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Expected impacts on greenhouse gas and air pollutant emissions due to a possible transition towards a hydrogen economy in German road transport

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HIGHLIGHTS

- Emission impacts from a full shift to German H_2 mobility are studied via scenarios.
- H_2 mobility could contribute significantly to Germany's climate & air quality goals.
- Total annual emissions could be cut by up to 179 $MtCO_2eq$ if green H_2 were used.
- Shifting only HDVs to green H_2 would also aid a deep emissions cut (−57 $MtCO_2eq$).
- HDVs represent a low-hanging fruit for road transport decarbonization with FCEVs.

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ABSTRACT

Transitioning German road transport partially to hydrogen energy is among the possibilities being discussed to help meet national climate targets. This study investigates impacts of a hypothetical, complete transition from conventionally-fueled to hydrogen-powered German transport through representative scenarios. Our results show that German emissions change between −179 and +95 $MtCO_2eq$ annually, depending on the scenario, with renewable-powered electrolysis leading to the greatest emissions reduction, while electrolysis using the fossil-intense current electricity mix leads to the greatest increase. German energy emissions of regulated pollutants decrease significantly, indicating the potential for simultaneous air quality improvements. Vehicular hydrogen demand is 1000 PJ annually, requiring 446–525 TWh for electrolysis, hydrogen transport and storage, which could be supplied by future German renewable generation, supporting the potential for CO_2-free hydrogen traffic and increased energy security. Thus hydrogen-powered transport could contribute significantly to climate and air quality goals, warranting further research and political discussion about this possibility.

Abbreviations: AD, activity data; BEV, battery electric vehicle; CCS, carbon capture and storage; CG, coal gasification; DE, Germany; EF, emission factor; FCEV, fuel cell electric vehicle; GWP, global warming potential; HDV, heavy duty vehicle; ICEV, internal combustion engine vehicle; IEA, International Energy Agency; LCA, life cycle assessment; LDV, light duty vehicle; LHV, lower heating value; NIR, National Inventory Report; PC, passenger car; PEM, proton exchange membrane; SMR, steam methane reforming; SOEC, solid oxide electrolysis cell; TTW, tank-to-wheel; UBA, Umweltbundesamt (German Environment Agency).

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Introduction

Transport is one of the most emission-intensive sectors for both climate forcers and air pollutants [1–3], yet meaningful mitigation of this source proves to be particularly challenging. In 2017, German transport was responsible for 18.4% of CO_2eq emissions, 96% of which comes from road traffic [4]. While Germany has decreased its emissions considerably in most areas of the economy since 1990, abatement of the transport sector has made little progress [4]. The major reasons for this are increasing kilometers traveled, the continued dominance of fossil fuels in transport, and high average vehicular CO_2 emissions [4]. The transport sector is in large part responsible for Germany failing to meet its target of a (lasting) 40% GHG emissions cut by 2020 compared to 1990 levels [5]; namely, it was originally estimated in 2019 that Germany would only achieve a total emissions reduction of about 33% [6]. Due to extraordinary circumstances, including countermeasures taken to contain the COVID-19 pandemic, Germany is now set to meet its original 2020 reduction target [7]. However, this is not expected to be a lasting reduction—for example, transport sector emissions were back to near normal levels already by mid-June.

Hydrogen energy not only offers the opportunity to decarbonize road transport, but also to strongly reduce local air pollution [8–13]. Hydrogen is a non-toxic, colorless, odorless gas, and has been safely produced and used in industry and space exploration for decades [14,15]. It possesses the highest energy density by mass among common fuels (though not by volume), and importantly its fueling infrastructure is comparable to that of conventional road fuels. It is also versatile: hydrogen can be produced from a wide array of energy forms, including renewable electricity; it can be easily stored, such as compressed or liquefied in pure form, in a blend with natural gas, or bound with larger molecules; and it can be easily transported by pipeline, truck or ship [9]. Moreover, hydrogen use in vehicles is safe [16] and in many ways even more so than gasoline and diesel, one of the important reasons being that hydrogen is 14 times lighter than air and thus disperses rapidly in the event of a leak, thereby lowering the risk of ignition (in contrast to gasoline and diesel) [15]. The most relevant powertrain for hydrogen energy is the fuel cell electric vehicle [FCEV]: this offers the advantage of high tank-to-wheel [TTW] efficiency, roughly two to three times greater than conventionally-fueled internal combustion engine vehicles [ICEVs] [17,18]. Additionally, FCEVs have zero tailpipe emissions with the only exhaust being water vapor, and produce virtually no noise when driving [8].

FCEVs also enjoy important advantages over battery electric vehicles [BEVs], in particular longer driving ranges (≥500 km) and shorter fueling times (approx. 3 min), both being comparable to ICEVs [19,20]. The longer range is afforded through higher energy density of compressed hydrogen compared with lithium-ion batteries [9]. If battery capacity is increased to extend BEV range, battery and vehicle mass (not to mention cost) likewise increase so that more energy is required to move the vehicle itself, which leads to diminished returns on range [21,22]. Indeed FCEV's greater on-board energy storage capability make it particularly competitive for segments of the fleet that require high payloads or extended range, i.e., heavy duty vehicles, long-haul transport, and passenger vehicles for long-distance travel [9,23,24]. Furthermore, a recent survey found that 78% of automotive industry executives believe that FCEVs will be the breakthrough for electric mobility—in large part due to their short fueling time—and that the long recharging time of BEVs will remain an insurmountable obstacle to their widespread acceptance [25]. This is likewise an important aspect for the trucking industry, for which long charging times may prove to be economically unacceptable [26]. Moreover quick fueling of the hydrogen tank does not impair FCEV lifetime, whereas high charging/discharging rates, in addition to overcharging, deep discharging and the climate all negatively impact BEV battery lifetime [13]. Hydrogen fueling stations can also service more vehicles than a BEV charging station, and a greater area on account of FCEV's longer range. Finally, the material manufacturing footprint of FCEVs (fuel cells, hydrogen tank and battery) could be lower than that of BEVs (battery) [27], though there is considerable uncertainty around such comparisons at present.

Transitioning to clean hydrogen energy in road transport nevertheless faces several challenges. While zero-carbon hydrogen is already possible via renewable-powered water electrolysis (green hydrogen), the vast majority of hydrogen production today is based on coal and natural gas (grey hydrogen) generating approximately 830 MtCO_2 per year [9]; to put this into perspective, this represents about 2% of total global anthropogenic CO_2 emissions for 2019 [28]. Cost represents another obstacle: FCEVs, fueling stations, and green hydrogen production—on account of renewable electricity and electrolyzers (i.e., electrolysis technology)—are all currently expensive [9,13,24,29]. For widespread FCEV adoption, hydrogen infrastructure is needed yet development has been slow thus far [9]; in contrast, BEVs are relatively mature in terms of lower capital and operating costs and readily-available infrastructure [13]. Electricity-based hydrogen for FCEVs involves the steps of converting electricity to hydrogen, transporting it (if made offsite), compressing or cryogenically storing it to obtain sufficient volumetric energy density, precooling it (if compressed) and converting it back to electricity with a fuel cell. This introduces energy losses that are avoided when using electricity directly via BEV. Moreover state-of-the-art electrolysis requires freshwater as input, which is a limited and valuable resource. While desalination can alternatively be employed to enable the use of seawater, this introduces energy and financial costs (albeit minor); research is currently exploring ways to use seawater in electrolysis directly [9,30]. Accordingly, the so-called hydrogen economy has seen waves of great expectation over the years that eventually came to naught.

Yet the International Energy Agency [IEA] recently announced that clean hydrogen is now experiencing “unprecedented political and business momentum” [9]. A multitude of countries, including those with the world's largest economies, have policies and projects in place for hydrogen energy [9]. In

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fact, Germany approved its highly anticipated national hydrogen strategy in June 2020 [31]. In 2017 the Hydrogen Council was launched by a group of leading global energy, transport and industry companies to bring together political and private stakeholders, with the goal of fostering hydrogen as "a key element of the energy transition" [32]; among their members are several German companies. Commercial FCEVs have already been in large-scale production for several years, with approximately 500 passenger FCEVs on the road in Germany [33] and about 17,000 worldwide [34] at the end of 2019. While these figures are lower in comparison with BEVs (5.1 million worldwide in 2018) [35], Toyota has targeted to sell over 30,000 FCEVs annually starting from 2020 [36]. There are now well over 400 hydrogen fueling stations in operation globally as of 2019, with Germany boasting the second largest network with about 90 stations [37]. It is widely reported that through further research and development, continued declining costs of renewable power, economies of scale, and coordinated energy policy and investment, costs can be appreciably reduced and technological challenges overcome for renewable hydrogen [9,13,23,24,29,38–40]. For instance, a recent report by the Hydrogen Council found that green hydrogen will become cost-competitive with grey hydrogen over the coming decade, after which point its costs will continue to decline [24]. Moreover, range, load and fueling advantages as outlined above can make FCEVs competitive with BEVs. In any case, the major reason that hydrogen commitment may be different this time around is the increased sense of urgency to adequately address climate change and ambition to deeply reduce emissions, as evidenced by the 2015 Paris Agreement and the landmark 2018 IPCC report to limit warming to 1.5°C above pre-industrial levels [9,29,41,42].

It should be noted, however, that hydrogen is leaked along its utilization chain, which impacts both the climate and air pollution. For example, Derwent et al. [43] recently reported a global warming potential [GWP] for hydrogen of 5 over a 100-year timescale. This makes potentially rising tropospheric hydrogen emissions from a hydrogen economy an important consideration. It is nevertheless worth noting that the effects from hydrogen emissions are highly uncertain, and that any adverse impacts they cause are likely to be less than those caused by current fossil fuel usage which would be replaced by hydrogen fuel [44]. Yet there is a lack of data on hydrogen emissions, and to our knowledge no published data currently exists on hydrogen loss from commercial FCEVs.

In this context, hydrogen emerges as a viable means of decarbonizing hard-to-abate sectors like road transport in which electrification alone may be insufficient to help Germany achieve its ambitious climate targets, culminating in GHG neutrality by mid-century[1] [9,23,45,46]. Additionally, this would serve to improve air quality, promote energy security, economic growth, as well as technological leadership in a potentially core field of the future global energy system. Indeed, Germany sees hydrogen as a "central pillar" of its energy transition, and is working to maintain its reputation for technological leadership by securing itself as the global leader in hydrogen technologies [47–49]. It is important to note, however, that the future mobility mix is expected to be diverse rather than there being a winner-takes-all technology; FCEVs will likely be complemented with low-carbon technologies like BEVs.

Scenarios can serve as an important tool for assessing GHG and air pollutant emission impacts of possible, relevant transitions in the energy system to provide valuable insight and support informed dialogue. Over the years, several scenario studies quantifying emission impacts from hydrogen implementation in the mobility sector have been performed, from the city level up to the global scale, and with many focusing on the European region in particular, e.g., Ref. [50–56]. In terms of German-focused studies, Rocco et al. [57] carried out a life cycle assessment [LCA] including an analysis of GHG emission impacts from penetration of FCEVs in the German road transport sector in 2050. Additionally, Emonts et al. [58] executed a pathway analysis exploring renewable hydrogen penetration in the German passenger car transportation sector via FCEVs by the year 2050, with their investigation also including the CO_2 reduction potential of the transport sector. To our knowledge, however, there have been no published studies on GHG *and air pollutant* emission impacts from a widespread shift to hydrogen-powered traffic in Germany in the near-term. All of these aspects are valuable for investigation based on the discussion above (noting that a focus on the near-term is important given the current momentum behind hydrogen mobility).

This paper investigates the impacts of a possible, complete transition from conventional fossil fuels to hydrogen energy in German road transport on GHG and air pollutant emissions, through a variety of emission scenarios covering relevant hydrogen production choices and variables as described herein. Our emission scenarios are comprehensive as they encompass emissions incurred from hydrogen production and those avoided by replacing conventional road transport fuel. Emission results are presented and put into context by comparing changes in CO_2eq with German total emissions, and by comparing changes in air pollutants with German energy emissions, for the year 2016. Other important parameters are also examined including the maximum allowable hydrogen leakage from FCEVs to avoid a net increase in hydrogen emissions, road transport sector hydrogen demand, and energy required to achieve this level of hydrogen demand. This work is an exploratory study with the main objective of understanding overall emission impacts of such a potential transition, using illustrative scenarios rather than assessing a realistic implementation thereof and estimating precise outcomes, which are currently too dependent on extensive, unpredictable policy developments to be reliable or useful. The results from these scenario studies can support informed discussion among policymakers, the public and other relevant stakeholders on hydrogen mobility in Germany and beyond.

Methodology

Study

In the following we describe the scenario design, and provide a summary of the main points in Table 1. The scenarios

[1] Germany's climate targets include 40% GHG emissions reduction by 2020, 55% by 2030, 70% by 2040 and 80–95% by 2050, compared with 1990 levels.

Table 1 – Summary of the scenario design.

Scenario element	Element description
Data year[a]	2016
German road transport fuels replaced with hydrogen energy[b]	Gasoline, diesel
Road transport vehicle categories switched to hydrogen technology[c]	PCs, LDVs, HDVs, two-wheelers
Domains of activity in emission scenario model	Road transportation, hydrogen economy, natural gas production, steam methane reforming, gasoline production, diesel production, coal production, coal gasification, electricity generation, electrolysis, hydrogen transport and storage, LPG production, and biofuel production
Emission source segments	Energy production and use
Specie emissions quantified	CO_2eq (CH_4 & CO_2), NMVOCs, NO_x, $PM_{2.5}$ and PM_{10}, CO, SO_x, NH_3

[a] Data representing the year 2016 was used, where possible.
[b] Other forms of German 2016 road transport energy are left unaltered (LPG, CNG, biofuels, electricity).
[c] In the scenarios *SMR-ng1-C_HDV* and *Elec-renewable_HDV*, only HDVs are switched to hydrogen technology.

investigated in this study cover several assumed hydrogen production methods (Table 2). Conventional fuels replaced are gasoline and diesel, which together supply 94.2% of German road transport energy for the year 2016 [59,60]. Consumption of alternative transport energies, i.e., electricity, LPG, CNG, and biofuels, are unaltered as they fall within Germany's low-carbon transition strategy for transport [5]. Hydrogen replacement is applied to all road vehicle categories: passenger cars [PCs], light duty vehicles [LDVs], trucks and buses, here collectively referred to as heavy duty vehicles [HDVs], and motorcycles and mopeds, here collectively referred to as two-wheelers. Additionally, two scenarios focus solely on HDVs due to the fact that certain advantages of FCEVs (i.e., longer range, heavy loads, and quick fueling times) are particularly consequential to this vehicle category, as discussed in Section Introduction. It is assumed that hydrogen is produced in Germany, and based on the literature that hydrogen delivery is by pipeline [9] and storage by compression at 700 bar [20,61].

Both GHG and air pollutant species are examined, including: CH_4 and CO_2 (analyzed together as CO_2eq), and NMVOCs, NO_x, $PM_{2.5}$ and PM_{10}, CO, SO_x, and NH_3. These pollutants are particularly relevant as their emissions are regulated under the European Union's National Emission Ceilings Directive (noting that of the SO_x compounds, specifically SO_2 is regulated) [62]. In keeping with the German National Inventory Report [NIR] which follows the Revised UNFCCC Reporting Guidelines, CO_2eq emissions are calculated here using the IPCC AR4 100-year GWP for CH_4 of 25 [63]. It should be noted that in the more recent IPCC AR5, the corresponding GWP is 36; furthermore, the 20-year timescale is also commonly used and results in a higher GWP of 87 due to CH_4's comparatively short atmospheric lifetime (~12 years) [64]. As a result, using AR5 data and the 20-year timescale would lead to higher CO_2eq emissions for scenarios with CH_4 emissions than the results presented here.

Emissions are quantified by multiplying activity data [AD] with emission factors [EF]. The scenarios are constructed as a projected snapshot of the present-day situation, in which the proposed changes are enacted immediately. Additionally, the scenarios are built by quantifying and aggregating emissions associated with each domain of activity relevant to hydrogen production and German road transport. The domains and the information flow between them forming the basis of the emission scenario model used in this study are depicted in Fig. 1. The model is summarized and the domains are presented in detail in the Supplement (Section S1); the model methodology is based on that described in Ref. [65] which was published in Ref. [51].

Emissions examined are those associated with energy production and use. It is important to note that scenario emissions include those released from activities occurring within Germany and abroad. Namely, emissions from upstream activities of imported fossil fuels are not German emissions (described further in the Supplement, Section S1.14). Due to the focus of this paper, attention is specifically on German emissions rather than total values unless explicitly stated. As this work does not have the aim of being an LCA, emissions associated with, e.g., the manufacture of materials for or construction of fuel cells and power plants, are not considered. Being an exploratory study, limiting socio-economic aspects are likewise not considered.

Table 2 – Hydrogen production methods explored in this work.

Method	Abbreviation	Description
Steam methane reforming	SMR	Natural gas is reacted with steam producing syngas (mainly CO/hydrogen). This subsequently undergoes the water-gas shift reaction yielding more hydrogen (and CO_2) [66].
Water electrolysis	Elec	Electricity is used to separate water into hydrogen and oxygen in a unit known as an electrolyzer [67].
Coal gasification	CG	Coal is reacted with steam and oxygen at high temperatures and pressures forming a gaseous mixture, which is then scrubbed to remove impurities, producing syngas (mainly CO/hydrogen). This subsequently undergoes the water-gas shift reaction yielding more hydrogen (and CO_2) [68].

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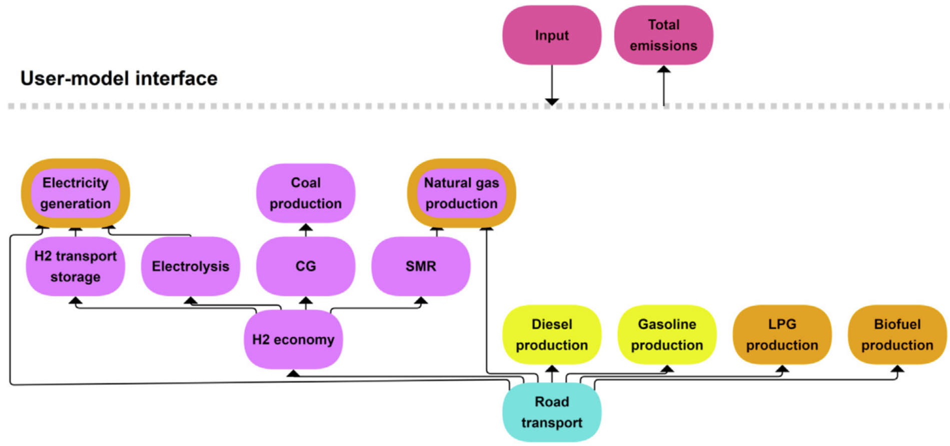

Fig. 1 – Schematic of information flow between domains forming the basis of the emission scenario model of this study. The arrows follow the flow of energy demand from end-use application, i.e., road transport, to the point of energy production. The main groups are hydrogen (purple), conventional fuels (yellow), and alternative fuels (orange).

All input data was obtained from peer-reviewed publications, official reports and institutions, and expert support (presented and described in detail in the Supplement, Section S1). The majority of EFs and AD represent the year 2016, which was the most recently available at the time when this study was conducted. However, hydrogen-related technology data (e.g., electrolysis efficiency) is generally based on present-day values. If German-specific data was not available, the best available data was used and adapted to Germany, where possible. Energy use data is based on the lower heating value [LHV], i.e., the condensing heat of vaporized water produced from combustion is not included. Finally, a sensitivity analysis has been performed to assess the impact of varying FCEV TTW efficiency on total emissions and is provided in the Supplement (Section S2).

Scenarios

Today, ~75% of global hydrogen production is based on natural gas, mainly via SMR, which is projected to remain the chief technology in the near-term [9]. While water electrolysis currently contributes <0.1% to the global supply [9], it enables green hydrogen (when powered by renewables), which is viewed as essential to the energy transition and is projected to have significant growth in the years ahead [40,69]. Thus SMR and electrolysis are highly pertinent and explored here. For these production types the impact of varying the following important parameters are also examined: CH_4 leakage rates from natural gas production (SMR), the current electricity mix vs. renewable electricity (electrolysis), electrolysis efficiencies (electrolysis), and centralized and decentralized hydrogen production (SMR and electrolysis).

Coal (via CG) accounts for nearly ~25% of today's global hydrogen production as a result of its predominance in China [9]. For completeness and in the interest of comparison with the other technologies, a scenario based on CG is explored due to its relevance to global hydrogen production and coal to German energy (e.g., coal will remain in Germany's electricity mix up to 2038 based on the recently adopted coal exit law [70]).

It is worth noting that carbon capture and storage [CCS] is a relevant technology with the potential to substantially lower the CO_2 emissions intensity of fossil fuel-based hydrogen (blue hydrogen) [9]. However, blue hydrogen is not emission-free: 5–15% of CO_2 remains uncaptured under optimal technological conditions [29], and CH_4 is still leaked throughout natural gas production and transport, while at the same time CCS necessitates more energy to run. Moreover, many open questions remain about its feasibility due to lack of progress [29], technological shortcomings, and Germany's low public acceptance of CCS [23], while the breadth and depth of technological options and lack of data clarity make it challenging to properly factor CCS into the emissions scenarios. For these reasons, blue hydrogen is not explored in this study.

Some emerging methods for low-carbon hydrogen production not considered in the present study include methane cracking and thermochemical water splitting [9,71–73]. The former technology involves the splitting of natural gas under high temperatures and in the absence of oxygen resulting in hydrogen and carbon black, and is currently at the pilot scale. The latter technology involves the splitting of water under high temperatures achieved by the concentration of solar energy, with the first pilot plants now in operation.

Finally, for each scenario, total hydrogen production is considered from one method alone and not a combination of different methods. This was done on account of the illustrative nature of the scenarios, and because the main goal here is to explore the benefits and trade-offs of each possibility. The scenarios are detailed in Table 3 and depicted in Fig. 2.

Results and discussion

Hydrogen demand

The total hydrogen demand required for replacing gasoline and diesel in road transport for all vehicle categories is

Table 3 – Description of emission scenarios explored in this study. The scenarios are grouped into sets by hydrogen production method, in addition to a baseline scenario for comparison. The SMR and electrolysis sets have multiple scenario variables which are combined, yielding four SMR scenarios, and five *Elec* scenarios (only one of which is based on renewable electricity because emissions are unaffected by the other variables given that renewable power generation assumes zero emissions); the CG set has no variables and therefore only has one scenario. The data used in the scenarios is provided in the Supplement (Section S1).

Scenario set	Variables	Variable description
Baseline	–	Present day (year 2016) emissions associated with the German road transport sector are quantified, including emissions from fuel combustion, gasoline evaporation, and energy production of road transport fuels.
Steam methane reforming: *SMR*	CH_4 leakage rate (natural gas production): *ng1*, *ng2*	Two sets of CH_4 leakage rates for natural gas production are examined: *ng1* (up-/downstream: 1.0%, 0.2%) and *ng2* (up-/downstream: 2.2%; 0.1%). Natural gas is mainly CH_4, a potent GHG, making leakage thereof an important consideration; thus this has been an area of intense research and discussion for many years, with studies reporting leakage rates from <1% to >10% of production [74]. *Ng1* is based on data from Ref. [75] and tailored to natural gas supply in Germany; as such it may be viewed as a standard estimate. *Ng2* is from a recent study [76] that found natural gas CH_4 leakage from about one third of production in the US to be 60% higher than official estimates; thus *ng2* represents a higher, yet plausible rate.
	Production site: -*C*, -*D*	Two cases of hydrogen production are examined: centralized ('*C*'; 100% at the plant) and decentralized ('*D*'; 100% at the hydrogen fueling station). The thermal efficiency of centralized SMR is higher ($\eta = 75\%$), it avoids downstream CH_4 emissions from distribution to the station, and the energy required for hydrogen compression is slightly lower; however, hydrogen must instead be transported which requires a low amount of energy. Decentralized SMR efficiency is slightly lower ($\eta = 67\%$), and energy needed for hydrogen compression slightly higher, but it avoids energy costs for hydrogen transportation; instead, CH_4 must be transported to the station which incurs downstream CH_4 emissions (though no additional energy).
Electrolysis: *Elec*	Electrolysis efficiency: *ef1*, *ef2*	Two efficiencies for low-temperature water electrolysis are examined: *ef1* ($\eta = 59\%$) and *ef2* ($\eta = 71\%$). Electrolysis efficiency is critical to the total electricity demand, and hence cost. Moreover, there is ongoing research to further improve the efficiency, making it a valuable parameter to explore. These efficiencies are based on proton exchange membrane [PEM] electrolysis, though values are similar for alkaline electrolysis (both technologies are among the most mature electrolysis methods today).
	Electricity supply: *cmx*, *renewable*	Two cases of the electricity supply are examined: 100% current mix ('*cmx*') and 100% renewable. *Cmx* EFs are averaged values of the current (2016) electricity mix in Germany. *Renewable* EFs are zero assuming wind and solar as the electricity sources.
	Production site: -*C*, -*D*	Like SMR, two cases of hydrogen production are examined: centralized ('*C*'; 100% at the plant) and decentralized ('*D*'; 100% at the hydrogen fueling station). The same tradeoffs between *C* and *D* production exist for electrolysis as for SMR, however the efficiency of water electrolysis does not differ between *C* and *D*.
Coal gasification: *CG*	–	Centralized CG is assumed with a thermal efficiency of 50.8%. It is important to emphasize that CG is not considered a realistic option due to coal's high emission and pollution intensity and that it is being phased out in Germany (thus no further variables are explored). Rather, CG is included in this study in the interest of completion and comparison with the other scenarios.

1000 PJ (Fig. 3). PCs and HDVs make up the majority of hydrogen demand in the scenarios (~95%), closely mirroring the share of total conventional fuel demand by these vehicle categories; thus the share required to replace conventional fuels for LDVs and two-wheelers is low (~5%). Hydrogen demand is about two thirds less (371 PJ) in the scenarios where only HDVs are targeted for fossil fuel replacement. To put these values into perspective, this work estimates 55 PJ hydrogen use in German refining of gasoline and diesel, one third of which is assumed as already achieved as a by-product through naphtha reforming. Accordingly, massive upscaling of hydrogen production will be necessary to meet the level of road transport demand in these scenarios. Also worth noting is that total hydrogen demand amounts to slightly less than half of gasoline and diesel energy demand in German 2016 road transport (2103 PJ) [59] on account of FCEV TTW efficiency being roughly twice that of conventionally-fueled ICEVs.

It is worth noting that hydrogen demand is affected by the assumed TTW (vehicle) efficiency. As discussed in the Supplement (Section S1.1), hydrogen demand may be slightly overestimated due to more recent (i.e., higher) ICEV TTW efficiencies applied to the entire auto fleet, which would imply a slightly less favorable emissions outcome from the shift to

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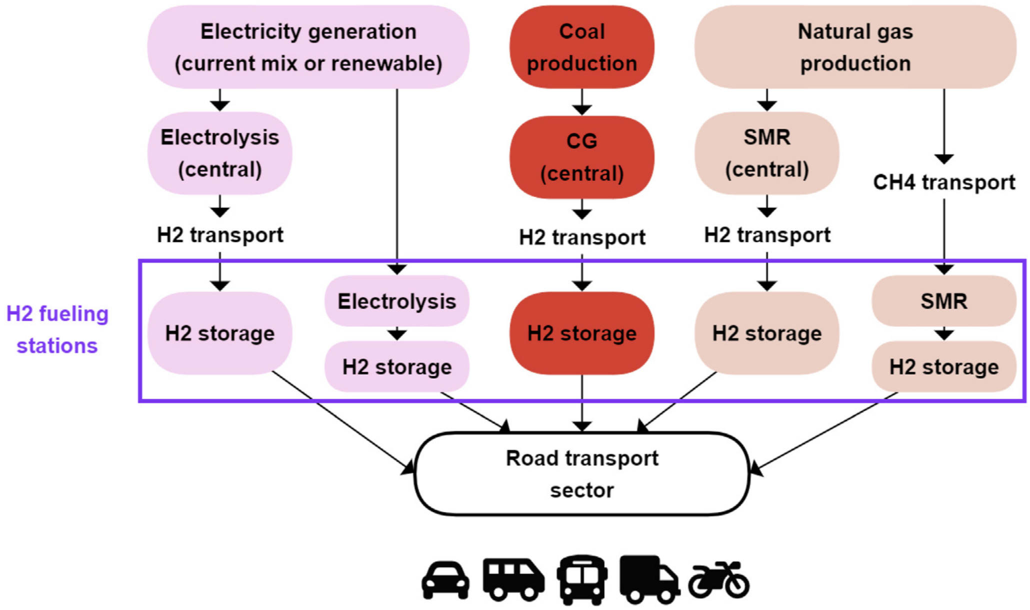

Fig. 2 — Steps in utilizing hydrogen energy in road transport for each scenario set. Scenario sets are Elec (pink), CG (red), and SMR (beige). In order to distinguish the scenarios sets of this study and avoid confusion, different colors are used than the standard hydrogen production color terminology. The average transport distance is about 6 km for hydrogen [61] and 2500 km for natural gas [77] based on the data used in this study (noting that the natural gas transport distance is based on CO_2 emissions data).

hydrogen transport than would be realized in reality. On the other hand, TTW efficiency data on FCEVs is rare and therefore a value representative of commercial PCs was applied to all vehicle categories in this study; this may over- or underestimate hydrogen demand and hence total emissions. Namely, the impact on total scenario CO_2eq emissions ranges from +10% to −5% when assumed lower and upper FCEV TTW efficiencies are applied, respectively, and based on the setup of our sensitivity analysis. However, the greatest sensitivity was seen among PCs, (i.e., for which the FCEV TTW efficiency was suited).

Production energy

Producing the level of hydrogen demand needed to cover all vehicle categories (i.e., 1000 PJ) by SMR requires between 1333 and 1492 PJ of annual natural gas for centralized and decentralized production, respectively (Fig. 4); this is equivalent to slightly less than half (44% and 49%) of 2016 German total natural gas primary energy consumption (3056 PJ) [78]. Coal demand for hydrogen production is higher (1968 PJ) on account of the lower thermal efficiency of CG (50.8%) compared with SMR (centralized: 75%; decentralized: 67%); this is equivalent to more than half (61%) of 2016 German total coal primary energy consumption (3204 PJ) [78].

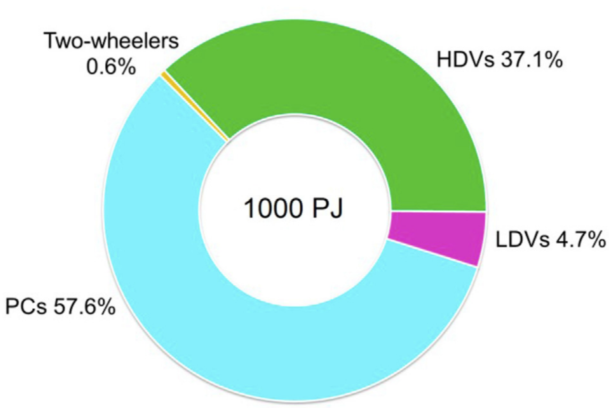

Fig. 3 — Hydrogen demand to power the 2016 German road transport sector to replace gasoline and diesel.

Based on the electrolysis efficiency, annual electricity demand for hydrogen production is between 391 and 466 TWh ($ef2 = 71\%_{LHV}$ and $ef1 = 59\%_{LHV}$, respectively), which equals 64% and 76% of 2016 German net electricity generation (614 TWh) [79]. It will be critical to optimize electrolysis efficiency to reduce the burden on renewable electricity demand. Yet the efficiencies of mature electrolysis technologies (i.e., PEM and alkaline) are not expected to improve significantly beyond the *ef2* explored in this work (note that *ef2* represents PEM efficiency estimated for 2030, as described in the Supplement, Section S1.10). For example, in the IEA's The Future of Hydrogen report [9], a long-term efficiency of up to $74\%_{LHV}$ for PEM and of up to $80\%_{LHV}$ for alkaline electrolysis are projected. On the other hand, solid oxide electrolysis cells [SOECs], the least developed technique, can offer higher efficiencies of up to ~$80\%_{LHV}$ today and $90\%_{LHV}$ long-term [9].

The amount of electricity required for hydrogen transport and storage (including fueling) is 55 and 59 TWh for decentralized and centralized hydrogen production, respectively; the electricity demand for centralized production is slightly higher on account of additional electricity required to deliver hydrogen via pipeline. According to Ref. [80], Germany has the potential to more than meet total scenario electricity demand

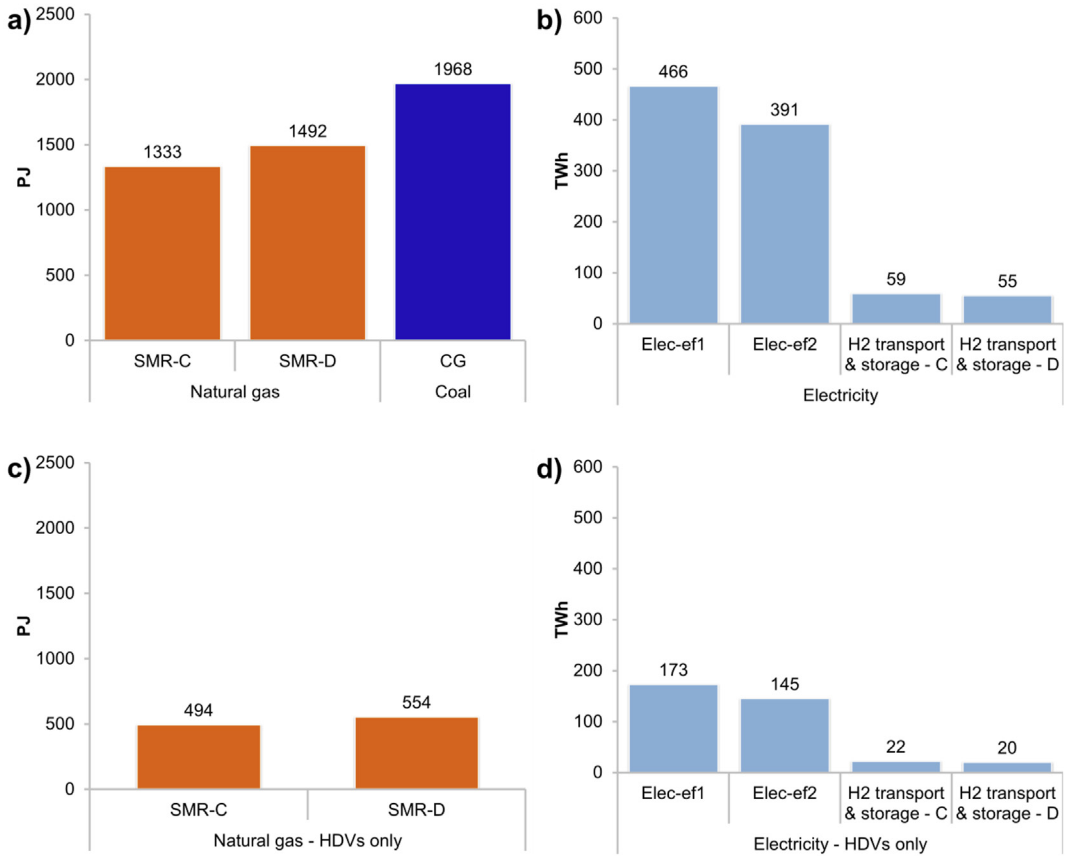

Fig. 4 – (a) Natural gas, coal and (b) electricity demand for hydrogen production to cover all vehicle categories, and (c) natural gas and (d) electricity demand for hydrogen production to cover HDVs only. The electricity requirements for hydrogen transport and storage are likewise displayed in (b) to cover all vehicle categories, and in (d) to cover HDVs only. SMR-D for HDVs was not explored as a scenario, and natural gas demand thereof is presented here for informational purposes only.

for road transport hydrogen (446–525 TWh)—covering hydrogen production, transport and storage—through domestic renewable power alone by means of solar and wind energy.

CO_2eq

The impacts of different scenario assumptions on CO_2eq emissions vary considerably, with German emissions ranging from +52% to −97% compared with the baseline (Table 4). To put these impacts into perspective, this translates to an increase of up to 11% and a decrease of as much as 21% of German country total emissions for the year 2016. All scenarios lead to a 99% decrease in CO_2eq emissions from the 2016 German road transport sector. In particular, the *Elec-renewable* scenario would contribute significantly to Germany getting back on track towards accomplishing its future emissions targets with a national emissions reduction of 179 $MtCO_2eq$. The *SMR*-based scenarios would also bring German emissions closer to this goal (up to −73 $MtCO_2eq$), though substantially less so than the former. On the other hand, the *CG* and *Elec-cmx*-based scenarios put Germany on a path further away from these targets (+50 and up to +95 $MtCO_2eq$, respectively). The range of emission impacts is extensive for the *Elec* scenarios, though narrower for *SMR* scenarios. This indicates that the assumed measures (variables) under the *SMR* set are less effective in their ability to reduce German emissions. Indeed the hydrogen production method is the most important factor of the variables examined in our study in influencing emissions outcomes. The exception to this is the electricity supply: switching from the current mix to renewable power under the *Elec* scenario set has the most significant effect on our results, flipping the highest emissions increase into the highest emissions decrease.

Among the fossil fuel-based hydrogen scenarios, the combustion of fuel in facilitating hydrogen production accounts for the overwhelming share of total CO_2eq emissions, while the contribution from producing fossil fuels (e.g., extraction, processing, and transport) is relatively low (Fig. 5). Accordingly, the *Elec-renewable* scenario set is able to achieve the greatest decrease among all scenarios by avoiding fuel combustion through the use of renewable electricity.

On the other hand, in *Elec* scenarios in which the current electricity mix ('*cmx*') is applied, the result is a significant increase in emissions. This is due to the high CO_2 intensity of the power supply (i.e., fossil fuels make up a robust share of 2016 German electricity generation, especially coal; see the Supplement, Section S1.9), the relatively low thermal efficiency of fossil fuel-powered generation (especially coal), and the fact that energy must be converted twice (i.e., first to generate

Table 4 – Absolute change in total and German CO_2eq emissions from scenarios relative to the baseline for the year 2016, in units of Mt, and percent change in total and German CO_2eq emissions from scenarios relative to the baseline, and percent change in German CO_2eq emissions from scenarios relative to official German country total emissions for the year 2016. Baseline and 2016 German total CO_2eq emissions are displayed at the top of the table, in units of Mt. The data used to calculate the scenario CO_2eq emission values comes from a wide range of sources, and is provided in the Supplement (Section S1).

	Total baseline		DE baseline		DE NIR 2016
$MtCO_2$eq emissions	196		184		858[b]
Scenario	Δ_{Abs}[a]	$\%_{Baseline}$	Δ_{Abs}	$\%_{Baseline}$	$\%_{DE\_NIR\_2016}$
SMR-ng1-C	−71	−36	−73	−39	−8
SMR-ng1-D	−61	−31	−64	−35	−7
SMR-ng2-C	−62	−32	−72	−39	−8
SMR-ng2-D	−52	−27	−64	−35	−7
Elec-ef1-cmx-C	83	42	95	52	11
Elec-ef1-cmx-D	81	41	93	50	11
Elec-ef2-cmx-C	44	22	56	30	6
Elec-ef2-cmx-D	42	21	54	29	6
Elec-renewable	−191	−97	−179	−97	−21
CG	53	27	50	27	6
SMR-ng1-C_HDV	−16	−8	−18	−10	−2
Elec-renewable_HDV	−61	−31	−57	−31	−7

[a] The change in absolute emissions from the scenario relative to the baseline.
[b] Source: [63]; this value represents the total German NIR CO_2eq emissions for the year 2016 and does not include LULUCF (emissions and removals from land use, land use changes and forestry).

electricity, and then to convert it to hydrogen). The efficiency of the electrolysis process, i.e., electricity consumption, is likewise an important factor: when the efficiency increases from *ef1* to *ef2*, the increase in emissions among *cmx*–based scenarios is cut by about 40%. In contrast, the impact of centralized (‘*C*’) and decentralized (‘*D*’) hydrogen production on emissions is low under the *Elec* scenario set. This is because the thermal efficiency of electrolysis is assumed to be the same for *C*- and *D*-based scenarios, and they only differ slightly in the amount of electricity consumption required for transporting and storing hydrogen. It is worth mentioning that the *Elec-cmx* scenarios do not include upstream emissions of energy carriers used in electricity generation; if these were included, CO_2eq emissions would be somewhat higher (8% higher total emissions and <1% higher German emissions; see the Supplement, Section S1.9).

All *SMR* scenarios lead to substantial emission decreases, which are afforded by the relatively high thermal efficiency of SMR and the relatively low emissions from fuel combustion of natural gas. It is important to highlight, however, that because the energy source of *SMR* is still a fossil fuel, the emission reduction it achieves is significantly lower than that of *Elec-renewable* (up to −73 vs. −179 $MtCO_2$eq, respectively). It is also worth noting that because *ng1* and *ng2* affect CH_4 leakage, the

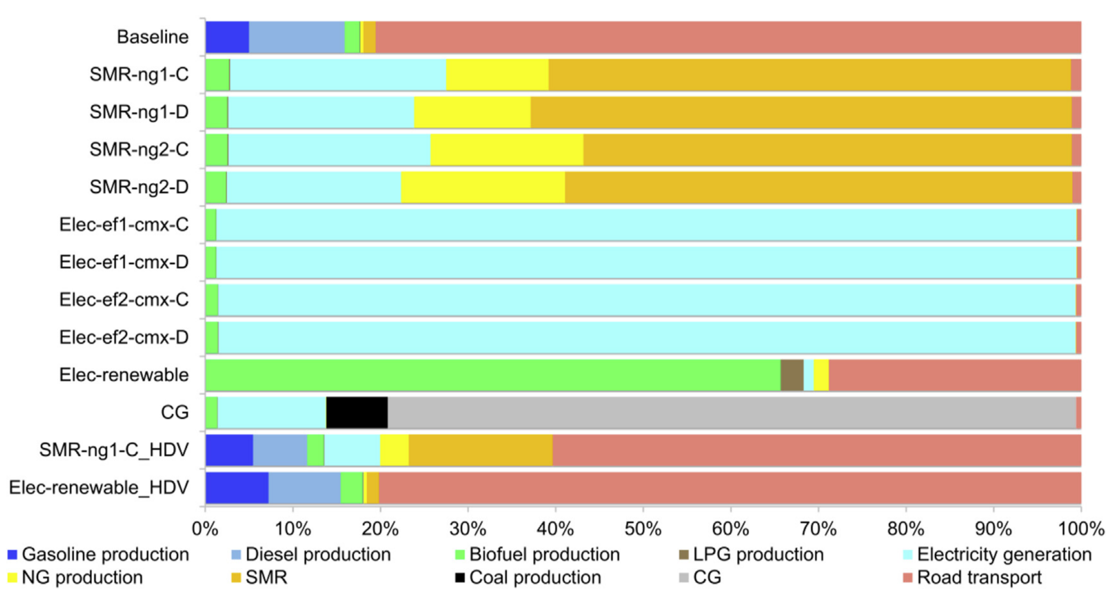

Fig. 5 – Contribution of domains to total CO_2eq emissions, per scenario, in %.

Table 5 – Percent change in 2016 German air pollutant road transport sector emissions from replacing conventional ICEVs, for all vehicle categories or HDVs only, with FCEVs, relative to the baseline.

Conventional ICEVs replaced with FCEVs	Change in German road transport emissions[a]						
	NMVOCs	NO_x	$PM_{2.5}$	PM_{10}	CO	SO_x	NH_3
All vehicle categories	−96%	−95%	−95%	−95%	−94%	−94%	−93%
HDVs only	−4%	−32%	−29%	−29%	−7%	−30%	−2%

[a] Sources [59]: and the *Umweltbundesamt* [UBA] (German Environment Agency) [M. Kotzulla and G. Gohlisch, written communications, 2019 and 2020]; further detail is provided in the Supplement, Section S1.1. Road transport emissions considered in this study include fuel combustion/exhaust emissions (and gasoline evaporation for NMVOCs) only; i.e., PM reduction does not include tire/brake wear and road abrasion emissions.

majority of which occurs upstream, and because the majority of German natural gas is produced outside of Germany, *ng1* and *ng2* have a small effect on German emissions. Considering, however, that the ultimate goal is to reduce global GHG emissions, CH_4 leakage is still an important factor for a hydrogen economy employing SMR.

The CG scenario leads to a high increase in CO_2eq emissions, and it is interesting to note that this increase is less than *Elec-ef1* and slightly less than *Elec-ef2* scenarios. This again emphasizes the importance of the electricity supply under the *Elec* set: if the current German mix (namely, the 2016 grid supply which was based heavily on fossil fuels) is employed, the emissions outcome can be more harmful to the climate than directly using coal under *CG*.

While HDVs only make up a small portion of the German vehicle fleet (namely, about one third thereof with respect to conventional fuel consumption), addressing this segment alone can achieve a strong emissions reduction under the *Elec-renewable-HDV* scenario (−57 $MtCO_2$eq); it is also notable that this reduction is only slightly less than the more extreme case of switching all vehicle categories to hydrogen under the *SMR*-based scenarios. On the other hand, the emissions reduction achieved under *SMR-ng1-C_HDV* amounts to about a third of that realized under *Elec-renewable-HDV*.

Air pollutants

Anthropogenic air pollutant emissions explored in this study—NMVOCs, NO_x, $PM_{2.5}$,[2] PM_{10}, CO, SO_x, and NH_3—mainly stem from incomplete fossil fuel combustion, though vaporization is also an important source of NMVOCs. Poor air quality is a serious problem in Europe, being responsible for about 500,000 premature European deaths in 2016 [81], in addition to posing a host of other serious hazards to human health [82,83], the environment [84,85], agriculture [86] and infrastructure [87]. Transport represents a major source of air pollution [3,88], meaning that a potential transition to a hydrogen economy in road transport has important implications for air quality. Since FCEVs have zero emissions at the tailpipe, replacing all gasoline and diesel ICEVs with fuel cell technology would drastically reduce pollutant emissions from the German road transport sector (−93% to −96%), depending on the species, for the year 2016 (Table 5). It is important to note that the remaining pollutant emissions result from use of alternative carbon-based fuels, i.e., CNG, LPG and biofuels. These reductions may also have important implications for secondary aerosol formation and ground-level O_3; e.g., the latter is a harmful air pollutant formed through reaction of NMVOCs and CO with NO_x in the presence of sunlight.

If HDVs are exclusively replaced with hydrogen energy, the emissions decrease for the road transport sector (Table 5) would still be high for most pollutants (approximately −30%), but for NMVOCs, CO and NH_3 the impact is lower (between −2% and −7%) on account of HDVs contributing a smaller share to these emissions in overall road transport. E.g., NMVOCs mainly stem from PCs, two-wheelers, and gasoline evaporation, while HDVs do not use gasoline, and the majority of CO and NH_3 emissions in road transport stem from PCs. Finally, the varying ratio of NMVOCs to NO_x emission reductions among *All vehicle categories* and *HDVs only* in Germany (Table 5) may lead to very different O_3 outcomes, on account of the non-linear relationship between these species in O_3 formation.

Shifting towards a hydrogen economy would not just avoid direct exhaust emissions from road transport, but would also incur emissions from activities related to hydrogen production (and avoid emissions associated with diesel and gasoline production). The impact of scenarios on German pollutant emissions are displayed in Table 6 (total pollutant emissions are provided in the Supplement, Section S3). In order to put the absolute emission numbers into perspective, changes relative to the German energy sector for the year 2016 are also presented in Table 6, and are focused on in the following discussion (caution is advised not to take these values out of context, since the relative changes depend on the reference year). The contributions of domains to scenario total air pollutant emissions are displayed in Fig. 6 (NH_3 is not displayed as its scenario emissions stem almost exclusively from road transport with a negligible fraction from diesel and gasoline production; i.e., the contributions to NH_3 do not differ between the hydrogen scenarios) (see Table 6).

The scenarios generally lead to reductions in German air pollutant emissions compared with 2016 energy sector emissions. *Elec-renewable* achieves the highest emission reduction among all species, followed by *SMR*. *Elec-cmx* reduces emissions for most pollutants, but the impact is low for PM and in fact increases for SO_x. CG achieves many decreases, but experiences increases in PM and a high increase in SO_x. Our results show that variables within scenario sets have a low potential to change pollutant emissions (with the exception of

[2] Only PM emissions from fuel combustion are considered in our study for the road transport sector, i.e., tire/brake wear and road abrasion emissions are not included.

Table 6 – Absolute change in German air pollutant emissions from scenarios relative to the baseline for the year 2016, in units of kt, and percent change in German air pollutant emissions from scenarios relative to German energy sector emissions for the year 2016. 2016 German energy sector air pollutant emissions are displayed at the top of the table, in units of kt. The data used to calculate the scenario air pollutant emission values comes from a wide range of sources, and is provided in the Supplement (Section S1).

	NMVOCs		NO_x		$PM_{2.5}$		PM_{10}		CO		SO_x		NH_3	
DE energy 2016 Abs[a]	255.3		1004.1		65.4		85.8		2037.9		278.7		17.3	
Scenario	Δ_{Abs}[b]	%	Δ_{Abs}	%	Δ_{Abs}	%	Δ_{Abs}	%	Δ_{Abs}	%	Δ_{Abs}	%	Δ_{Abs}	%
SMR-ng1-C	−105.9	−41	−341.4	−34	−6.4	−10	−6.6	−8	−658.1	−32	−14.6	−5	−11.0	−63
SMR-ng1-D	−105.9	−41	−336.7	−34	−6.5	−10	−6.6	−8	−657.4	−32	−15.8	−6	−11.0	−63
SMR-ng2-C	−105.6	−41	−341.4	−34	−6.4	−10	−6.6	−8	−658.1	−32	−14.6	−5	−11.0	−63
SMR-ng2-D	−105.6	−41	−336.7	−34	−6.5	−10	−6.6	−8	−657.4	−32	−15.8	−6	−11.0	−63
Elec-ef1-cmx-C	−98.2	−38	−191.2	−19	−0.2	0	0.1	0	−564.2	−28	120.4	43	−11.0	−63
Elec-ef1-cmx-D	−98.3	−38	−193.0	−19	−0.2	0	0.1	0	−565.1	−28	119.2	43	−11.0	−63
Elec-ef2-cmx-C	−99.5	−39	−224.2	−22	−1.2	−2	−1.0	−1	−581.4	−29	98.7	35	−11.0	−63
Elec-ef2-cmx-D	−99.5	−39	−226.0	−23	−1.3	−2	−1.0	−1	−582.3	−29	97.5	35	−11.0	−63
Elec-renewable	−107.1	−42	−422.3	−42	−7.5	−12	−7.7	−9	−685.0	−34	−31.9	−11	−11.0	−63
CG	−104.6	−41	−197.6	−20	2.2	3	6.1	7	−599.3	−29	345.8	124	−11.0	−63
SMR-ng1-C_HDV	−8.8	−3	−110.5	−11	−1.9	−3	−2.0	−2	−39.3	−2	−3.8	−1	−0.2	−1
Elec-renewable_HDV	−9.3	−4	−140.5	−14	−2.3	−4	−2.4	−3	−49.1	−2	−10.2	−4	−0.2	−1

[a] Source: UBA [M. Kotzulla and G. Gohlisch, written communication, April 15, 2019].
[b] The change in absolute emissions from the scenario relative to the baseline.

Elec-renewable vs. *Elec-cmx*). This is in part due to air pollutant emissions associated with current mix electricity generation being relatively low except for SO_x; accordingly, differences between *C* and *D* hydrogen production and *Elec-1* and *Elec-2* are relatively low. The most substantial relative reductions are seen for NMVOCs, NO_x, CO, and NH_3. The lowest relative reductions are seen for SO_x, PM_{10} and $PM_{2.5}$, with the latter two seeing no change or even a small relative increase in emissions for some scenarios, and the former a significant relative increase in emissions for some scenarios. This is because road transport is responsible for a significant portion of NMVOCs, NO_x, CO, and NH_3 emissions from the German energy system (35% and more), while for $PM_{2.5}$ and PM_{10} (12% and less) and SO_x (<1%) the contribution is lower. Despite the majority of emissions from road transport being avoided by replacing ICEVs for all vehicle categories with FCEVs (Table 5), this sector still represents one of the main sources of pollutant emissions in many of the hydrogen scenarios (Fig. 6) due to alternative road transport fuels (i.e., LPG, CNG and biofuels). Other main sources of pollutant emissions are SMR, CG and electricity generation, i.e., activities related to fossil fuel combustion. Energy production is an important source of total NMVOCs in the hydrogen scenarios (Fig. 6), as these compounds are typically found in association with fossil fuels. Yet German NMVOC emissions incurred from fossil fuel production are low because most fossil fuels are imported (though implying that some NMVOC burden will be carried elsewhere; German emissions allocation is described in the Supplement, Section S1.14); thus *SMR* and *CG* achieve similar NMVOC reductions to *Elec-renewable*. Due to the importance of fuel combustion for emissions of NO_x, CO and PM, the hydrogen production method—electrolysis (i.e., from electricity generation with *cmx*), SMR, and CG—and electricity generation for hydrogen transport and storage, are important sources for these species. Aside from *Elec-renewable*, the *SMR* scenario set achieves the greatest decrease in NO_x CO, and PM due to the higher thermal efficiency of SMR combined with the relatively lower NO_x, CO and PM emissions (approximately 60%, 70% and 100% lower, respectively) from natural gas stationary combustion compared with coal (see the Supplement, Sections S1.4 and S1.8). *Elec-cmx* and *CG* scenarios cause large increases in German SO_x emissions as a result of high SO_x release from current electricity generation and CG. NH_3 emissions in our study only stem from road transport and gasoline/diesel production; therefore, all scenarios experience the same NH_3 emission reductions (Table 6). It is worth noting that the majority of German NH_3 emissions (95% in 2016) stem from agriculture; as such, reducing road transport NH_3 emissions could have an important effect on urban emissions thereof.

Hydrogen emissions

Anthropogenic hydrogen emissions are released from incomplete fuel combustion and leakage throughout the hydrogen utilization chain [89]. Hydrogen functions as an indirect GHG by reacting with and thus reducing the abundance of the hydroxyl radical, the main oxidizing agent in the troposphere, which extends the atmospheric lifetimes of GHGs like CH_4 and hence their climate forcing and leads to O_3 production [43,90–93]. Since hydrogen emissions can influence O_3 concentrations, they can additionally impact air pollution and possibly contribute to depletion of the O_3 layer in the stratosphere (though any negative effects would likely be less than those from the fossil fuels to be replaced) [44]. Since, to the best of our knowledge, there is currently no data on hydrogen loss from commercial FCEVs (Introduction), scenario hydrogen emissions are not quantified in this work. Instead, the maximum allowable hydrogen loss rate from FCEVs that would be required to avoid a net increase in

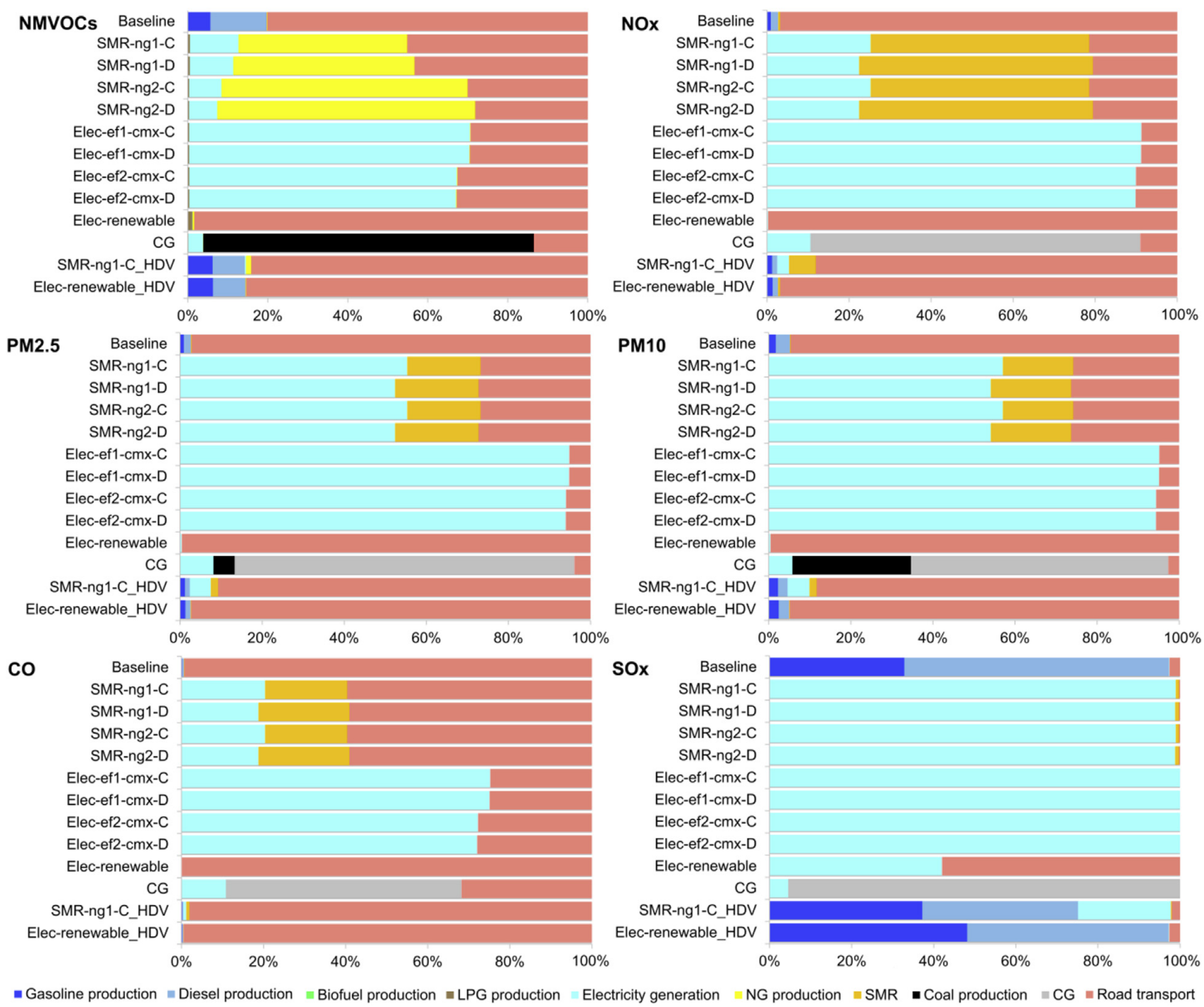

Fig. 6 – Contribution of domains to total air pollutant emissions, per scenario, in %.

German hydrogen emissions is explored here to provide a first estimate; this is done by assessing current hydrogen emissions from German road transport released based on our scenarios, i.e., stemming from incomplete fuel combustion and hydrogen refinery operations for gasoline and diesel (calculation described in the Supplement, Section S1.2). Based on this, we calculate a maximum allowable FCEV hydrogen loss rate of 106 mg/km for Germany when hydrogen fuel is implemented in all vehicle categories.

Conclusions

Our study shows that a deep transition of the German road transport sector from conventional fossil fuels to hydrogen energy can significantly reduce national CO_2eq emissions. However, the outcome depends strongly on the hydrogen production technology, and notably for electrolysis the electricity supply.

The scenario assuming renewable-powered electrolysis—that is, green hydrogen—has the greatest drop in emissions (−179 MtCO_2eq), and would contribute significantly towards achieving Germany's future GHG emissions reduction targets. According to our calculations on electricity requirements for hydrogen production (via electrolysis), transport and storage, the level of electricity demand (446–525 TWh) could be fully met through future German renewable power based on the domestic potential of solar and wind energy as estimated in the literature [80]. This highlights a clear potential for the transition of the German vehicle fleet to CO_2-free hydrogen and the opportunity to greatly enhance domestic energy security. Additionally, the green hydrogen scenario facilitates the largest reduction in regulated air pollutant emissions, with a decrease of up to 42% for NMVOCs, NO_x and CO, and up to 12% for PM and SO_x, compared with the German energy sector for the year 2016 (with all scenarios leading to the same decrease in NH_3 of 63%). Such changes will have important implications for air quality which would be valuable to investigate in a follow-up modeling study.

Steam methane reforming [SMR] also decreases domestic emissions, though to a considerably lesser extent (between −64 and −73 $MtCO_2eq$) than renewable electrolysis on account of its energy source still being a fossil fuel. While combining SMR with CCS—namely, blue hydrogen—can substantially reduce direct emissions of CO_2, it is not emission-free and, due to several issues [29], open questions remain about its feasibility. Given these considerations in conjunction with the fact that green hydrogen is projected to be less expensive than its blue counterpart in the next 5−15 years [40], and that economies of scale are required to bring down costs of green hydrogen, it seems hard to justify diverting limited capital away from renewable-based towards natural gas-based hydrogen, not to mention prolonging the fossil fuel economy and foreign energy dependency. It may at first be worth using (at least in part) the current electricity mix with electrolysis in the interim to build up a green hydrogen economy infrastructure. However, our findings indicate that electrolysis powered by the current electricity supply would lead to the largest increase in national GHG emissions (up to +95 $MtCO_2eq$) along with an increase in SO_x emissions and no effect on PM (and hence no benefit through its reduction). Thus if electrolysis with grid electricity using the current mix were to be employed over a longer term, rather than as a bridge technology, then other measures would need to be implemented by policymakers in order to ensure that longer-term climate objectives can still be met. On the other hand, it is important to note that as the CO_2 intensity of German electricity generation continues to decrease (generally through an increase in renewables and a decrease in fossil fuels), employing electrolysis with future grid electricity (assuming that this current trend continues) would lead to lower emissions than found in our results, for which the 2016 German electricity supply is assumed. Unsurprisingly, coal gasification [CG] leads to a strong increase in domestic GHG emissions (+50 $MtCO_2eq$), along with SO_x and PM, supporting the exclusion of this technology from future German hydrogen production.

We find a hydrogen loss rate of less than 106 mg/km from FCEVs when shifting the German vehicle fleet to this technology is required to avoid a net increase in domestic hydrogen emissions. It would be interesting to explore hydrogen emissions from commercial FCEVs to understand potential changes to the hydrogen budget in a future road transport hydrogen economy.

By only shifting HDVs to green hydrogen, a deep cut in emissions can already be achieved (−57 $MtCO_2eq$), which is only slightly less than all vehicle categories being replaced with SMR-based hydrogen. We also find that the burden of hydrogen demand to fuel the vehicle fleet would be nearly two thirds less if limited to HDVs (from 1000 to 371 PJ). Accordingly, HDVs represent a low-hanging fruit for FCEVs on the path to road transport decarbonization; this is notable considering that the competing technology, i.e., the BEV, has major challenges with heavy load, long-range, and short recharging requirements associated with this vehicle segment.

It is important to note that some uncertainty is associated with the estimations of scenario results presented here due to lack of data on FCEV TTW efficiency, especially for HDVs, LDVs and two-wheelers. Therefore further research on this parameter would facilitate more robust estimates for vehicular hydrogen demand and hence emissions. Additionally, it is worth emphasizing that the scenarios explored here are illustrative, considering extremes. Namely, the entire conventionally-fueled German vehicle fleet is assumed to be replaced by hydrogen that is produced by a particular method. In reality, the future vehicle fleet will likely be diverse with FCEVs complemented by other technologies, and hydrogen may be produced by a combination of methods and may also be imported. Based on the results here and as the direction of Germany's hydrogen plans unfold, it would be valuable to perform follow-up studies based on more realistic scenarios, looking at the benefits and trade-offs from each case.

The exploratory nature of this analysis and the type of data that is available would make an extensive statistical (uncertainty) analysis not very meaningful, and could actually be rather misleading, since applying standard statistical techniques on the limited data could lead to the misimpression that the uncertainties are much smaller than they are in reality. This would, however, be an important aspect for future development, if a shift towards expanded hydrogen usage in the transport sector is being more seriously considered politically, so that bounds on the anticipated impacts can be estimated based on the uncertainty in the estimates of the most important parameters.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2020.11.014.

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