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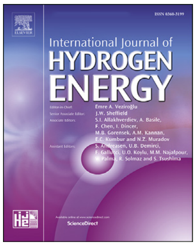

Hydrogen-powered aviation in Germany: A macroeconomic perspective and methodological approach of fuel supply chain integration into an economy-wide dataset

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HIGHLIGHTS

- The hydrogen momentum affects the aviation sector, but a macroeconomic perspective is currently lacking.
- This article derives a methodology for evaluating the macroeconomic effects of hydrogen use in aviation and applies this approach to an economy-wide dataset for Germany.
- The study investigates three hydrogen supply pathways, provides an exemplary cost break-down for ten hydrogen components and translates them into a national data framework.
- Eight macroeconomic sectors relevant for hydrogen-powered aviation are identified and quantified by assigning the respective techno-economic cost components.
- The article highlights meaningful research potential on macroeconomic analyses of hydrogen-powered aviation and employment effects related to future hydrogen demands.

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ABSTRACT

The hydrogen (H2) momentum affects the aviation sector. However, a macroeconomic consideration is currently missing. To address this research gap, the paper derives a methodology for evaluating macroeconomic effects of H2 in aviation and applies this approach to Germany. Three goals are addressed: (1) Construction of a German macroeconomic database. (2) Translation of H2 supply chains to the system of national accounts. (3) Implementation of H2-powered aviation into the macroeconomic data framework. The article presents an economy-wide database for analyzing H2-powered aviation. Subsequently, the paper highlights three H2 supply pathways, provides an exemplary techno-economic cost break-down for ten H2 components and translates them into the data framework. Eight relevant macroeconomic sectors for H2-powered aviation are identified and quantified. Overall, the paper contributes on a suitable foundation to apply the macroeconomic dataset and to conduct macroeconomic analyses on H2-powered aviation.

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Finally, the article highlights further research potential on job effects related to future H2 demand.

Introduction

The subject of this paper is to derive a methodology that enables the evaluation of macroeconomic effects when changing a transport sector to a more sustainable fuel. This methodology bases on the setup of a hydrogen (H2) supply infrastructure for H2-powered aviation shown for an exemplary country: Germany. In the introduction, the general relevance of H2, its importance for the chosen country, the potential of H2 in aviation, the investigation of macroeconomic effects and the key research questions are laid out.

An increasing number of countries set themselves targets to achieve net-zero greenhouse gas (GHG) emissions over the next decades [1]. It is a necessary step to avoid the most devastating impacts of climate change [2–4]. As part of such net-zero efforts, H2 as an energy carrier could play a central role in the general energy transition as shown by several reports [1,5–7] and scientific articles [8–14]. H2 offers a solution to decarbonize industrial processes and economic sectors where reducing carbon emissions is hard to achieve [6] and direct electrification is difficult to implement [15–17]. In order to be a sustainable alternative to fossil fuels, H2 itself must be produced in an environmentally friendly way. This is not the case for the majority of today's H2 generation technologies, which are predominantly based on carbon-intensive processes (steam methane reforming of natural gas, gasification of coal and reforming of naphtha into gasoline). Resulting H2 is called *"grey"* H2 and is mostly used in sectors like oil refining, ammonia (e.g., fertilizer production) and methanol (e.g., fuel additive, plastic production). In contrast, water electrolysis, supplied by renewable electricity, produces *"green"* H2 in a net-zero way [10,12–14,18–22]. However, this process only accounts for less than 1% of the current global H2 production due to low electrolysis capacities [16]. Besides the limited availability, the main challenge for the success of a green H2 economy is its higher production costs compared to grey H2 [20,22]. A key enabling factor is the large-scale deployment of electrolysis, which leads to economies of scale and potential learning effects. Policy frameworks such as national H2 strategies and roadmaps have already been adopted by more than 30 countries worldwide to accelerate the required developments [7,16].

Germany is one of the most active EU members in expanding H2 technology as part of their general energy policy [10,19]. The new German government (since December 2021) pursues ambitious targets towards renewable energy, including 80% of electricity coming from renewables by 2030 and GHG neutrality (Climate Change Act) by 2045 [23]. With *"The National Hydrogen Strategy"* and the creation of the *"National Hydrogen Council"* to support the State Secretaries' Committee, H2 is becoming an important part of the German energy transition [8]. In essence, it focuses on the production of green H2, a sustainable energy system and a means of economic growth. The strategy focuses on the electricity, industrial, transport and heat sectors as well as a domestic and international H2 market development [15]. As in the global average, green H2 generation plays a minor role in Germany today. The majority of domestic H2 production [57 terawatt (TWh)] stems from fossil sources [24]. However, Germany plans huge investments for speeding up the green H2 economy [8].

The momentum of a H2 economy also affects the aviation sector. Air transport accounts for 12% of global transport-related CO_2 emissions [1]. Decarbonization of current aviation's CO_2 emissions is a challenge [7,14,16] – especially given the expected increase in air travel demand, which could more than double by 2050 [25,26]. In contrast to other transportation segments, such as the passenger car sector, the technical options for the electrification of the aviation industry are limited. Compared to conventional jet fuel, batteries have a relatively low energy density [27,28]. The potential of battery-electric aircraft is thus restricted to commuter and short-haul flights [25]. For this reason, the development of H2-powered aircraft for true decarbonization of the sector and strong reduction in terms of climate impact is discussed as one countermeasure [17,21,29–35]. Shifting from fossil kerosene to H2 poses two major challenges: The development of new H2-powered aircraft and the establishment of the necessary H2 supply infrastructure. Starting with the aircraft design, adjusted or new airframe shapes that integrate efficient H2 propulsion systems, including H2 storage, need to be developed. While gaseous H2 (GH2) has a higher gravimetric energy density, it comes with a significantly lower energy density by volume compared to kerosene [35,36]. Aircraft design studies show that only liquid hydrogen (LH2) – which increases the volumetric energy density compared to GH2 – enables feasible commercial aircraft concepts [25,34,35,37]. Regarding the supply infrastructure, one of the biggest challenges for LH2 are the costs [5,21,29–31,36], as well as handling the fuel in its liquid form, which requires temperatures around −253 °C (20 K) [33,36]. The specific energy costs of LH2 are currently four to six times higher than kerosene. However, price projections predict that it might become increasingly competitive until 2050 [25,38]. While researchers currently address these challenges (see review by Hoelzen et al. [39]), the aviation industry is also becoming increasingly interested in H2: For instance, Airbus aims to bring the first H2-powerd aircraft to market by 2035 within its ZEROe project [40], and ZeroAvia conducted the first commercial H2-powered flight [41].

Various economic models can be used to investigate H2-related issues. Many (techno-economic) studies analyze the role of H2 in the energy transition by using energy system models [9,11,22,32,42–45], including aviation [13,18]. So called bottom-up energy system models deal with detailed technological descriptions of the energy system [46], assess technological feasibilities [47] and capture important interactions within the energy system, i.e., specific resource potentials, costs and conversion efficiencies [48]. However, such models do not cover the impacts on the overall macroeconomy [18,48] and neglect macroeconomic assessments [49], e.g., Gross Domestic Product (GDP), economic linkages, domestic production, social welfare (consumption), trade (imports and exports) and job generation.

In macroeconomic modeling, there are only few studies focusing on H2 applications (see Refs. [50–53]). Three illustrative examples of the existing literature are briefly reviewed: First, Bae and Cho [54] analyzed the economic impacts of building a H2 economy in Korea using a Computable General Equilibrium (CGE) model (for further explanation on this methodology, see Section Macroeconomic modeling). The analysis builds on Korean national input-output (I-O) data for creating a Social Accounting Matrix. The study forecasts the energy mix for H2 production from natural gas, coal, nuclear and renewables in 2040. In their results, the use of H2 substitutes fossil fuels in the road vehicles sector, which leads to an increase in the overall GDP due to positive effects on the transportation sector's output, investments and exports. Second, Lee [55] used a CGE model to investigate the development of a H2 supply chain in Japan. The study draws on an I-O database and incorporates the supply chains, sales and outputs of six H2-related industries (Bio-H2, steam reforming, electrolysis, H2 fuel cell vehicles/cars, H2 fuel cells and H2 fueling stations). Results reveal that the development of Japan's H2 application industries will accompany industrial and economic growth. Real GDP increases by around 2% annually to 2030. H2-related and energy industries enjoy the greatest positive effects from the development of H2 fuel cell vehicles and will be responsible for strengthening the country's exports. Third, Espegren et al. [9] applied a CGE model representing the Norwegian economy, focusing on the role of H2 when the production of fossil fuels is restricted and exports of oil and gas are phased out by 2050. The model bases on data from national statistics (e.g., supply and use tables) and considers H2 production via electrolysis by using renewable power (green H2) and reformation of natural gas with carbon capture and storage ("*blue*" H2). Simulations indicate reduced real GDP growth, stagnating until 2050, largely due to fossil fuel restriction and its impacts on available energy products such as electricity. H2 will play a central role in the Norwegian transport sector (maritime, heavy-duty, passenger car) and as an export product to Europe. However, job losses in the oil sector are only partially compensated by the H2 sector, due to the lower export compared to today's exports of oil and gas. The reviewed scientific studies use macro-data (e.g., from national statistics) via macroeconomic modeling (e.g., CGE models) with respect to H2 and possible applications, but do not consider H2 use in aviation. A complete qualitative and quantitative description of the integration of the H2 supply chain (generation, compression, liquefaction, transport, storage, application) into the respective macroeconomic dataset is missing.

Next to scientific studies, some industry reports also use macroeconomic approaches to assess H2 developments (see Refs. [56–58]). For example, the IEA [1] applied a multi-country general equilibrium model by the International Monetary Fund as part of the global "Net Zero by 2050" report. The model estimated the impacts of changes in H2 investment on future global GDP. Capital investment in H2 technology rises by 2050 as production facilities scale up and H2 in transport becomes more widespread. The surge in private and government spending on clean energy technologies creates a large number of jobs, stimulates economic output in the engineering, manufacturing and construction industries and positively affects global GDP. However, there are large differences between regions as a decline in fossil fuel use, investment and prices results in a fall in GDP in the respective producer economies. Such industry reports frequently fail to describe the methodology transparently and lack a scientific approach. It is difficult to draw conclusions about which results can be attributed to the model analysis. However, in a recent potential study of green gases for Central Germany, Ludwig Bölkow Systemtechnik (LBST) [59] provided a more comprehensive picture. The report determined value-added and employment effects using the I-O calculation method (based on data from the Federal Statistical Office). Investments in green H2 lead to positive economic effects driven by H2 demand from the chemical industry and power to liquid (PtL) production. Gross value added will exceed EUR 1 billion and over 8900 jobs will be created by 2040. H2 must be imported to fulfill demands, but the effects would increase (+10%) due to renewable energy expansions and consequently higher coverage of regional H2 demand by domestic generation. Domestic production leads to reduced import dependency, but imported H2 is likely to become cheaper. The potential study is one of the few investigations with detailed focus on Germany and H2 integration into a macro-framework, but limited to regional analysis and selected macro-indicators. For instance, it is not considered whether there will be job losses in other sectors.

A spotlight including H2-powered aviation in macroeconomic studies is missing. However, according to BMWi [15] and National Hydrogen Council [60] macroeconomic assessments of H2-powered aviation are essential. The implementation of H2 affects the direct and indirect value chain of aviation such as on the fuel side, i.e., production, transport, storage, liquefaction and application [21,32,61], and the aircraft side [14,17,33,36]. Recent findings by Hoelzen et al. [39] underline the need for macroeconomic analyses to examine whether H2-powered aviation would have positive or negative effects on a state's economy.

The overall objective of this paper is to derive a methodology that enables the evaluation of macroeconomic effects of H2 supply infrastructure for H2-powered aviation using Germany as an example. To achieve this, three goals are in scope for this study: (1) Explanation on the construction and investigation of a macroeconomic database for Germany, a so-called Social Accounting Matrix (SAM). (2) Translation of the components and pathways of LH2 supply chains to the German system of national accounts, with a focus on the aviation sector. (3) Implementation of H2-powered aviation into the macroeconomic data framework including exemplary quantification.

The structure of the paper is as follows: Section Methodology for macroeconomic analyses and Social Accounting Matrix provides an introduction to the methodology of macroeconomic analysis with particular emphasis on the description, application and structure of the SAM approach. Chapter Status-quo Social Accounting Matrix for Germany and the role of aviation fuel illustrates a SAM for Germany and describes the macroeconomic dataset and status quo. It specifically deals with the aviation sector within the macroeconomy and highlights its interrelations with other industries. Section Introduction of H2-powered aviation supply components to economic sectors translates H2-powered aviation supply components to economic sectors. It further provides an exemplary cost overview of LH2 supply components and chains. Subsequently, the techno-economic cost considerations along three supply chains are allocated to macroeconomic sectors. Section Integration of new aviation fuel supply chain costs in the SAM presents an insight into how the new H2 supply chain costs for aviation can be implemented in the macroeconomic SAM framework. Finally, Chapter Disucssion on hydrogen-related job effects and future hydrogen demands discusses potential employment effects related to global and national H2 trends and future H2 demands, and Section Summary and conclusion summarizes, concludes and outlines limitations of the paper.

Methodology for macroeconomic analyses and Social Accounting Matrix

This chapter focuses on a methodological introduction to macroeconomic analysis with the purpose to provide a solid foundation on the approach of SAM. This is done in several steps: First, macroeconomic modeling is illustrated using equilibrium models as an example. Second, a general definition of the SAM approach and its areas of application is presented. Third, a detailed description of the structure and contents of a SAM is given.

Macroeconomic modeling

Macroeconomic modeling can be defined in a straightforward way as a quantitative depiction of an economy. The well-established method of CGE modeling is an approach to represent a macroeconomy via a comprehensive system of equations. A CGE model takes an economy-wide perspective and seeks to explain the behavior of supply, demand and prices in a whole economy with several markets [62], deals with the transactions of goods, services and production factors [47], determines the equilibrium across all markets, and calculates economic indicators endogenously [46]. More specifically, general equilibrium theory combines assumptions on the optimizing behavior of economic agents with the analysis of equilibrium conditions: The behavior of market actors is captured by maximization of profits and utility, respectively; producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers with given preferences maximize their well-being subject to budget constraints. The modeling approach also includes a set of equilibrium conditions that cover factor and commodity markets as well as macroeconomic balances (e.g., government budget and trade balance). The consistent macroeconomic framework generates microeconomic representations of price-responsive market interactions and income-expenditure circles [63,64]. Generally, a CGE model is classified as top down model [47,62], and its framework is appropriate to cover economy-wide linkages as well as to carry out simulations [65]. As a result, a CGE analysis quantifies changes in various key macroeconomic indicators (e.g., GDP, social welfare, domestic employment) as well as sector-specific economic activities (e.g., outputs, factor reallocation, substitutions, imports, exports, price dynamics, opportunity cost) as compared to a baseline situation.

A SAM typically forms the data basis for a CGE model [66–68]. Fig. 1 displays a SAM within a macroeconomic modeling framework. The comprehensive dataset is adjusted context-specifically and processed in a system of equations. Hence, two methods are merged for comprehensive macroeconomic analysis: The SAM approach and general equilibrium modeling. For example, Lofgren et al. [69] provided detailed insights on the construction and application of a standard CGE model. The application bases on an aggregated SAM for Zimbabwe. Similarly, Gronau et al. [70] used a SAM for CGE calibration to simulate papyrus as a renewable energy resource for an energy transition in rural Zambia. Finally,

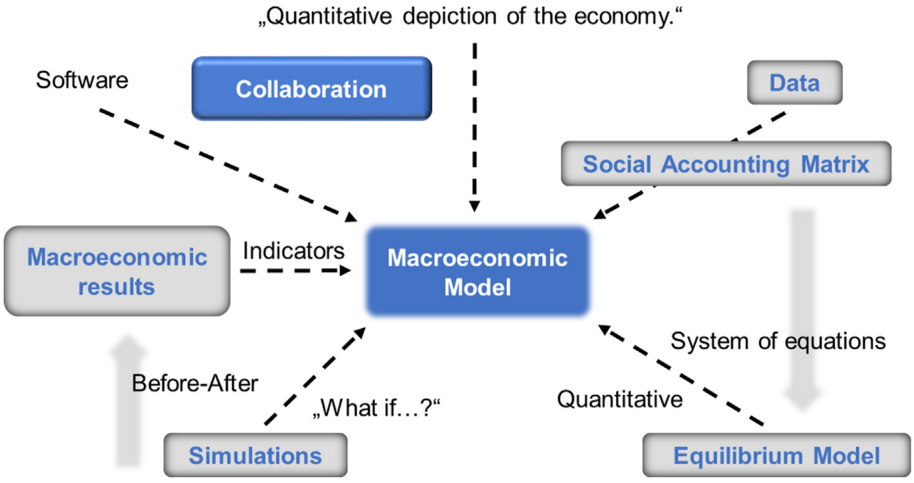

Fig. 1 – Conceptual framework of macroeconomic modeling by using a SAM and an equilibrium model.

Fig. 1 highlights the relevance of simulations, investigation of key performance indicators (such as changes in GDP) and possibility of transdisciplinary collaboration in macroeconomic modeling. A well-established modeling software is the General Algebraic Modeling System (GAMS). Within the scope of this paper, a SAM for Germany is applied contextually to the H2 and aviation sectors.

General description of Social Accounting Matrix and application

A SAM is a comprehensive and economy-wide database recording data about all transactions between economic agents in a specific economy for a particular period of time. It conforms to the System of National Accounts and is an extension of the I-O framework or supply and use tables [71]. The coherent framework analyzes the aspects relating to production and monetary flows between institutions, representing all the transactions of a socio-economic system in a comprehensive, flexible and disaggregated form. It reflects the full process of production, trade, income generation and redistribution among institutional sectors [67]. According to the European Commission et al. ([71], p.16), a SAM is a valuable structure for analyzing *"who does what with whom, in exchange for what, by what means, for what purpose, with what change in the stock"*. Put simply, it is a representation of a country's GDP. The general SAM framework was first described by Pyatt and Thorbecke [72]. Subsequently, Pyatt and Roe [73] provided a detailed description of the framework using the example of Sri Lanka, and Pyatt and Round [74] carried out a review of the early experience of compiling SAMs. More recent SAM investigations relate to Spain [75], Italy [76], Ireland [77], Saudi Arabia [78], Ecuador [79] and Kenya [80]. In the context of H2 implications, the SAM method is applied to Korea [54] and South Africa [81]. Furthermore, I-O data form the basis for H2-related macro-analyses for Taiwan [50,51], Japan [55] and Norway [9].

The Social Accounting Matrix structure

The general structure of a SAM is illustrated as a square matrix (Table 1). Each cell of the matrix indicates the payment from the respective column to the row account. In general, columns represent payments (expenditures) and rows represent receipts (incomes). The underlying double-entry accounting principle requires that, for each account, total income (row total) equals total expenditure (column total). An aggregated macro-SAM has typically nine superordinate accounts: (1) Commodities (the outputs of activities, i.e., goods and services), plus trade and transport margins (part of the costs of supplying commodities), (2) activities (or processes; represent agents/sectors that produce commodities), (3, 4) two production factors (labor and capital),[1] (5, 6, 7) three institutions (households are the owner of labor and capital factors; enterprises possess activities and capital; the government refers to the public administration sector), (8) a saving-investment (S-I) account (accumulation account; records the allocation of resources for asset formation and stock changes) and (9) the Rest of the World (RoW) account (covers transactions beyond the geographical/national border). Table A1 (see Appendix A) provides a more detailed overview and description of the SAM accounts.

Status-quo Social Accounting Matrix for Germany and the role of aviation fuel

In the previous chapter, a solid foundation on the SAM methodology was provided. This chapter aims to describe the macroeconomic database and status quo using a SAM for Germany, with a particular focus on the aviation sector. First, the database is outlined, followed by an exemplary SAM for Germany in 2017, which is analyzed using macroeconomic indicators. Finally, the aviation sector is explored on a macro-level. Key connection of aviation in the economy, value contribution of the sector, kerosene production and utilization, employment effects and the relevance of the electricity sector are highlighted.

Source and depth of data

The German Federal Statistical Office provides the primary source of data for constructing a SAM for Germany. In this study, the 2017 supply and use tables are employed as the main database, which includes 63 economic sectors producing 85 product groups [82]. Each sector disaggregates into groups, classes and subclasses [83]. Data from national accounts by the German Federal Statistical Office [84,85] and energy balance sheets [86] supplement the SAM construction. The final SAM Germany is for the year 2017, which is considered to be an economically representative year. Detailed data from national accounts (e.g., I-O tables) are provided every few years and retrospectively by German statistical offices. This study uses the most recent available datasets.

State of the art Social Accounting Matrix Germany

Table A2 presents a SAM for Germany in 2017. The accounts are numbered according to the structure in Table 1. The SAM framework depicts a high-level overview of the German economic system with the possibility of in-depth sectoral analyses. Accounts can be flexibly aggregated or disaggregated depending on the focus of analysis, which in this context is H2 and aviation. The macroeconomic data framework of this paper covers 60 accounts with a focus on H2-powered aviation: 22 economic sectors (industries; production activities) and 27 product groups (commodities and services). Following the logic of supply and use tables, the SAM is not square, i.e., industries can produce multiple commodities.[2] Moreover, the SAM incorporates a margins account, two factors of production (labor and capital), three institutions (households, enterprises and government), a savings-investment account,

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[1] Further production factors can be added, depending on the research scope and data availability. For instance, SAMs may contain a land input factor (e.g., see Gronau et al. [70]).

[2] Information on the numbering of activities and the allocation of commodities to corresponding industries is given in Section Social Accounting Matrix Germany – focus on aviation.

Table 1 – The basic structure of the Social Accounting Matrix.

	(1) Commodity	Margins	(2) Activity	(3) Labor	(4) Capital	(5) Households	(6) Enterprises	(7) Government	(8) S-I	(9) RoW	Total
(1) Commodity		Transaction costs	Intermediate inputs			Household consumption		Government consumption	Investment	Export	Domestic demand
Margins	Transaction costs										Margins
(2) Activity	Marketed output										Gross output
(3) Labor			Compensation of employees							Labor income from RoW	Labor income
(4) Capital			Gross operating surplus and property income							Capital income from RoW	Capital income
(5) Households				Labor income	Capital income		Enterprise transfers	Government transfers I		Household transfers from RoW	Household income
(6) Enterprises					Capital income	Household transfers		Government transfers II		Enterprise transfers from RoW	Enterprise income
(7) Government	Net taxes on products		Net taxes on production		Capital income	Transfers and direct household taxes	Transfers and direct corporate taxes			Government transfers from RoW	Government income
(8) Saving-investment						Household savings	Enterprise savings	Government savings	*Capital account transfers*	Capital transfers & financial balance	Savings
(9) Rest of the world	Imports			Labor distribution to RoW	Capital distribution to RoW	Household transfers to RoW	Enterprise transfers to RoW	Government transfers to RoW			Payments to RoW
Total	Domestic supply	Margins	Production	Labor expenditure	Capital expenditure	Household expenditure	Enterprise expenditure	Government expenditure	Investment	Incomes from RoW	

Table 2 – Overview of selected macroeconomic indicators for Germany in 2017.

Indicator	Value	Unit
Gross Domestic Product	3267	EUR billion
Gross output/Total domestic production (excl.tax)	6018	EUR billion
Intermediate input share	51 (3071)	Percent (EUR billion)
Labor value added share	28 (1693)	Percent (EUR billion)
Capital value added share	21 (1253)	Percent (EUR billion)
Employment (full-time, part-time, self-employed)	44	Million person
Labor factor income	1693	EUR billion
Domestic supply/demand (of all commodities)	7591	EUR billion
Domestic sales	4497	EUR billion
Investment	685	EUR billion
Import	1253	EUR billion
Export	1518	EUR billion

three tax accounts (indirect and direct) and a connection to international trade (RoW account). Table 2 gives an overview of selected macroeconomic indicator calculations: A meaningful measure is the GDP along the production, expenditure and distribution chain. The German GDP 2017 is around EUR 3267 billion. The country has thus one of the highest GDP per capita ratios in the European Union with a value of EUR 39,500 per head. The European Union's GDP average was around EUR 32,000 per head in 2017 [85]. Another measure is the total production value which provides information on domestic value generation. It comprises intermediate input uses (51%) plus value added by labor (28%) and capital (21%). The relation between inputs (EUR 3071 billion) and factor utilization (EUR 2946 billion) is thus relatively balanced across the macroeconomy. An interesting reference for macro-analyses is the employment situation. In 2017, there were 44 million economically active persons [82], which is not explicitly displayed in the SAM, but inherently links to the total labor factor income (EUR 1693 billion). Such estimates enable to calculate the gross monthly wage per month and capita (slightly above EUR 3000), or an in-depth job analysis in specific economic sectors (e.g., jobs generation per ton kerosene, see below). Additional interesting figures often used for macro-level analysis are domestic supply/demand of commodities, sales and investment of the entire economy or a specific sector. Imports and exports are relevant for trade analyses of cross-border activities. These macro indicators form the basis for subsequent calculations (e.g., trade-to-GDP-ratio, a measure of a country's trade openness).

Social Accounting Matrix Germany – focus on aviation

The aggregated SAM used in this article covers 22 economic sectors and 27 product groups relevant for a macro-level examination of H2-based aviation in Germany. Specific attention is paid to major industries and services related to aviation. This concerns diverse products and sectors, for example, the mineral oil, storage and transport services, maintenance, travel agencies and machine sectors. All remaining national sectors are allocated to agriculture, manufacturing industry and services aggregates. Table 3 provides a classification and description of economic sectors of the SAM (Table A2), derived from the 2017 supply and use tables. The numbering is applied to the SAM in order to display the sectors. The same numbers are applied to the corresponding commodities, which represent the output of the activities. Since the number of goods and services exceeds the number of industries, a specific labeling for the disaggregated commodities is used. The SAM contains three activities that account for more than one commodity, labeled as follows in Table A2: (2) Mining and quarrying produces hard coal (2A), brown coal (2B), crude oil and natural gas (2C) and ores, stones and earths (2D); (3) Coke and mineral oil produces coke products (3A) and mineral oil products (3B); and (9) energy supply produces electricity and heat (9A) as well as gas distribution (9B).

The SAM illustrates that aviation interacts with various sectors of the economy. Fig. 2 shows the key economic linkages and value flows from/to the aviation sector (also see Table A2). Demand for air travel is driven by passenger and freight transportation. The aviation industry receives billions from various economic players. In 2017, the sector's total supply/demand was EUR 31,738 million (see Table 4). Nearly half (44%) originates from the demand of domestic sectors/companies, indicating aviation's extensive integration in economic processes. 61 out of 63 economic sectors have a demand for aviation. Flight services are used for business travels and freight transport. Main industrial demand for aviation (nearly 30% of total demand) stems from the (a) travel agencies, (b) machines, (c) electronic and optical devices and data processing equipment, (d) delivery and express services and (e) motor vehicles sectors. Households' direct demand for flights makes up 26%, and the remaining third represents sales abroad to persons and/or companies (economic units) that do not have their permanent residence in Germany.

In order to supply air travel services, the aviation industry needs various inputs, namely 47 out of 85 product groups. Main inputs (around 50% of industrial supply for aviation) are (a) mineral oil, (b) storage and transport services, (c) maintenance general, (d) hospitality and (e) renting movables. The aviation sector also has a high level of internal uses for service generation. This sums up to a total domestic production value of the air transport system (ATS) of EUR 25,966 million in 2017 (Table 4). Interestingly, purchases of inputs account for 69% of product generation. Value added by labor (20%) and capital (11%) accounts for the remaining share of domestic output. According to Destatis [87], around 65,000 employees were directly employed in the aviation sector in 2017 (companies with economic focus on aviation; mainly airlines). Additional direct employment in aviation-related sectors (such as aircraft manufacturers, airports) is recorded in the respective sectors. This is an indication why aviation employment statistics vary widely by definition: A report by BDL [88] stated that 329,800 people have been directly employed in 2017 in the aviation industry, including German airports, airlines, air traffic control and manufacturers. The study also considered indirect effects for jobs (353,800) in supplier and upstream sectors as well as induced effects (165,100) by aviation employees (direct/indirect) consumption. BMWi [89] highlighted that 114,000 people have been employed in the aviation industry of which 81,000 relate to the civil aircraft industry (aircraft

Table 3 – Exemplary classification of economic sectors of the SAM relevant for aviation (based on Refs. [82,83]).

	Economic sector	Description	Product groups (CPA[a])	Sector/ industry code (WZ 2008[b])
1	Agriculture aggregate	Agriculture, forestry, fishery and aquaculture	1–3	A
2	Mining and quarrying	Extraction of hard coal and brown coal	5	B
		Production of crude oil and natural gas	6	
		Mining of ores, stones and earths	7-9	
3	Coke and mineral oil	Processing of coal to coke and crude oil to mineral oil products (e.g., otto fuels, jet fuel)	19	C
4	Electronic and optical devices and data processing equipment	Production of data processing equipment, electronical and optical products (e.g., computers, peripheral equipment, telecommunications, consumer electronics, watches, as well as measuring, monitoring, navigation and control instruments, electromedical equipment, solar cells, etc.)	26	C
5	Machines	Construction of machines, lifting and handling equipment (incl. pumps, compressors, tools)	28	C
6	Motor vehicle	Manufacture of motor vehicles for transport of persons and freight (incl. parts, fittings, trailers)	29	C
7	Other vehicles	Ship, rail, aircraft/aerospace and motorcycle/bicycle construction (incl. engines, seats, rotor blades, propellers)	30	C
8	Maintenance general	Repair, installation, maintenance and restoration of metal products, machines, electrical equipment (incl. engines, aircraft, compressors, pipes, pipelines)	33	C
9	Energy supply	Electricity and heat: Operation of power generation plants [fossil thermal, nuclear, gas, diesel and renewable energy (wind, hydro, solar)], transmission; trade; heating-cooling supply (district heating)	35.1, 35.3	D
		Gas distribution: Production of gas and distribution (natural and synthesis gas) to the consumer through pipes	35.2	
10	Water supply	Supply of water, obtained and distributed (incl. sea and groundwater desalination)	36	E
11	Construction	Structural engineering (incl. airport buildings, warehouses), civil engineering (incl. roads, bridges, tunnels, railroad, ports, industrial plants, pipes, pipelines, electric networks) and construction site/installation/expansion (parts of engineering; specialized activities; e.g., installation of lighting equipment and repair work at airport)	41–43	E
12	Maintenance motor vehicles	Trade, repair and maintenance of motor vehicles (relates to product group 29)	45	G
13	Trade	Wholesale and retail trade	46 & 47	G
14	Pipeline and land transport	Land transportation and transport services in pipelines; Passengers and freight transport by road and railway as well as goods via pipelines and tank truck transport	49	H
15	Aviation	Passenger and freight transportation in the aerospace industry (incl. airlines)	51	H
16	Storage and transport infrastructure	Operation of storage facilities (cold stores, storage tanks, etc.); Provision of transport services, such as operation of transport infrastructure (e.g., airports, ports); Operation of airports, i.e., support activities for air transport of passenger and freight (handling facilities, control, regulation of air traffic, ground services)	52	H
17	Delivery and express services	Postal, courier and express services (e.g., collection, transport and delivery of letter and parcel post)	53	H
18	Hospitality	Provision of accommodation of visitors (e.g., hotels, pension, camping) and food and beverages for immediate consumption (e.g., restaurant, catering, bars)	55 & 56	I
19	Renting movables	Rental and operating lease of property, plant and equipment (excl. operating personnel) and lease of non-financial intangible assets (excl. copyrights). Rental and operating lease such as motor vehicles, sports and recreational equipment, data processing equipment, consumer durables, machinery and equipment for economic activities [incl. means of transportation for example aircraft without crew (airplanes, helicopters, hot air balloons)] in return for a periodic rental fee or lease payment	77	N

Table 3 – (*continued*)

	Economic sector	Description	Product groups (CPA[a])	Sector/ industry code (WZ 2008[b])
20	Travel agencies	Sale of travel, transport and accommodation services and in the compilation and organization of packages through travel agencies or directly, e.g., by tour operators, incl. travel-related services (e.g., reservation)	79	N
21	Manufacturing industry aggregate	Food, beverages and tabaco	10–12	C
		Clothing	13–15	
		Wood products and papers	16 & 17	
		Data carrier	18	
		Chemicals and pharmaceuticals	20 & 21	
		Rubber and plastic	22	
		Glassware and ceramic	23	
		Raw iron & steel, non-iron metals & castings	24	
		Metals	25	
		Electronic equipment (e.g., home appliances)	27	
		Furniture and other goods	31 & 32	
		Waste water and disposal	37–39	E
22	Service aggregate	Shipping services	50	H
		Publishing, media and radio	58–60	J
		Telecommunication	61	
		IT	62 & 63	
		Finance	64	K
		Insurance and real estate	65–68	K-L
		Tax and business consulting	69 & 70	M
		Engineering offices/services	71	
		Research & development, market research	72 & 73	
		Freelance and veterinary	74 & 75	
		Time-work	78	N
		Security	80–82	
		Public administration	84.1	O
		Defense	84.2	
		Social insurance	84.3	
		Education and public health	85 & 86	P
		Homes and social care	87 & 88	Q
		Culture and gambling	90–92	R
		Sports & recreation, church	93 & 84	R-S
		Repair to data processing & consumer goods	95	S
		Personal and home services	96–98	S-T

[a] CPA = Classification of Products by Activity.

[b] WZ 2008 = NACE Rev. 2 (European Classification of Economic Activities/Sectors) & ISIC Rev. 4 (International Standard Industrial Classification of All Economic Activities/Sectors of the United Nations).

manufacturers) in Germany. According to Airbus [90], the company employs around 46,000 people at numerous German sites, which corresponds to about half of all employees in the German aviation and aerospace manufacturer industry. In 2017, around 300 companies have been active in the national aviation sector [87], such as Lufthansa, Eurowings, Condor, TUIfly and SunExpress [91]. Frankfurt, Düsseldorf, Munich, Hamburg and Berlin Tegel were the airports with the highest volume of passengers in Germany in 2017 [87].

The aviation sector has significant spendings on jet fuel. Kerosene is the main fuel of the aviation industry and thus, an important part of its supply chain. Results show that there are two channels for the supply of jet fuel in Germany: (1) By domestic production through crude oil processing and (2) by importing the final product (Table 4). Basis for jet fuel is crude oil as primary energy. The SAM reveals marginal domestic crude oil production in Germany and a strong dependence on imports. Accordingly, imports cover more than 95% of crude oil demand in 2017 [86]. Refineries treat crude oil and process it into various mineral oil products (secondary energy). Around 15,000 employees worked in the coke and mineral oil sector in 2017 [82], in line with data from BMWi [92]. The analysis reveals high dependence of the sector's production processes on intermediate inputs (e.g., crude oil and natural gas, chemical products, electricity and heat, pipeline, storage and transport services, tax and business consulting, security), which account for 89% of the output value. Main outputs of the mineral oil sector are otto fuels, crude gasoline, diesel fuel, heating oil, liquid petroleum gas and also kerosene [93]. The domestic kerosene production was 5,346,000 tons at German refineries in 2017 [86]. In Germany, its domestic production price 2017, ex works excluding tax and trade margins, was 0.30 Euros per kg (see Statistisches Bundesamt [85]). As a result, kerosene has a value share of about 3% in the coke and mineral oil sectors total production. An in-depth job analysis reveals 88 direct jobs per megaton of kerosene produced in the coke and mineral oil sector in Germany. The job calculation is based on the value share of kerosene production in the mineral oil sector multiplied by the total sector employment, converted to megatons. More specifically, this translates into 7 jobs per TWh (assuming an energy density of 43.521 MJ/kg for jet fuel [94]) kerosene produced in Germany. Next to domestic production, 5,924,000 tons of kerosene were imported. Main user of kerosene in Germany is aviation, with a total volume of 9,933,000 tons [86]. This equates almost 90% of the total demand. The remaining part comprises conversion processes in the mineral oil sector, utilization in public administration and defense, stock changes and exports [86]. In Germany, the average kerosene (purchaser) price was 0.50 EUR/kg [59]. A comparable 2017 sales price to airlines of 0.46 EUR/kg was approximated from EIA [95]. The difference between the jet fuel sales and production price comprises trade margins and product taxes (see Statistisches Bundesamt [85]).

Table 5 illustrates the kerosene separation from the mineral oil sector and its integration into the SAM framework. For an exemplary consideration in the dataset, jet fuel is first separated from the mineral oil sector in terms of its value. A domestic production price of 0.30 Euros per kg is used (see Ref. [85]). The supply chain is defined in line with the general mineral oil sector. The intermediate inputs (1419.2 million), factors (168.6 million) and production tax (2.2 million) are distributed as a share of total production value (1603.8 million); plus processed kerosene in the conversion operation (13.8 million). According to Destatis [82], a margin of 9% on mineral products (of total domestic supply value) is set. About 50% of the total demand is covered by imports (2962 million; including cost, insurance and freight). The product tax (on carbon, imports, less subsidy, etc.) is treated as a residual and is 9% of the total supply value. For the overall mineral oil sector, the product tax accounts for 34% of total supply value in 2017 (based on Ref. [82]). There is no value-added tax on kerosene. However, a detailed product tax consideration is not focus of this analysis. For kerosene utilization a sales price of 0.50 EUR/kg is assumed [59]. Aviation is the main user (4966.5 million), but a considerable amount is also used for exports (647 million). The hands-on description on the kerosene separation from the kerosene sector is particularly useful for investigating/enabling kerosene-substitutes, such as H2, in macroeconomic modeling applications. Alternatively, in a SAM representation, the mineral oil sector can also remain unchanged. In this case, only the product kerosene would be separated from the mineral oil products and appear as one output of the mineral oil activity.

In evaluating a kerosene alternative, the focus is set on the SAM's electricity sector as it is relevant for green H2 production through renewables. The sectoral aggregate of the total electricity mix is defined by a disaggregated representation of gross electricity generation. Germany's conventional energy sources for gross electricity generation in 2017 were brown coal (23%), hard coal (14%), natural gas (13%), nuclear energy (12%) and, to a minor extent, mineral oil (1%). The renewable share was 33%, comprising of wind energy (16%), photovoltaics (6%), biomass (7%) and hydropower (3%). Germany's total gross electricity generation was 654 TWh (6554 billion kWh) in 2017 [96]. An increased green LH2 demand is expected to result in additional energy production from renewables in the future. According to Destatis [97], about 207,500 persons worked in the electricity sector in 2017, i.e., employees in the operation of power generation plants (fossil thermal, nuclear, gas, diesel and renewable energy), transmission and trade. This would translate into 317 jobs per TWh in the electricity sector which is a much higher employment factor compared to the previously examined mineral oil sector (7 jobs/TWh). Furthermore, a recent study estimated total employment in the renewable energy sector alone at 315,000 [98], but taking into account all direct and indirect employment effects, for example, construction/engineering, parts production and maintenance. Finally, the SAM illustrates cross-border trade in electricity. In 2017, electricity import is about 4% and export about 12% of domestic power generation [86].

So far, the paper has examined the aviation sector in the current macroeconomic system. In the next step, the focus will be on H2 and H2-powered aviation. Results demonstrate that there was no significant production of green H2 in Germany in 2017. Only marginal production of grey H2 is part of the chemicals sector (manufacturing industry aggregate in the SAM). Green H2 production/utilization is not present in the SAM 2017 dataset, respectively did not play a role on macroeconomic level.

Introduction of hydrogen-powered aviation supply components to economic sectors

After a description of the macroeconomic status quo and the role of aviation, this chapter focuses on translating the components and pathways of LH2 supply chains to the German system of national accounts. For this purpose, this chapter first outlines three different supply chains of LH2 for aviation. Subsequently, cost splits per LH2 supply component along three H2 supply chains are derived. A further subchapter allocates the H2 supply components, pathways and costs to relevant macroeconomic sectors. Finally, this chapter discusses the macroeconomic consideration of H2-aircraft technology and airport infrastructure changes (demand/application side), which is beyond the scope of this study. The methodological procedure in this chapter (supply costs per path, allocation of cost data by economic sector) is similar to a recent study by LBST [59], which investigated green gases at the macro-level for central Germany. In addition, studies by Lee et al. [51], Lee and Chiu [99] and Lee [55,100] provided meaningful insights of H2 integration into a macroeconomic dataset.

Liquid hydrogen supply chains for aviation supply chains for aviation

LH2 as an aircraft fuel requires new fuel supply chains. Hoelzen et al. [39] provide a holistic view from H2 fuel infrastructure to H2-powered aircraft. The authors highlight six basic supply chain components: H2 production, compression, liquefaction, storage, transport and LH2 refueling equipment.

Starting with the converting units, water electrolysis is used to generate H2 [101]. The electricity required for this is drawn from renewable energy plants (not considered further in this study) to produce green H2. Water electrolysis is a very energy intensive process and requires around 45–55 kWh

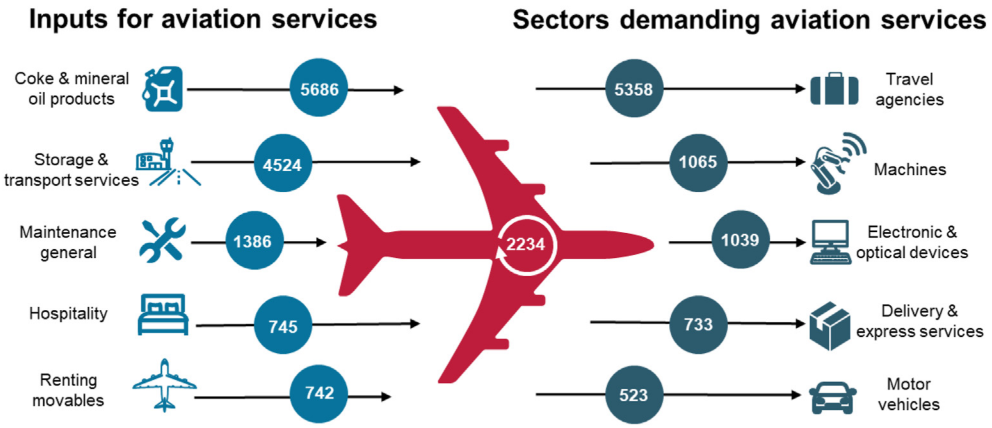

Fig. 2 – Top 5 inter-industry connections of aviation in Germany. Values in million Euro.

electric energy per kg H2 generated [101]. The following conversion step is the compression of gaseous H2 to either enable more volumetric compact buffer storage or its transport with the required mass flows to the airport [102]. The next conversion system is H2 liquefaction. In H2 liquefaction plants (LFP), gaseous H2 is cooled down to −253 °C [103]. As a result, it is converted in its liquid and volumetrically denser aggregate form [102]. This process is also relatively energy intensive with 6–12 kWh electricity requirement per kg of liquefied H2 [104]. Since H2-powered commercial aircraft will most likely be powered by liquefied and not gaseous compressed H2, the LFP takes a central role in the overall fuel supply chain [25,39]. Next to the group of conversion components, H2 storages (liquid or gaseous) are required to decouple the operation of the conversion units and to ensure a reliable supply [105]. Storage installations can be above ground or underground, such as in salt caverns or rock formations [106]. Then, transport of H2 connects and enables cost-optimized electrolysis operation at sites that are not necessarily the same as the site of LH2 demand (airport). The most efficient form of transporting GH2 is through pipelines, while LH2 is rather transported in containers with trucks, trains or vessels (inland or large oversea carriers) [107]. Finally, the refueling system at the airport describes the "last mile" to the aircraft via truck or pipeline and hydrant systems [38]. Given the availability of the described components, there are manifold options in arranging these in so-called supply pathways. Fig. 3 shows three supply routes (S1, S2a, S2b) and two refueling setups (R1, R2) that can be combined to form a supply chain for aviation [38].

Three main supply pathways are of interest for the macroeconomic analysis in the article: The first is a completely nationally (inland) sourced supply chain. Domestic H2 is

Table 4 – Details on the aviation sector.

Indicator	Value	Unit
Gross output/Total domestic production (excl.tax)	25,966	EUR million
Intermediate input share	69	Percent
Labor value added share	20	Percent
Capital value added share	11	percent
Employment	65,073	Person
Labor factor income	5269	EUR million
Imports of aviation services	5475	EUR million
Aviation share in GDP	1	Percent
Sectors total supply/demand	31,738	EUR million
Demand for aviation by other industries	44	Percent
Demand by households	26	Percent
Demand from abroad (export of services)	30	Percent
Supply for aviation services via imports	17	Percent
Supply via domestic production	79	Percent
Supply share of product taxes	4	Percent
Kerosene		
Total domestic production	5346	1000 ton
+ Import	5924	1000 ton
+ Stock removal	38	1000 ton
= Total volume	11,270	1000 ton
– Aviation use	9933	1000 ton
– Export	1294	1000 ton
– Conversion use, mineral oil sector	46	1000 ton
– Public administration and defense use	35	1000 ton

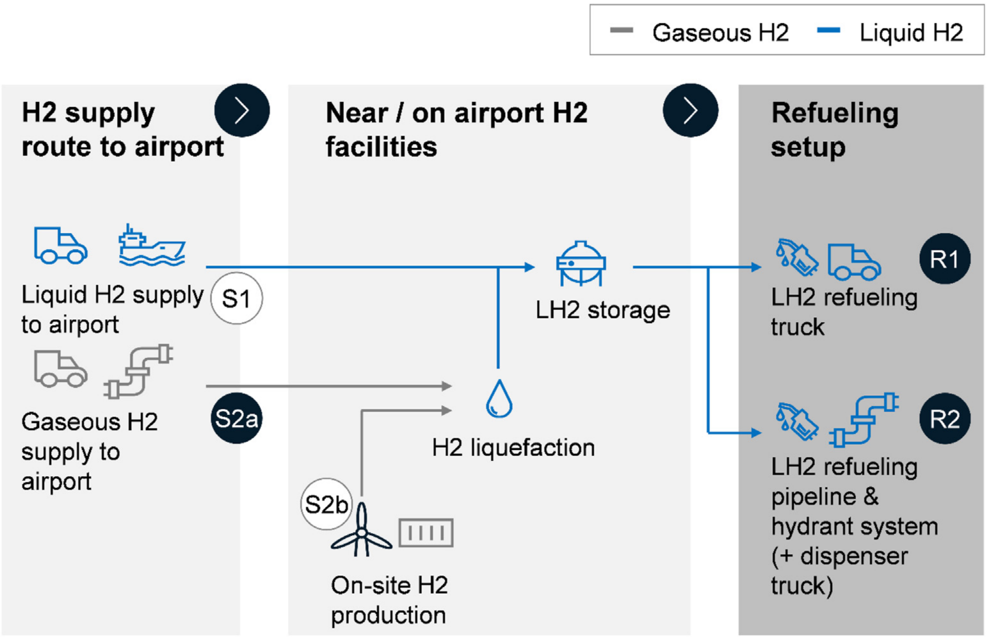

Fig. 3 – Overview of H2 supply chains for aviation [38].

generated in Germany – either on-site at the airport or at a central location close to the airport (S2b), or off-site from a central location inland. For the off-site production, H2 is either transported via pipelines to the LFP at the airport (S2a) or liquefied at the generation site and then transported in its liquid form by truck, train or inland vessel (S1). For domestic production, the off-site pathway, using inland pipeline transport, is considered in the following (S2a). Second, H2 is imported from another country in its gaseous form and arrives via pipelines connected to the airport (S2a). In this case, the LFP is placed at or close to the airport fuel processing site (inland). Third, H2 is imported (most likely from overseas) in its liquid form via large carriers (S1). Once unloaded, it is transported to the airport in LH2 trucks, trains or inland vessels. No LFP is required at the airport.

Once H2 arrives or is produced in its liquid form at the airport, there are two different refueling routes independent of the three supply scenarios described before: A truck (R1) or pipeline and hydrant refueling setup (R2). In the R1 setup, LH2 is transported by trucks from a central fuel farm to the aircraft stand. Such trucks have an LH2 storage on-board, but also a dispensing unit to prepare (purging) and fill the aircraft's LH2 storage. In the R2 setup, LH2 is transported via pipelines underground the apron to the aircraft. At the aircraft stand, a dispensing truck then connects the pipeline hydrant with the aircraft [108–111,145]. Since the R2 setup requires very high LH2 demands at airports to become economically viable (see Ref. [38]), the R1 refueling truck setup is considered in the following.

Costs of liquid hydrogen supply components and chains

A LH2 cost assessment is essential in order to translate the techno-economic supply components and pathways into the

Table 5 – Kerosene sketch as part of the mineral oil sector in the SAM. Values in million Euro.

	(1) Commodity Kerosene	(2) Activity Kerosene	(2) Activity Defense	(2) Activity Aviation	(8) S-I	(9) RoW	Total
(1) Commodity Kerosene		13.8	17,5	4966.5	−19	647	5625.8
(1) Aggregated Commodity		1419.2					
(2) Activity Mineral Oil							
(2) Activity Kerosene	1603.8						1603.8
(3) Labor		46.1					
(4) Capital		122.5					
(7) Government	544.2[a]	2.2[b]					
Margins (trade)	515.8						
(9) Rest of World	2962						
Total	5625.8	1603.8					

[a] Taxes minus subsidies on product.
[b] Taxes minus subsidies on production.

German system of national accounts. Studies for the aviation sector usually refer to US dollars as the main currency. Since data from German national accounts are in Euro, all cost components are converted based on an exchange rate of 0.85 EUR/USD. The cost values are taken from Hoelzen et al. [38] for the LFP, LH2 storages and refueling systems at the airport (LH2 truck refueling; R1). For example, reports by Hydrogen Council [7] and IRENA [101] provide data for the H2 electrolysis inland production, LH2 import and GH2 import price scenarios, and Clean Sky [25] for the transport of GH2 via pipeline and LH2 via trucks. Due to lack of data, LH2 inland transport via train or vessels is not considered in this study. Costs of the supply chain do not specifically refer to the German setup, but to the assumptions made (see Table B1, Appendix A) and cost projections for 2040/2050. It is important to mention that these are rough calculations and not concrete results. However, the focus of this paper is on the methodological procedure and thus, it is seen as a justifiable approach to derive such macroeconomic methodologies and evaluations.

Fig. 4 provides an overview of the exemplary LH2 supply costs for the three H2 supply chain scenarios and ten specific cost components. As a result, the GH2 international supply with a LFP at the airport (2.35 EUR/kg) might be the best economic choice. This is followed by LH2 inland production (2.71 EUR/kg) – given that renewable energy supply is sufficiently available for the H2-powered aviation application. International supply chains of LH2 to German ports combined with an on-land transport via LH2 trucks might lead to LH2 costs at the dispenser of 3.30 EUR/kg. However, this could be still a viable option, if GH2 import and LH2 inland production are not sufficiently available to cover all relevant H2-powered applications. Notably, all costs highly depend on the techno-economic assumptions used, influenced by the airport location as well as the availability of the supply technology and resources, such as renewable energy. For the sake of the paper's macroeconomic analysis, no sensitivity studies are conducted or cost ranges are tested. Approximated values act as placeholders and methodological approximation of integrating H2-powered aviation into a macroeconomic SAM data framework.

Allocation of hydrogen supply components to macroeconomic sectors

For the cost allocation of novel LH2 fuel supply chains to macroeconomic sectors, a cost break-down for each of the ten components is conducted (see Table 6). Eight relevant sectors for a H2 switch of aviation fuel supplies are identified: Machines (sectoral code 25, see Table 3), motor vehicles (code 29), electricity and heat (code 35.1, 35.3), gas distribution (code 35.2), water supply (code 36) and pipeline and land transport (code 49). Two maintenance sectors (code 33 and 45) support industrial processes. In addition, imports become prominent for LH2 or GH2 purchases abroad. Subsequently, the relative costs of the H2 supply chain components are assigned to respective macroeconomic sectors (component to sector approach). The sector description of machines fits well for all stationary supply components, i.e., electrolysis, compressors, GH2 and LH2 storages, LFP. Mobile components, such as LH2 truck and trailer systems and refueling trucks at the airport, are allocated to the motor vehicles sector. The supply component GH2 pipeline transport refers to the macroeconomic sector of pipelines and land transport. Furthermore, related installation, operation and maintenance costs of supply components are assigned to the maintenance general (incl. pipelines) and maintenance motor vehicles sectors. Costs for renewable electricity and water are allocated to the electricity and heat and water supply sectors, respectively. Purging gases that are required for safe refueling and fuel transfer operations (e.g., when filling LH2 transport trucks) can be seen as "gas distribution". Finally, imported GH2 via pipeline or LH2 via large vessels are linked to the import account.

Building on the breakdown of LH2 supply costs across the three supply chains (Fig. 4) and the relative split of LH2 cost components (Table 6), the paper contributes a translation to macroeconomic sectors (see Fig. 5). The LH2 inland supply pathway creates direct revenue streams to eight macroeconomic sectors in Germany. The approach assumes that all supply components and services are sourced from companies with a national subsidiary (permanent place of business in the

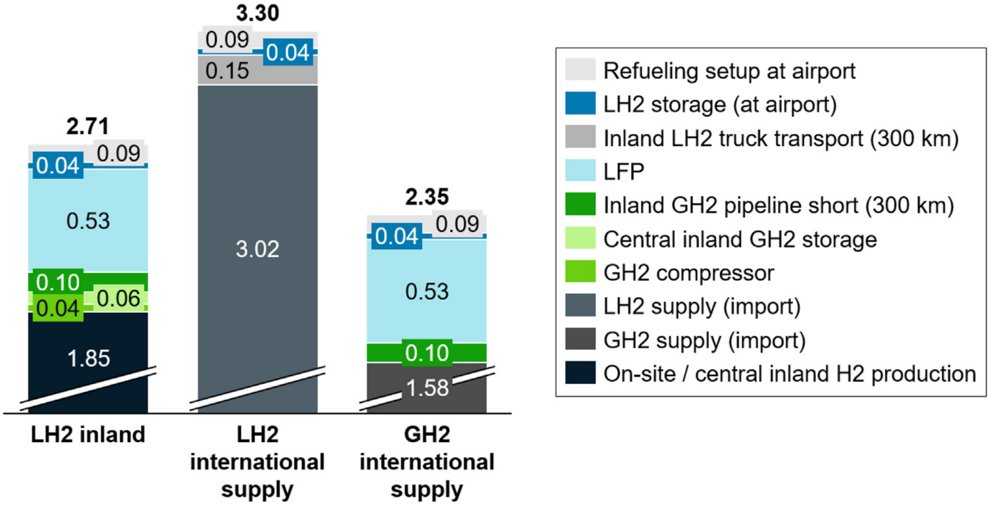

Fig. 4 – 2050 LH2 supply costs of three H2 supply chains for aviation in EUR per kg LH2 refueled into the aircraft – cost split shown per H2 supply chain component.

Table 6 – Relative cost allocation of H2 supply components to different relevant macroeconomic sectors based on assumptions shown in Appendix B. A cost share of 5% for labor (wages) and 10% for capital (depreciation, rent of durables, interest, profit) was assumed to be included in all component costs (see IRENA [101]), but not for import prices.

Component to Sector	Machines	Motor vehicles	Maintenance general (incl. installation for machines)	Electricity and heat (energy supply)	Water supply	Gas distribution (energy supply; industrial gases and services)	Maintenance motor vehicles	Pipeline and land transport	Import
On-site/central inland H2 production	11%	–	8%	65%	1%	–	–	–	–
GH2 compressor	30%	–	9%	46%	–	–	–	–	–
Central inland GH2 storage	45%	–	12%	28%	–	–	–	–	–
Inland GH2 pipeline transport	–	–	16%	21%	–	–	–	48%	–
LFP	30%	–	14%	41%	–	–	–	–	–
LH2 storage	61%	–	14%	10%	–	–	–	–	–
Inland LH2 truck transport	–	48%	–	–	–	25%	12%	–	–
Refueling setup at airport	–	27%	–	35%	–	15%	8%	–	–
GH2 supply (import)	–	–	–	–	–	–	–	–	100%
LH2 supply (import)	–	–	–	–	–	–	–	–	100%

economic territory of Germany) and are thus, accounted in the national (German) SAM. In that case, the largest cost stream (1.51 EUR/kg) relates to the electricity and heat sector, followed by machines (0.43 EUR/kg) and maintenance and installation (0.25 EUR/kg). The results seem reasonable, since water electrolysis and H2 liquefaction are energy intensive processes plus related to high investment costs [high capital expenditures (CAPEX)]. With very low costs for water supply to the electrolysis, these costs account for less than 1% of the total supply costs. The pipeline CAPEX costs (pipeline and land transport sector) for transporting GH2 from a central inland H2 production site to the airport are also very low with 0.05 EUR/kg. For the import supply chains, the main LH2 cost flows are allocated in the macroeconomic import account – 92% and 68% for the LH2 and GH2 import, respectively. For all supply chain setups, the costs for airport refueling setup including the LH2 storage account for roughly 3% of the total LH2 costs.

Overall, the linkage of LH2 supply costs to macroeconomic sectors emphasizes the difference of macroeconomic effects for a specific country depending on the LH2 supply pathways chosen. The macroeconomic contribution to the national economy is largest with a LH2 inland scenario (2.71 EUR/kg). This share decreases to 32% (0.76 EUR/kg) in the GH2 and to only 8% (0.28 EUR/kg) in the LH2 import supply pathways. The section also highlights that the electricity and heat sector would benefit most from a switch to H2-powered aviation in case of inland H2 production since this pathway would require significant electricity input. However, all figures depend on the assumptions taken in this exemplary methodological approach and will be subject for further detailed analyses in future publications (see Appendix B for details on techno-economic assumptions). Finally, the H2 cost analysis covers direct effects (revenues streams) in eight macroeconomic sectors, which lead to (follow-up) indirect benefits in related sectors of the economy. An investigation of these effects is possible with macroeconomic modeling, such as equilibrium models, which is beyond the scope of this paper.

Macroeconomic considerations of introducing hydrogen-aircraft technology

New H2-powered aircraft technology and airport infrastructure will be required in addition to the novel supply chains when LH2 is introduced as an aviation fuel. The accompanied changes that are needed in terms of aircraft and airport infrastructure also imply macroeconomic considerations.

Adjustments on the aircraft technology are necessary since LH2 fuel is not applicable to current aircraft systems, i.e., propulsion and storage [37,112]. The development of new H2-powered aircraft can have an effect on the national economy, especially for Germany, where well-known aircraft manufacturers and suppliers are located. For a better understanding of the cost – and consequently the macroeconomic effects – of switching aircraft propulsion systems from kerosene to LH2 as a fuel, a typical "direct operating cost (DOC) for aviation" framework can be used. Hoelzen et al. [39] investigate costs of energy, aircraft CAPEX, aircraft maintenance, crews and fees. Besides a change in energy costs (which is also subject to this study), operating costs in the field of aircraft CAPEX and aircraft maintenance could be affected. For aircraft crews as

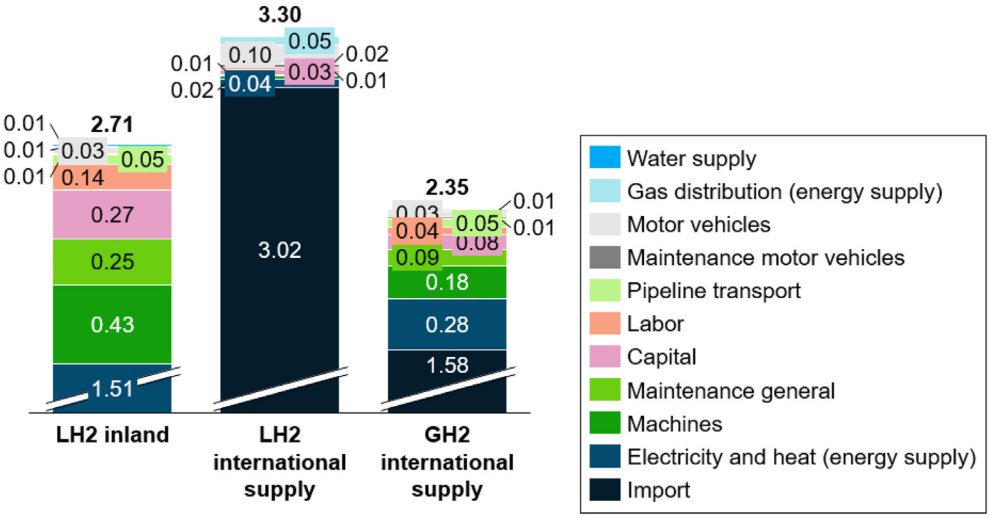

Fig. 5 – 2050 LH2 supply costs of three H2 supply chains for aviation shown in EUR per kg LH2 refueled into the aircraft – cost split shown per linked macroeconomic sector.

well as airport and navigation fees it was found that direct operating costs might not change (crew requirement unchanged, fees on passenger handling at airport most likely unchanged for similar sized aircraft). Consequently, macroeconomic effects result mainly from new investment and maintenance costs for H2-powered aircraft. Investments and expenses for new aircraft relate to the German macroeconomic sector called “other vehicles” (code 30, see Table 3), which explicitly addresses the construction of aircraft (including components such as engines, seats, rotor blades and propellers). Aircraft maintenance costs translate to the macroeconomic sector of “maintenance general” (code 33), covering repair, installation, maintenance and restoration of aircrafts (including engines). A first indication in this field shows that for a single-aisle (short-range) aircraft the plane CAPEX translated into DOC per 100 available seat kilometers (ASK) could increase by 12% and the maintenance costs by 11% compared to a kerosene-powered reference aircraft [39]. For a smaller widebody (medium-range) aircraft, the operating costs of both cost categories increase by 13% and 17%, respectively. The translation of changes in DOC (per 100 ASK) and aircraft technology into macroeconomic considerations is a promising field of future research in H2-powered aviation. More precisely, if changes are made to the aircraft design (including respective cost increases), this will have direct effects on the corresponding macroeconomic sectors, but also indirect effects on supplier industries domestically and abroad. According to the macroeconomic SAM data framework 2017, the “other vehicles” (incl. aircraft) sector comprises 19 demand sectors, 60 supply sectors (inputs, incl. services), as well as import and export activities. An in-depth analysis can be conducted to quantify these intersectoral implications using macroeconomic modeling applications, such as CGE models.

In addition to required aircraft adjustments, the switch to H2-powered aviation will also involve modifications to the future airport infrastructure [113]. On the one hand, these are caused by the new aircraft. If there are remarkable changes to the airplane itself, this will have subsequent effects on the airport construction and on-ground infrastructure. Among others, airport boxes that serve as parking area for aircraft are likely to be redesigned [25]. On the other hand, the use of LH2 as an energy carrier induces macroeconomic effects caused by advanced safety measures [114] and different handling conditions compared to kerosene [25]. For instance, the restructured handling of LH2 might lead to massive investments in the airport infrastructure. Additionally, safety measures could require specific job qualifications and thus, lead to an increase in demand for high-skilled labor. Therefore, modifications in the airport infrastructure would affect macroeconomic sectors such as “construction” (e.g., changes to airport buildings, roads and pipes; code 41–43, see Table 3) and “storage and transport infrastructure” (e.g., changes in operations of airports and transport infrastructure like ground services; code 52). This paper already considers initial airport infrastructure changes from the use of LH2 by taking into account the refueling setup at the airport (see Figure 3, R1). The approach attributes the accompanying refueling costs to the LH2 supply costs, assuming that they are part of the supply side. However, an alternative assumption could be that the refueling costs are assigned to the demand side (i.e., they are explicitly demanded by airlines/aviation and not considered as part of the fuel costs). Refueling costs would then be part of the “storage and transport infrastructure” sector (code 52). Future examinations are needed to assign the different cost components to the dimensions of fuel supply, airport infrastructure and aircraft adjustments. This will be especially helpful to compare the kerosene case in the existing ATS and the LH2 case in terms of their macroeconomic costs and linkages.

Integration of new aviation fuel supply chain costs into the Social Accounting Matrix

In the previous sections, we presented a general SAM methodology of macroeconomic analysis and outlined the conceptual approach for its application to H2-powered aviation.

The final step of our methodological procedure is the integration of H2-powered aviation into the macroeconomic data framework. A SAM benefits from the possibility to include new segments via modification and/or extension of the structure. New accounts allow the inclusion of additional/supplementary information and meet specific data needs about significant issues of a study [67,71]. Based on the previous results, this paper differentiates relevant accounts for H2-powered aviation investigations (Table 7).

Table 7 highlights the three LH2 supply chains in the macroeconomic SAM framework. Besides the cost components described in the previous section, taxes minus subsidies as well as margins are added to the LH2 supply costs.[3] As we integrated taxes minus subsidies and margins as relative mark-ups on the respective H2 price, the fuel costs along the supply chains increase by percentage values which are specified in parentheses in Table 7. For LH2 inland production (S2a), the value of intermediate inputs is 2.30 EUR/kg and for value added (labor and capital) 0.41 EUR/kg. The production tax is set at 0.03 EUR/kg. For the import routes (S1 and S2a), the share of domestic production is lower because several process steps of the supply chain are completed abroad. Hence, the import price already contains the electrolysis and accounts for the majority of the costs. In the case of imports, governments usually impose tariffs on imported commodities. After entering the economy, imports are part of the domestic supply chain and thus, their production value is also taxed. This leads to gross production values of 2.74 EUR/kg (inland LH2), 3.42 EUR/kg (international LH2) and 2.42 EUR/kg (international GH2), respectively. H2 is then transferred to the commodity account where margins are incurred (i.e., services on trade and transport). Finally, commodities are also taxed net of subsidies. It should be emphasized that taxes and subsidies are of particular interest for political interventions since they are suitable instruments to influence H2 prices [9,16,54] and may therefore receive special attention in future studies. In this representation, the only (domestic) demand sector is aviation, which uses LH2 as an intermediate input (like kerosene). The LH2 commodities, obtained via three supply chains (domestic LH2, import LH2, import GH2), are demanded by the aviation sector. These different LH2 commodities are assumed to have the same characteristics and only vary in terms of their supply price. It should be noted that such a differentiation is only used for illustration purposes here. Usually, a SAM does not differentiate between different types of one commodity but instead merges them into one commodity account (for example, see Ref. [55]). This commodity account can be supplied by various activities – like the different supply chains in our case. Demand sectors, such as aviation, are then supplied from this so-called composite commodity, which also includes imports. The commodity price is then determined by the production costs of the different activities and their accompanied share in the overall commodity supply. However, data concerning the production quantities of the respective supply chains are needed to calculate such a composite price, which is beyond the scope of this study.

For macroeconomic follow up analyses, future LH2 production/supply and/or demand (scenarios) as well as kerosene-H2 substitutions need to be defined. In a study by LBST [59], H2 potentials are added to supply pathways (total LH2 produced/delivered in 2050) for macroeconomic evaluations. In Table 7, the EUR per kg H2 values can thus be multiplied with H2 (kg) scenarios to adjust and scale up. Based on the resulting economy-wide dataset, it is possible to conduct modeling applications of the paper's three supply pathways. Value chains could be investigated individually or simultaneously and compared with the kerosene case. A study by FCH JU [115] provides a possible approximation of 8.9–41.2 TWh/a green H2 demand in 2030 in Germany, which could be tested for macroeconomic impacts. Finally, aviation's switch from kerosene to LH2 needs to be made possible by integrating a suitable H2-kersonene-substitution-factor in the modeling framework, taking into consideration the different energy density of both fuels and potential changes in aircraft efficiencies, for example 0.40 kg LH2 per kg kerosene [36]. Alternatively, a specific quantity of kerosene input can be restricted/excluded for/from the aviation sector and replaced by LH2. The article aims to facilitate follow up research in that area at this point.

Discussion on hydrogen-related job effects and future hydrogen demands

Next to linking LH2 cost and revenue streams to macroeconomic sectors which supports national analyses, a H2 economy comes along with possible employment effects. As an important argument for the use of political instruments, effects of technological innovations on the national employment situation are often of high interest and thus, considered in macroeconomic models [116,117]. For this reason, Table 8 provides an overview of potential employment effects estimated by selected studies. Given the scope of this study, a particular focus is set on employment potentials in Germany.

On a global scale, approximately 2,000,000 direct H2 jobs (operation, construction and maintenance) are expected by 2050. Additional 3,000,000 indirect jobs (along the supply chain) could emerge [118]. However, the projections of total job potentials vary significantly among studies due to different demand assumptions. For better comparability, the paper refers the job potential to the H2 demand or supply assumed in the respective study. Some studies use (TWh) as energy unit while others state the H2 projection using a unit of weight – mostly (Mt). The study converts all projections to Mt as a reference unit by using a 33 kWh energy density of 1 kg H2. According to Hydrogen Council [119], an overall job

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[3] H2 is part of the product group CPA 20.11.11 from the supply and use tables [82]. Accordingly, the basis for the taxes minus subsidies assumptions is the chemical products sector. For domestic production, 1% of the sector's gross output and for commodities 2% of the domestic supply were derived as tax minus subsidy rates from the data. In addition, we assume a net import tariff of 3% for the international supply paths. According to Hoelzen et al. [39], margins for H2 in aviation can vary between 5 and 20%. Since we already incorporate transport costs in the supply chains explicitly (e.g., pipeline transport and motor vehicles), margins consist of trade services and are set to 10% of the gross production value.

Table 7 – Sketch of the LH2 supply chains in the SAM framework.

	(2) Activity LH2 inland	(2) Activity LH2 international supply	(2) Activity GH2 international supply	(2) Activity Aviation	(1) Commodity LH2 inland	(1) Commodity LH2 international supply	(1) Commodity GH2 international supply	(1) Commodity LH2 international import	(1) Commodity GH2 international import	Total
(2) LH2 inland					2.74					2.74
(2) LH2 international supply						3.42				3.42
(2) GH2 international supply							2.42			2.42
(1) Water supply	0.01									0.01
(1) Gas distribution	0.01	0.05	0.01							0.07
(1) Motor vehicles	0.03	0.10	0.03							0.16
(1) Maintenance motor vehicles	0.01	0.02	0.01							0.04
(1) Pipeline transport	0.05		0.05							0.1
(1) Maintenance machines (general)	0.25	0.01	0.09							0.35
(1) Machines	0.43	0.02	0.18							0.63
(1) Electricity and heat	1.51	0.04	0.28							1.83
(1) LH2 international import		3.11								3.11
(1) GH2 international import			1.63							1.63
(1) LH2 inland				3.07						3.07
(1) LH2 international				3.84						3.84
(1) GH2 international				2.71						2.71
(3) Labor	0.14	0.01	0.04							0.19
[4] Capital	0.27	0.03	0.08							0.38
(7) Government[a]	0.03 (+1%)	0.03 (+1%)	0.02 (+1%)		0.06 (+2%)	0.08 (+2%)	0.05 (+2%)	0.09 (+3%)	0.05 (+3%)	0.41
Margins (trade)					0.27 (+10%)	0.34 (+10%)	0.24 (+10%)			0.85
(9) Rest of World								3.02	1.58	4.6
Total	2.74	3.42	2.42	9.62	3.07	3.84	2.71	3.11	1.63	

[a] Taxes minus subsidies on production (column activity) and products (column commodity).

creation of 54,545 jobs per Mt H2 demand is assumed through a global H2 economy, given a projected H2 demand of 675 Mt.

For Germany, a study by LBST [120] estimates the direct H2 employment effects along the value chain for 2030 and 2050. In a “H2 scenario”, H2 is generated via electrolysis close to the renewable energy production site, transported via pipelines and stored (e.g., in salt caverns). For 2050, over 1,000,000 jobs could emerge along the H2 value chain. Highest job potential is seen on the production site, i.e., in the renewable energy sector (energy plants for H2 production) and its future expansion, followed by H2 storage, production (electrolysis) and finally transport. Employment potential is around 50.000 jobs/Mt H2 in each scenario. A study by FCH 2 JU [115] investigates the impacts of renewable H2 deployment in Germany by 2030. Two H2 demand scenarios (high and low) were developed, based on different levels of national ambition. To cover the estimated H2 demand in the power, transport, buildings and industry sectors, renewable electricity capacity would have to be installed to produce green H2 via electrolysis. Derived relative values forecast job potentials for Germany up to 67,000–86,000 jobs/Mt H2. H2-related expenditures in 2020–2030 are estimated to generate employment of 6560–25,300 direct jobs (in production, operations and maintenance) and contribute to a further 16,630–57,500 indirectly related jobs. Most of these jobs are expected in the installation and operation of renewable electricity and electrolyzers, followed by H2 infrastructure such as refueling stations, and in the automotive and steelmaking industry. Further (marginal) employment effects will occur in gas grid and H2 storage, H2 transport and combined heat and power sectors. While the relative values for Germany from FCH 2 JU [115] and LBST [120] are in similar dimensions, the estimates for H2 demand and absolute employment impact are significantly different, which indicates the degree of future uncertainty. However, the difference might also depend on the consideration of cross-border trade. The analysis by FCH 2 JU [115] covers only national H2 production to satisfy domestic demand, i.e., H2 imports are not included in the analysis. Connecting total H2 employment potential to projected demand is an appropriate way to make different studies comparable, but can be misleading when applied only on a national level. For instance, countries such as Germany might have a significant H2 demand but cannot cover it by pure domestic production. These countries will import the majority of its H2 supply, implying a substantial share of the value chain abroad (see Section Allocation of H2 supply components to macroeconomic sectors), including accompanied employment. As a consequence, it seems reasonable to consider national H2 job potential relative to the domestically produced H2.

A study by Gas For Climate [121] focuses on the employment effects via green H2 development in Europe in 2050. The production of 51.82 Mt of H2 through electrolysis could create 308,000 direct (developing and operating renewables gas production, feedstock and electricity to produce green H2) and 659,000 indirect jobs (suppliers of each sector of the value chain; purchases of inputs to meet demand). Almost two-

Table 8 – Overview on future hydrogen demand and employment.

Country	Year	Scenario	TWh/a H2 demand	Mt/a H2 demand[a]	Absolute job effect, number	Relative job effect, Jobs/Mt H2[b]	Source
Global	2050	Direct jobs	n/a	n/a	2,000,000	n/a	[118]
		Indirect jobs	n/a	n/a	3,000,000	n/a	[118]
		n/a	n/a	n/a	n/a	54,545	[119]
		n/a	20,600	n/a	n/a	n/a	[124]
Germany	2030	H2-55%	334	10.12	594,000	59,281	[120]
	2050	H2-80%	537	16.27	802,000	49,876	[120]
	2050	H2-95%	644	20.12	1,006,000	52,151	[120]
Germany	2030	Low	8.9	0.27	23,190	86,465	[115]
		High	41.2	1.25	82,800	66,990	
Spain	2030	Low	4.1	0.12	10,530	347,525	[125]
		High	16.9	0.51	35,830	70,838	
UK	2030	Low	4.1	0.12	12,530	101,375	[126]
		High	21.1	0.64	45,970	72,657	
Netherlands	2030	Low	n/a	0.08	6000	72,000	[127]
		High	n/a	0.33	17,200	51,600	[127]
	2050	Low	n/a	2.12	16,400	7748	[127]
		High	n/a	4.94	92,600	18,739	[127]
EU (28)	2030	Low	42.5	1.29	104,060	81,539	[128]
		High	182.8	5.54	357,630	62,203	
Country	Year	Scenario	TWh/a H2 supply	Mt/a H2 supply[a]	Absolute job effect, number	Relative job effect, Jobs/Mt H2	Source
EU	2050	Optimized gas	1710	51.82	967,000	18,661	[121]
Germany (regional)	2040	With H2 import	22.0	0.67	8917	13,309	[59]
	2040	Without H2 import	22.0	0.67	10,109[c]	15,088	[59]

[a] Based on own calculation via 33 kWh/kg H2 division.
[b] Own calculation (excl. the estimate by Hydrogen Council [119]).
[c] Own calculation based on Kutz et al. [59].

thirds of the jobs from H2 production come from production of renewable electricity, which is required as feedstock energy for green H2 generation. A major part of these jobs will relate to the construction of renewable electricity plants and to some extent to the plants operation. In addition, job creation appears in the construction and operation of green H2 production plants and the required infrastructure. Finally, the study reveals an employment factor of around 18,661 jobs/Mt produced H2. A more recent study by LBST [59] estimates the job potential induced by H2 production for Central Germany by using the macroeconomic method of I-O modeling. The results are in a similar range compared to the Gas For Climate [121] study, providing an employment factor of 13,309 jobs/Mt H2 produced. Interestingly, the study addresses the issue of cross-border value chains and thus, computes an additional scenario without H2 imports. In this scenario, where the complete H2 is produced domestically, the employment factor is larger (15,088 jobs/Mt). Hence, the study indicates that domestic employment potential highly depends on the share of supply chain activities that is located in the respective country.

In follow-up research, relative figures of specific sectors can be compared for an in-depth job analysis in order to derive macroeconomic implications. For instance, according to the macro-level analysis above, 7 jobs per TWh (88 jobs/Mt) kerosene produced are directly employed in Germany, which is less than 2% of the directly expected 403 jobs per TWh (13,309 jobs/Mt H2) H2 produced, estimated by LBST [59]. Apart from the job potential relative to H2 demand or supply, some studies take into account a financial perspective and refer the absolute projected employment numbers to the investment in H2 technologies (e.g., Refs. [6,122]) or the expected revenue (e.g., Ref. [123]). This approach seems to be a valuable extension to the demand/supply consideration, especially from a macroeconomic perspective perspective and could be examined in future studies.

Finally, it must be noted that most studies focus on the job creation potential on the supply side only. However, several job opportunities might emerge on the demand side, for example, related to new components built in aviation sector (such as the LH2 tank on board, H2 combustion and fuel cells, the whole LH2 fuel system in aircrafts) and changes at airports (like logistical process adjustments and construction parts). Yet, this effect varies with the country under consideration. Taking Germany as an example, there are many (original equipment) manufacturers compared to other countries. Future studies should address this research gap and shed light on the demand side, taking into account the job potential triggered by H2 applications in different industries such as steelmaking, chemistry, heavy-duty transport or aviation.

Summary and conclusion

The paper aimed to derive a methodology that enables the evaluation of macroeconomic effects when introducing a more sustainable fuel, namely LH2, into the aviation sector. Germany was used an exemplary country. The article highlighted the key role of H2 as an energy carrier in the general energy transition as part of international net-zero efforts. Germany is ambitious in expanding the H2 technology. The momentum of a H2 economy affects the aviation sector since decarbonization of the current aviation industry is a challenge. For this reason, the development of H2-powered aircraft is discussed as one countermeasure. Many (techno-economic) studies analyze the role of H2 in the energy transition, but mainly neglect macroeconomic effects. In macroeconomic modeling and analysis, (a) few studies focus on H2 applications, (b) a complete qualitative and quantitative description of the integration of the green H2 supply chain into a respective economy-wide dataset is missing and (c) there is no spotlight on H2-powered aviation, despite macroeconomic implications of this emerging field. Hence, this paper addressed three research aims: (1) Explanation on the construction and investigation of a macroeconomic database for Germany, a so-called Social Accounting Matrix. (2) Translation of the components and pathways of LH2 supply chains to the German system of national accounts, with a focus on the aviation sector. (3) Implementation of H2-powered aviation into the macroeconomic data framework.

The article provided a solid overview of the construction of a SAM data framework for Germany. It covered an economy-wide database suitable for analyzing H2-powered aviation. Aviation links with various sectors of the German economy. 61 out of 63 economic sectors have a demand for aviation. In order to supply air travel services, the aviation industry needs various inputs, namely 47 out of 85 product groups. Kerosene is the main fuel of the aviation industry and an important part of the macroeconomic system. Jet fuel is either imported or produced at German refineries. An in-depth job analysis reveals 88 direct jobs per megaton (7 jobs per TWh) of annually produced kerosene in the coke and mineral oil sector in Germany.

For the macroeconomic analysis of H2-powered aviation in national accounts, the paper investigated three LH2 supply pathways. First, a completely domestically (inland) sourced supply chain. Second, GH2 import via pipelines. Third, LH2 import via large oversea vessels. Subsequently, an exemplary LH2 cost assessment was conducted in order to translate ten supply components and pathways into the German system of national accounts. For the cost allocation of novel LH2 fuel supply chains to macroeconomic sectors, a techno-economic cost break-down for each component was conducted. Eight relevant sectors for a H2 switch of aviation fuel supplies were identified. In addition, GH2 and LH2 imports became prominent. Subsequently, relative costs of the H2 supply chain components were assigned to respective macroeconomic sectors. Building on the breakdown of LH2 supply costs across the three supply chains and the relative split of LH2 cost components, the paper contributed a translation to macroeconomic sectors. The macroeconomic benefit to the national economy was largest (100% domestic H2 production; 2.71 EUR/kg) in the LH2 inland scenario (excluding tax contribution and margins). It creates direct effects (revenue streams) to eight macroeconomic sectors in Germany, which might lead to (follow-up) indirect benefits in related sectors of the economy. The macroeconomic contribution decreased to 33% (0.77 EUR/kg) in the GH2 and to only 8% (0.28 EUR/kg) in the LH2 import supply pathways. The final step of analysis was the implementation of

H2-powered aviation into the macroeconomic SAM data framework. A hands-on application was shown for further analysis, demonstrating the general procedure.

The study revealed several future research paths: First, besides the macroeconomic effects coming from the LH2 supply chain, new H2-powered aircraft and airport construction/design might have an impact on the national economy, as well. If changes are made to the aircraft and/or airport, this has direct effects on the corresponding macroeconomic sectors, but also indirect effects on supplier industries and related sectors in Germany and abroad. Second, the paper provided an overview of related job effects of H2 on the supply side, but neglected demand side effects occurring in application sectors, such as aviation. An in-depth job analysis using macroeconomic tools, such as I-O and CGE models, could reveal interesting perspectives on the labor market development induced by demand-side effects in application sectors. Third, for macroeconomic follow-up analysis, more accurate projections of future LH2 production and/or demand potentials (scenarios) are needed to scale economic effects.

It needs to be critically addressed that all cost components highly depend on the techno-economic assumptions made, influenced by the airport location (country), the aircraft operated, the availability of the supply technology and resources such as renewable energy, and cost reduction achievements by 2050. However, the paper rather aimed for a methodological procedure of integrating H2-powered aviation into an economy-wide data framework, instead of an accurate quantification. Values are thus an approximation and need critical assessment in future research. Finally, a further methodological challenge is the allocation of cost components (products) to specific macroeconomic sectors (industries), also mentioned by LBST [59]. Given the relevance of H2 for the energy transition, research as well as policy makers should therefore aim to establish H2 supply chain components in the national accounts system.

After compiling a suitable SAM database for Germany, macroeconomic (equilibrium) models can be applied. For example, particular attention can be placed on import relationships, since this study did not explicitly address possible H2 exporting countries. However, national strategies should consider whether to position themselves as H2 export or import hub - and develop national collaboration accordingly [5]. For example, Morocco is a potential exporter and accelerates international partnership with countries like Germany and Portugal [16]. Future considerations might further investigate the kerosene case including existing aircraft/airport infrastructure and compare it to the LH2 case and related changes to the ATS. Such analyses should also be presented in a methodologically transparent and reproducible manner, with science communication taking a central role [see 146].This paper provides a suitable foundation to perform such analyses by using the economy-wide SAM dataset as a basis for macroeconomic evaluations.

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. Overview and description of Social Accounting Matrix accounts

Table A1 – Overview and description of Social Accounting Matrix accounts.

Row (R), column (C)	Account	Description
R1, C2	Intermediate inputs	Value of input needed for production process
R1, C5	Household consumption	Goods and services consumption of households
R1, C7	Government consumption	Government's consumption of goods and services
R1, C8	Investment	Asset investments and stock changes
R1, C9	Exports	Sales of goods and services to markets abroad (non-residents)
R2, C1	Marketed output	Total gross output (domestic production/sales)
R9, C1	Imports	Purchases of goods and services from markets abroad
R3, C2	Compensation of employees	Total cost of employment (gross wages and salaries, work remuneration)

Table A1 – (continued)

Row (R), column (C)	Account	Description
R3, C9	Labor income from RoW	Wages and salaries of national workers employed outside the territory
R9, C3	Labor distribution to RoW	Labor payments sent to abroad
R4, C2	Gross operating surplus and property income	Net operating surplus, self-employed income plus depreciation (=gross operating surplus) & interest, dividends, reinvested earnings, capital gains and leases/rent (=property income)
R4, C9	Capital income from RoW	Remunerations from capital ownership abroad
R9, C4	Capital distribution to RoW	Property income transferred to RoW
R5, C3	Labor income	Households' work compensation
R5/6/7, C4	Capital income	Gross operating surplus and property income distributed to households, enterprises and the state
R5, C6	Enterprise transfers	Monetary social security benefits, change in pension entitlements and transfers (e.g., bonus payments)
R5, C7	Government transfers I	Social/public transfer payments to households (e.g., retirement, unemployment)
R5, C9	Household transfers from RoW	Transfers from abroad (e.g., commuter and property income)
R9, C5	Household transfers to RoW	Transfers to abroad (e.g., remittances of migrants)
R6, C5	Household transfers	Net social contribution to enterprises
R6, C7	Government transfers II	State payment to domestic corporations (e.g., investment grants)
R6, C9	Enterprise transfers from RoW	Transfers (e.g., dividends or returns on investment) received abroad
R9, C6	Enterprise transfers to RoW	Corporate monetary flows to abroad (e.g., payments of dividends, investments)
R7, C2	Net taxes on production	Taxes minus subsidies on production activity (e.g., labor, capital)
R7, C1	Net taxes on products	Taxes per unit of a good/service (e.g., value-added tax, import tariffs) minus subsidies per unit of a good/service
R7, C5	Transfers and direct household taxes	Income and property taxes plus social contributions paid by households
R7, C6	Transfers and direct corporate taxes	Corporate income and property taxes plus other transfers
R7, C9	Government transfers from RoW	Payments from abroad (e.g., taxes on income and property, social contributions, monetary social benefits)
R9, C7	Government transfers to RoW	Payments to abroad (e.g., development aid)
R8, C5	Household savings	Savings by households (gross or net = including or excluding depreciation
R8, C6	Enterprise savings	Savings from corporates
R8, C7	Government savings	Savings of the government
R8, C8	Current account transfers	Transfer between asset investments and stock changes (balancing)
R8, C9	Capital transfers and financial balance	Accumulation of capital transfers from and to RoW & financial balance [net lending to (+) or net borrowing from (−) RoW]
R1, Margin and Margin, C1	Margins	Representation of transaction costs. Paid by commodities, received by commodities providing the services (wholesale, retail, trade and transport services)

Table A2 – Aggregated Social Accounting Matrix for Germany 2017 with a focus on H2-powered aviation (1/3).

		(1) Commodity																										
		1	2A	2B	2C	2D	3A	3B	4	5	6	7	8	9A	9B	10	11	12	13	14	15	16	17	18	19	20	21	22
(1)																												
Margins		19195	307	175	12963	2007	52	12383	38517	28952	38632	6095	0	0	-9545	0	0	-39922	-464454	0	0	0	0	0	0	0	339284	15359
(2)	1	57869	0	0	0	0	0	0	0	0	150	0	0	0	465	0	599	0	0	0	0	0	0	372	85	0	1416	178
	2	0	178	1490	1400	6076	0	202	0	0	14	0	0	88	6	0	71	0	112	4	0	0	0	40	1	0	520	691
	3	0	0	1	0	0	348	43729	0	0	7	0	0	55	0	0	28	0	2587	284	0	0	0	11	15	0	3227	966
	4	0	0	0	0	2	0	0	69147	509	624	760	2003	3	0	0	22	0	1986	0	0	0	0	280	343	0	2544	9975
	5	0	0	0	0	51	0	0	1568	228217	5648	264	7882	15	0	0	384	0	7812	0	0	0	0	601	1041	0	6328	11626
	6	0	0	0	0	0	0	0	374	2949	359723	2032	82	74	0	0	258	13703	1082	50	0	0	0	1869	2291	0	2564	27131
	7	0	0	0	0	0	0	0	14	81	89	48123	1297	4	0	0	134	0	347	0	0	0	0	330	102	0	445	2964
	8	0	0	0	0	21	0	0	113	499	97	330	39121	3	0	0	2	0	1066	0	0	0	0	188	17	0	380	770
	9	0	0	0	0	0	0	0	0	170	73	0	0	106083	13417	4261	12627	0	139	460	0	0	0	0	1130	0	1873	7375
	10	0	0	0	0	0	0	0	0	19	7	0	0	412	195	5902	539	0	0	0	0	0	0	0	47	0	2243	300
	11	0	0	0	0	206	0	0	0	691	566	0	729	0	0	0	307443	0	301	0	0	131	0	354	0	0	1629	534
	12	0	0	0	0	0	0	0	0	85	595	0	0	0	0	0	27	71259	284	0	0	0	1240	0	6	0	0	130
	13	0	0	0	0	0	0	5	143	223	3401	4	172	0	0	0	183	1583	420376	0	0	0	7468	0	1975	0	3596	1597
	14	0	0	0	0	0	0	0	0	14	61	7	0	0	0	0	238	134	546	95899	0	5501	0	0	444	0	120	1053
	15	0	0	0	0	0	0	0	0	0	12	0	44	0	0	0	0	0	246	0	24887	199	0	41	0	0	0	570
	16	0	0	0	0	0	0	0	0	3	202	1	0	0	0	0	83	77	214	6193	0	128240	0	0	514	0	28	2520
	17	0	0	0	0	0	0	0	0	0	66	0	0	0	0	0	0	0	0	0	0	0	41534	0	1	0	0	26
	18	0	0	0	0	0	0	0	0	0	77	0	0	0	0	0	13	0	531	0	0	0	0	92600	5	0	242	1439
	19	0	0	0	0	0	0	0	0	0	53	0	0	0	0	0	80	0	0	0	0	0	0	0	66266	0	0	12
	20	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	3	0	106	103	0	0	0	0	0	34489	0	334
	21	0	0	0	0	762	693	1006	2936	7468	4035	1731	4250	1190	837	744	3860	12	30784	339	0	6	0	2007	4231	1	985737	40888
	22	0	0	0	0	0	0	318	6	5	2672	0	132	0	0	0	2293	60	5785	100	0	650	0	0	1840	0	180	2424036
(3)																												
(4)																												
(5)																												
(6)																												
(7)		2819	37	1	6148	100	10	46482	9255	2112	13906	2869	634	14308	252	520	34235	3606	4	-3445	1376	321	817	11477	1926	4430	96843	72043
(8)																												
(9)		34830	5272	5	53503	8609	752	30925	120869	86268	120161	26404	3638	2698	0	0	1649	8708	4702	11059	5475	16118	302	18094	12037	1657	536456	142627
Total		114713	5794	1672	74014	17834	1855	135050	242942	358265	550884	88620	59984	124933	5627	11427	364771	59220	14556	111046	31738	151166	51361	128264	94317	40577	1985655	2765144

Table A2 – Aggregated Social Accounting Matrix for Germany 2017 with a focus on H2-powered aviation (2/3).

		Margins	(2) Activity																						(3) Labor	(4) Capital
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22		
(1)	1		4359	33	0	0	0	0	0	0	8	0	0	0	0	0	1	0	0	1071	0	0	51101	2991		
	2A		1	6	464	0	0	0	0	0	3335	0	8	0	0	0	0	0	0	1	0	0	1548	13		
	2B		0	5	26	0	0	0	0	0	1421	0	0	0	0	0	0	0	0	0	0	0	94	10		
	2C		48	122	24891	137	1422	483	130	107	11741	20	140	160	1254	27	1	40	17	259	6	4	8708	2608		
	2D		108	1203	1	4	2	1	1	0	0	0	3006	0	0	1	0	0	0	0	0	0	11099	534		
	3A		0	0	123	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1551	16		
	3B		3099	382	6372	178	429	926	121	87	2449	51	4837	751	5699	4661	5686	5375	1135	398	86	97	11602	9726		
	4		4	3	40	18182	5010	2121	324	2806	1212	140	275	78	1937	62	5	86	155	105	48	6	11413	11337		
	5		1978	315	133	883	54680	15143	1497	2896	776	339	3807	558	756	113	0	98	40	262	0	0	10018	2202		
	6		459	8	6	42	9118	127966	3	180	158	29	32	4085	217	1505	0	1030	3	1	0	0	1363	385		
	7		32	0	0	0	13	23	18463	2988	0	0	0	7	0	27	473	0	0	0	0	0	173	4848		
	8		74	858	156	909	4341	5385	618	851	2410	58	213	21	228	1139	1386	147	16	39	0	0	12488	3154		
	9A		959	347	1020	547	1618	2077	171	218	23966	865	769	694	5585	2352	15	608	384	1983	102	74	15730	14040		
	9B		35	15	37	30	56	100	7	12	2153	8	46	58	286	9	0	2	3	90	3	1	2076	633		
	10		127	37	20	54	137	150	5	18	30	4	115	37	120	37	1	35	22	265	4	2	1266	1449		
	11		972	244	331	464	1065	1505	99	136	5245	413	24393	617	3343	1046	36	3289	647	1772	318	100	12328	71212		
	12		136	52	45	150	428	2630	47	51	206	26	847	2721	3382	1969	8	3504	3628	268	725	31	2316	3630		
	13		59	4	90	419	427	576	101	80	103	21	96	2	4756	3	0	6	0	16	0	0	4413	200		
	14		196	194	4132	687	1563	3683	73	191	1605	33	583	185	16366	6195	5	16720	0	18	0	5581	14990	8152		
	15		5	15	16	1039	1065	523	152	153	13	2	42	11	358	5	2234	16	733	5	10	5358	980	1258		
	16		162	52	756	1037	3224	4601	68	275	259	33	856	332	35279	15983	4524	37578	9108	281	157	14	13136	8486		
	17		11	36	134	1202	2576	1268	33	311	496	35	168	411	16615	1788	126	598	2260	1078	47	134	6011	12153		
	18		2	8	50	174	721	291	23	66	79	4	1027	44	1730	1081	745	1191	21	77	13	11437	1372	5977		
	19		2132	99	202	577	1342	1686	464	210	2410	105	8109	419	8293	1789	742	2094	307	1214	10504	520	10995	14179		
	20		7	0	6	52	167	251	33	27	97	16	40	9	60	1206	248	68	5	137	8	95	454	1587		
	21		10655	938	2520	10013	49825	67887	8827	9952	6997	488	84454	4542	12225	1380	211	1307	529	24848	168	273	384908	84802		
	22		7686	1655	4228	10952	29088	36528	4949	5668	22950	1366	40726	9885	75307	13115	1436	15707	5937	14801	7131	4530	129967	670099		
Margins																										
(2)																										
(3)			7946	3685	1472	23025	70623	66581	10466	13044	19379	1933	80268	27685	158727	27547	5269	31415	13320	31597	4617	3009	235124	856364		
(4)			25375	1782	3917	17501	32506	71590	7253	2284	39478	3782	57666	20128	86548	22168	2814	17260	3312	14296	42288	3971	136449	640718		
(5)																									1696317	742212
(6)																										534799
(7)			-5493	-1205	70	-60	-9	207	2	-4	-1368	-107	60	186	1655	-1191	33	-99	45	25	176	-189	-156	5314		52263
(8)																										
(9)																									11813	111588
Total			61134	10893	51258	88198	271437	414182	53930	42607	147608	9664	312584	73626	440726	104017	25999	138075	41627	94907	66411	35048	1093517	2438077	1708130	1440862

Table A2 – Aggregated Social Accounting Matrix for Germany 2017 with a focus on H2-powered aviation (3/3).

		(5) Households	(6) Enterprises	(7) Government	(8) S-I	(9) RoW	Total
(1)	1	38801		0	5350	10998	114713
	2A	284		0	98	36	5794
	2B	77		0	-54	93	1672
	2C	16476		267	-1514	6460	74014
	2D	130		0	129	1615	17834
	3A	54		0	-282	392	1855
	3B	58008		267	-3358	15986	135050
	4	36224		815	34295	116259	242942
	5	4125		0	67220	190426	358265
	6	79642		0	79685	244967	550884
	7	6346		640	13353	41234	88620
	8	416		0	19384	5696	59984
	9A	41392		533	5112	3772	124933
	9B	0		0	-33	0	5627
	10	7463		0	29	0	11427
	11	5649		0	227550	1997	364771
	12	27316		0	0	5104	59220
	13	0		0	0	3184	14556
	14	25029		479	0	4386	111046
	15	8393		0	0	9352	31738
	16	3940		2478	0	8547	151166
	17	2889		0	0	981	51361
	18	88199		0	0	13932	128264
	19	5876		0	0	20049	94317
	20	34606		0	0	1398	40577
	21	478323		41682	64842	633059	1985655
	22	698885		601058	173065	178425	2765144
Margins							0
(2)	1						61134
	2						10893
	3						51258
	4						88198
	5						271437
	6						414182
	7						53930
	8						42607
	9						147608
	10						9664
	11						312584
	12						73626
	13						440726
	14						104017
	15						25999
	16						138075
	17						41627
	18						94907
	19						66411
	20						35048
	21						1093517
	22						2438077
(3)						15034	1708130
(4)						187776	1440862
(5)			132605	521897		1774	3094805
(6)		133829		10104		51010	729742
(7)		874599	99515			20369	1360477
(8)		406986	428181	146317	17995	-8209	991270
(9)		10848	69441	33940	288404		1786099
Total		3094805	729742	1360477	991270	1786099	

B. Techno-economic assumptions for liquid hydrogen supply technology

Even though the LH2 supply costs for the three different supply pathways are only needed as exemplary values to demonstrate the macroeconomic methodology, the following parts outline relevant techno-economic input data.

Calculation of costs per component

In general, the annuity payment method is used, based on an interest rate of 6% [38] and an exchange rate from USD_{2020} to EUR_{2020} of 0.85. For the different inland supply components, electricity costs of 0.03 EUR_{2020}/kWh_{el} [129] are taken for the central production site and 0.043 EUR_{2020}/kWh_{el} at the airport site in 2040/2050 [38]. The electrolysis system is assumed to reach 4000 full load hours of utilization per annum. An overview of the ingoing techno-economic assumptions that are used to derive the LH2 supply costs at the dispenser and the underlying cost shares is shown in Table B1. Further information regarding the LH2 refueling systems at airports – in this study, a refueling truck setup is considered – can be found in Hoelzen et al. [38]. In that publication, the calculation methods are shown in detail.

Table B1 – Techno-economic assumptions for considered inland supply components with respective sources.

LH2 supply component	Specific CAPEX	Lifetime, in years	O&M factor (of total CAPEX)	Energy consumption/ costs	Water consumption
On-site/central H2 production (electrolysis)	255 EUR_{2020}/kW_{el} [1,16,101,130]	30 [132–134]	5% (incl. stack replacement costs) [135]	45 kWh_{el}/kg_{H2} [16,101,130,131]	10 kg_{H2O}/kg_{H2}
GH2 compressor at H2 production site	0.8 EUR_{2020}/W_{el} (compressor power) [105,136,137]	15 [106]	3% [138]	0.7 kWh_{el}/kg_{H2} feed [139]	–
Central inland GH2 storage (including compressor)	8.5 EUR_{2020}/kg_{H2} stored [132,138,140]	30 [105,141]	2% [105,142]	0.7 kWh_{el}/kg_{H2} feed [139] for compressor	–
Inland GH2 pipeline transport	2.75 Mn EUR_{2020}/km [143]	40 [143]	1.3% [143]	1.5 kWh_{el}/kg_{H2} feed [143]	–
LFP	788,000 $EUR_{2020}/t_{LH2}pd$ liquefaction capacity [38]	20 [38]	4% [38]	6.1 kWh_{el}/kg_{H2} feed [38]	–
LH2 storage	26.7 EUR_{2020}/kg_{LH2} stored [38]	20 [38]	2% [38]	0.1 kWh_{el}/kg_{H2} feed [38]	–
Inland LH2 truck transport	544,000 EUR_{2020} per truck system	12 [38]	3% [38]	7.4e-5 $EUR_{2020}/km/kg_{H2}$ [38]	–

Reflection of hydrogen losses on inland supply chain impacting the costs

H2 losses along the inland supply chain are considered. To compensate for them, additional H2 has to be either produced inland or a larger quantity has to be imported via the international LH2 or GH2 supply route. An overview of the losses that are used for the production/import cost calculations is provided in Table B2.

Table B2 – H2 losses to be considered as % of kgH2 feed at the specific component based on [38,105,144].

LH2 supply component	LH2 inland supply	LH2 international supply	GH2 international supply
On-site/central H2 production (electrolysis)	–	–	–
GH2 compressor at H2 production site	0.5%	–	–
Central inland GH2 storage	0.5%	–	–
Inland GH2 pipeline transport	0.5%	0.5%	–
LFP	1.65%	–	1.65%
LH2 storage	0.25%	0.25%	0.25%
Inland LH2 truck transport	–	–	0.25%
LH2 refueling system	1%	1%	1%
Total resulting losses (inland only)	**4.3%**	**1.74%**	**3.1%**

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