_2eqv/kWh. If RES electricity is used in electrolysis and therefore, in the end, for hydrogen vehicles, a reduction of specific emissions by 191 g CO_2 eqv/kWh can be achieved. Direct use in the electricity system, in turn, yields a contribution to climate change abatement that is nearly three times higher than in the transport sector.

To put it the other way around, since the potentials for renewables are limited, any shift of RES electricity to the transport sector creates a need to maintain fossil power production or even build new capacities. This is a bad bargain for the environment, but the next decades are unlikely to bring a better one (Fig. 2). For these reasons, using RES for hydrogen electrolysis is by no means an emission-free option, but induces emissions from fossil power plants needed to meet the stable electricity demand of end users. In a holistic assessment of the energy system, the resulting specific emissions have to be assigned to hydrogen production from renewables.

4.2. *Holistic assessment of the specific emissions of hydrogen production from renewables*

The ecological impacts at the system level are illustrated in Fig. 3, taking the stretched introduction (100% hydrogen vehicles by 2050) as an example. The specific

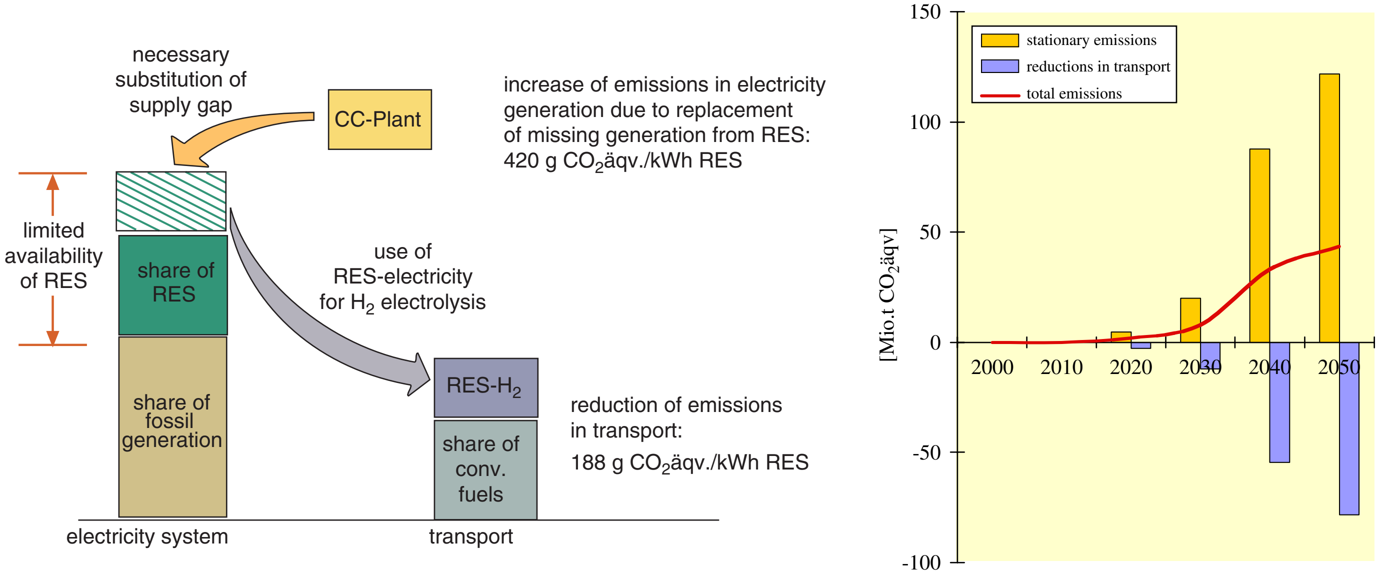

Fig. 2. Holistic assessment of the specific emissions of hydrogen production from renewables.

energy consumption of the vehicle fleet improves in accordance with the trend line (BAU).

If we consider the transport sector in isolation, it does look as though using RES electricity could cut specific GHG emissions down to zero (CGH_2 RES, isolated view). For the holistic assessment a best-case assumption was made, i.e. the resulting supply gap is covered by new, highly efficient combined-cycle power plants (spec. emissions of 421 g CO_2eqv/kWh). The overall emissions related to the CGH_2 supply jump to 121.8 million tons CO_2eqv in 2050 (CGH_2 RES, system view) (Table 5). This path even surpasses the BAU case, which relies heavily on fossil fuels, by 50%. With the present generation mix in Germany, specific emissions would be at approx. 590 g CO_2eqv/kWh, with worse results in the net balance.

Using RES electricity in hydrogen fuel generation is counter-productive from an ecological point of view as long as the specific emissions of the German electricity system are above 191 g CO_2eqv/kWh. This level represents a share of RES in total power generation of more than 50%. Even the ambitious UBA sustainability scenario does not expect this situation to be achieved before 2040, and then only with the help of imported electricity from solar thermal power plants.

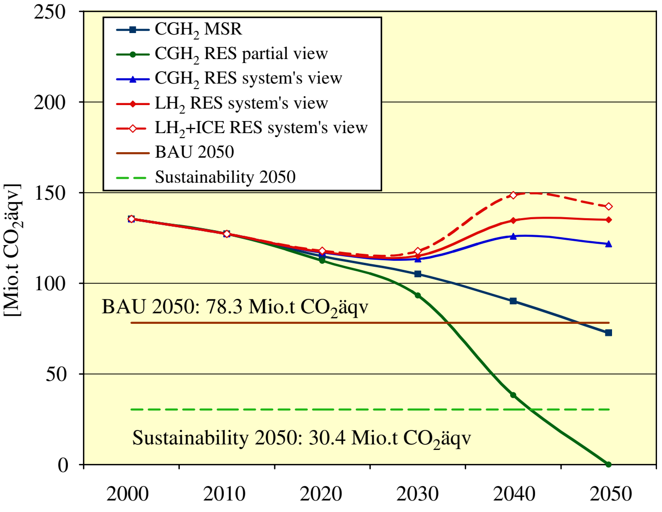

Fig. 3. Holistic assessment of the specific emissions of hydrogen production—stretched introduction (100% by 2050).

4.3. Limits to an acceleration of hydrogen production of renewables

The simulation exercise demonstrates quite obvious that any strategy to establish a renewable hydrogen system has to take into account the limits to accelerating the growth of RES capacity in Germany. Comparable obstacles hamper RES imports from foreign sources since the countries of origin also need to discuss the allocation of RES. And finally, building the necessary infrastructures for energy transport will simply need time. In theory, the RES potentials appear to be sufficient for covering the total energy demand of the passenger car sector before the year 2050. In reality, however, it will hardly be possible to access these capacities without violating other criteria of sustainable development.

In terms of hydrogen production from RES electricity, a realistic and ecologically sound pathway can only be achieved if

- the final energy demand for H_2 can be reduced through a substantial decrease of average fleet consumption (high savings), and
- the new fuel option H_2 is introduced along a moderate introduction and the production is based on a generation mix that starts from MSR and slowly converts to the use of RES.

Moreover, in this context hydrogen pathways that incorporate relatively high conversion losses have to be seen critically. In the case of a development consistent with current trends, a 100% introduction of LH_2 for internal combustion engines will most likely fail to deliver a contribution to climate change abatement compared to the BAU case without alternative fuels.

When considering the use of RES for mobile applications, one has to take into account that for the decades to come, higher emission reduction effects are likely to be achieved in the stationary sector. One example is the substitution of fossil power plants through RES electricity. From a holistic energy system perspective, the input of renewable energies into hydrogen electrolysis will induce an overall net increase of GHG emissions.

Table 5
GHG-Emissions of analysed fuel paths (in Mil. t CO_2-Äqv.)

Fuel path	2000	2010	2020	2030	2040	2050	2000–2050 cumulative
BAU (basis path)	135.5	127.3	115.1	105.4	92.9	78.3	5.584
BAU_stretched_CGH2_MSR	135.5	127.3	115.0	105.1	90.1	72.6	5.519
BAU_stretched_CGH2_RES isolated view	135.5	127.3	112.4	93.3	38.4	0.0	4.459
BAU_stretched_CGH2_RES systems view	135.5	127.3	117.0	113.4	126.0	121.8	6.251
BAU_stretched_LH2_RES systems view	135.5	127.3	117.3	115.1	134.6	135.1	6.432
BAU_stretched_LH2_ICE_RES systems view	135.5	127.3	118.0	117.8	148.6	142.5	6.645

Source: Ramesohl et al., 2003.

As long as the total energy system relies largely on fossil fuels, substitution effects will eliminate any gains from RES-based hydrogen production for transport uses. A clean and abundant energy source for transport will not be available for quite some time.

An accelerated introduction (100% coverage as early as 2035) does not provide any advantages for climate change mitigation. In effect, compared to the stretched introduction, a higher energy and hydrogen demand would result. From a climate policy point of view, there is no need for an accelerated introduction of the hydrogen ICE as an end-use application.

5. Conclusions

The analysis has shown that a substantial decrease in the average energy consumption of the vehicle fleet is a necessary condition if the long-term GHG reduction targets essential to combating climate change are to be met. Alternative fuels can complement the required energy saving measures and broaden the scope of action, but do not obviate the need for massive efficiency gains.

In this context, a forced introduction of hydrogen as an alternative transport fuel before the year 2050 does not promise any substantial contribution to mitigating GHG emissions, nor is it necessary from the holistic energy systems perspective if the two key strategies, energy efficiency and growth of renewable energies, are vigorously pushed ahead in all energy sectors. This means both squeezing the energy demand of the vehicle fleet as well as realising the energy efficiency potential in stationary applications, which would relieve some of the demand pressure on scarce RES supplies. Once RES are available in large quantities and form a major part of the energy supply, a situation targeted for 2050, hydrogen can play its role in supporting RES up to the ultimate goal of a practically GHG-free energy system. Summing up, different phases of increasing the share of RES and introducing alternative fuels can be distinguished in the transition to a hydrogen system:

- Until 2010: Entry phase into short-term alternative fuels and acceleration of RES growth backed by energy policy through target setting and support policies.
- 2010–2020: Stabilisation of RES growth and gradual withdrawal of policy support, consolidation of the contribution of CNG and biofuels.
- 2020–2035: Full consolidation of new RES technologies in all end-use sectors and start of trans-European exchange of RES energy, first application of hydrogen in distinctive niches while maintaining the established alternative fuels.
- 2035–2050: Growing dominance of RES in all end-use sectors and start of significant use of hydrogen.
- Beyond 2050: Gradual substitution of fossil energy by RES and large-scale establishment of hydrogen from RES in order to realise a hydrogen system by the end of the 21st century.

The paper discussed the energy- and climate-policy aspects of an introduction of alternative fuels in the sector of private passenger cars. To provide a comprehensive analysis of the whole transport sector, the next step should focus on the areas of freight and public transport, which are characterised by specific conditions and market mechanisms. The basic conclusions, however, are not likely to change substantially. In fact, they will probably underpin what we have seen with the already scarce RES reservoir and the related allocation effects: Additional demand will certainly increase competition. Moreover, the present focus on ecological criteria needs to be complemented by economic analyses of costs and business perspectives as well as other drivers of hydrogen technology such as urban air quality, technology competition, etc.

Further open questions still remain with regard to the technological aspects of bridging technologies such as natural gas (CNG) that may provide contributions to the establishment of a hydrogen infrastructure (Flynn, 2002). A more profound analysis of transition processes and the related time frame, the key technologies and synergy potentials promises to provide a better understanding of the feasibility, but also the probable costs, of the intended change of systems.

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