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Review

Fostering Macroeconomic Research on Hydrogen-Powered Aviation: A Systematic Literature Review on General Equilibrium Models

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Abstract: Hydrogen is a promising fuel to decarbonize aviation, but macroeconomic studies are currently missing. Computable general equilibrium (CGE) models are suitable to conduct macroeconomic analyses and are frequently employed in hydrogen and aviation research. The main objective of this paper is to investigate existing CGE studies related to (a) hydrogen and (b) aviation to derive a macroeconomic research agenda for hydrogen-powered aviation. Therefore, the well-established method of systematic literature review is conducted. First, we provide an overview of 18 hydrogen-related and 27 aviation-related CGE studies and analyze the literature with respect to appropriate categories. Second, we highlight key insights and identify research gaps for both the hydrogen- and aviation-related CGE literature. Our findings comprise, inter alia, hydrogen's current lack of cost competitiveness and the macroeconomic relevance of air transportation. Research gaps include, among others, a stronger focus on sustainable hydrogen and a more holistic perspective on the air transportation system. Third, we derive implications for macroeconomic research on hydrogen-powered aviation, including (I) the consideration of existing modeling approaches, (II) the utilization of interdisciplinary data and scenarios, (III) geographical suitability, (IV) the application of diverse policy tools and (V) a holistic perspective. Our work contributes a meaningful foundation for macroeconomic studies on hydrogen-powered aviation. Moreover, we recommend policymakers to address the macroeconomic perspectives of hydrogen use in air transportation.

Keywords: hydrogen; air transportation; sustainable aviation; macroeconomics; computable general equilibrium model; systematic literature review

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1. Introduction

Global warming leads to rising sea levels, droughts and extreme weather phenomena [1]. Caused by greenhouse gas (GHG) emissions such as carbon dioxide, climate change is a result of industrialization [2]. Since 1990, global GHG emissions have increased significantly [3], which is expected to continue if no drastic interventions are undertaken [4]. The aviation industry accounts for 12% of transportation emissions and over 2% of the world's total emissions [5]. Today, only one tenth of the global population uses air transportation, but the number of passengers is predicted to rise [6]. As a consequence, GHG emissions caused by worldwide aviation could triple by the midcentury [7]. In order to address this issue, the aviation industry aims to achieve net-zero carbon emissions by 2050 [8]. To decarbonize the sector, the potential of sustainable technologies, such as battery electric aircraft [9], biofuels [10] and hydrogen [11], is currently being discussed [12]. Battery electric aircraft do not cause onboard emissions [13], but the extraction of raw materials (e.g., lithium) causes severe environmental and social issues [14]. Furthermore, battery electric concepts are limited to short-haul flights due to low energy densities [15]. Contrarily, biofuels can keep up with conventional jet fuel in terms of energy density [16] and have shown proof of concept [17]. Some European countries see biofuels as a means for decarbonizing aviation [18] and have introduced blending quotas [19]. However, biofuel utilization in transportation demands large agricultural areas, and biofuels could therefore compete with crop production for land and eventually cause shortages in food supplies [20,21]. In addition, the cultivation process necessitates large quantities of water and fertilizers [22,23] what makes the sustainability of biofuels questionable.

Next to batteries and biofuels, hydrogen is a promising alternative to decarbonize the air transportation system (ATS). Hydrogen's gravimetric energy density is comparable to existing jet fuels [24]. Therefore, hydrogen-powered aircraft can potentially cover typical distances in aviation [25]. Hydrogen is a secondary energy carrier [26] and can be produced from several primary energy sources [27]. For instance, it can be generated by electrolysis, which causes no direct emissions when renewable electricity is used [28,29]. This so-called green hydrogen is considered sustainable [30] and seen as an integral part of the energy transition [31,32]. Recently, green hydrogen has been discussed as a carbon-free alternative in sectors that are challenging to electrify, such as shipping [33,34], heavy-duty transport [35,36], steelmaking [37,38], chemistry [39,40] and heating [41,42]. In addition, hydrogen has a long tradition in air transportation. It has been used as a fuel for balloons in the 18th century and as an energy source for rocket propulsion [43]. Moreover, several projects have experimented with hydrogen-powered aircraft in the last century [43]. Due to the threats of climate change and aviation's net-zero ambitions, hydrogen is regaining momentum as a potential fuel for industrial aviation players such as Airbus [44] and Lufthansa [45]. This momentum is reflected by a fruitful academic literature dealing with several aspects of hydrogen-powered aviation. One research strand evaluates the different application potentials of hydrogen in aircraft. For instance, hydrogen can be combined with fuel cells to power electric propulsion systems [46,47]. Moreover, it is used to produce sustainable aviation fuels (SAF), i.e., power-to-liquid fuels [12,48]. In addition, liquid hydrogen can be applied in aircraft engines for direct combustion [12,49,50]. Besides its application potential, scholars have addressed several bottlenecks that need to be overcome to realize hydrogen-powered aviation: (1) Technological challenges include modifications in aircraft design [51], the development of new propulsion systems [52] and the integration of suitable hydrogen tanks [53–55]. (2) Aside from the aircraft, scholars have shed light on the on-ground infrastructure [56] and safety concerns related to hydrogen handling [57]. (3) The current lack of cost competitiveness compared to conventional jet fuel has been revealed in technoeconomic investigations [25,58]. For example, Hoelzen et al. [59] analyzed the overall supply costs of liquid hydrogen, underlining the current cost disadvantage compared to kerosene. Next to technological and technoeconomic studies, the environmental benefits of hydrogen-powered aviation have been discussed with regard to carbon abatement [60] and the overall climate impact [61]. Moreover, the approach of life cycle assessment is being applied to green hydrogen use in aviation and demonstrates its ecological advantages over other technologies [62,63]. Finally, recent reviews by Baroutaji et al. [43] and Gunasekar et al. [50] have demonstrated the increasing academic interest for hydrogen use in air transportation.

Despite the growing body of hydrogen-powered aviation literature, a discipline neglected so far is macroeconomic research [59,64]. Yet, hydrogen use in aviation is related to several macroeconomic aspects, given that green hydrogen's supply chain significantly differs from kerosene [25]. First, the modified supply chain leads to a change of sectors involved in supplying aviation fuel [59]. The production of kerosene is characterized by a high share of crude oil input [64], which is substituted by electricity when green hydrogen is introduced [65]. Additionally, new industries such as the liquefaction or storage of hydrogen become relevant in the supply chain [59]. Studies have proven that inter-industrial relations are affected by the introduction of new energy sources [66,67]. Moreover, Wietschel and Seydel [68] have shown such sectoral shifts for the introduction of hydrogen in the energy system. Second, an adjusted supply chain for aircraft fuels influences the labor market [64]. A green hydrogen supply chain offers several new jobs that are not yet existent [69]. Research indicates that the generation of renewable electricity, which is a prerequisite for green hydrogen, has superior employment effects compared to fossil energies [70,71]. In addition, hydrogen processing and application opportunities have potential for employment creation [68,72]. Third, trade activities and cross-border relations are concerned. Global energy trade is a necessity for prosperity [73]. Regions such as the European Union cannot fulfill their energy demand by only their own production [74], implicating an import dependency [75]. This accounts for fossil fuels (e.g., oil or gas), but also for renewable energy sources (e.g., photovoltaics or hydropower). Some countries have suitable conditions for renewable energy generation while others lack this potential [76]. Global energy trade will therefore also play a crucial role in the context of green hydrogen, but the global hydrogen economy does not necessarily correspond to existing energy trade relations and might create new trade flows and dependencies [77]. As shown by Lebrouhi et al. [78], hydrogen partnerships are already built up worldwide with macroeconomic consequences. Recent agreements between Germany and Canada or France and Saudi Arabia are prominent examples [79]. While new trade relations are established, existing trade paths based on fossil fuels will potentially phase out [80]. Fourth, shifting the supply chain from kerosene to green hydrogen directly affects jet fuel costs [64]. Today, neither liquid hydrogen [59] nor hydrogen-based SAF [63] is an economically viable option compared to kerosene. Policy interventions could eliminate cost drawbacks and help in implementing hydrogen in the aviation sector [81]. Recent studies have proposed carbon taxes [58] and subsidies on sustainable alternatives [82] as potential instruments to making green alternatives cost-competitive. Similar policy interventions have proven effectiveness in the energy sector [83,84] and the passenger car industry [85]. Macroeconomic models are suitable for analyzing the effectiveness of such policy interventions [86,87]. Moreover, the use of macroeconomic models reveals effects along the supply chain (e.g., sectoral output, employment, trade) [64].

Macroeconomic models provide a wide range of application possibilities and have the ability to unveil the economic consequences of new technologies [88], policy instruments [89] or external shocks [90]. The related literature incorporates a broad variety of macroeconomic approaches: (I) Regression models represent a statistical method used by scholars to investigate impact factors for phenomena such as inflation [91] and macroeconomic stability [92]. Regression methods are also used to examine the relationship between economic growth and innovations [93], energy consumption [94] and carbon emissions [95]. (II) Linear programming (LP) seeks to optimize objective functions given distinct budget constraints [96]. For instance, it is applied to carbon trading markets [97] and water allocation problems [98]. (III) Input–output (IO) models analyze intersectoral linkages within an economy [99]. This approach enables supply chain analysis, which makes it suitable for the macroeconomic investigation of new technologies [100]. IO models have already been used to analyze the macroeconomic effects of hydrogen applications [101,102]. However, they lack in terms of simplified economic assumptions about fixed relative prices and capacity constraints [103]. (IV) Computable general equilibrium (CGE) models go beyond these limitations, as they consider price effects as well as elasticities [104] and represent economy-wide interdependencies via a comprehensive set of equations [105]. This approach depicts linkages between different markets, industries and individual agents, such as households, firms and the government [106]. The main assumption of CGE models is an equilibrated economy, i.e., supply equals demand in each market [107]. CGE scholars often use IO tables or a social accounting matrix (SAM) as data input (see [108–110]). A SAM illustrates transactions within an entire economy for a particular period and covers aspects such as sectoral production, trade activities and household consumption patterns [111]. Given this density of information, CGE models are capable of investigating complex economy-wide dependencies, policy instruments and macroeconomic indicators, such as the gross domestic product (GDP) [112]. A static CGE model evaluates the consequences of economic shocks at a distinct point in time [113], whereas a dynamic model covers a certain period [114]. Recursive-dynamic models emerged as a hybrid method and cover a long-term timespan by computing the equilibrium sequentially for each period [115]. As a quasi-static approach with a dynamic character, recursive-dynamic CGE models are appropriate for examining future scenarios [116]. The evaluation of new technologies and their macroeconomic consequences is a broad field of CGE application. For instance, scholars have employed CGE models to the adoption of electric vehicles [117], photovoltaics [118], information technology [119] and automation in production [120]. Moreover, the approach is applied to trade policy [121] and carbon abatement measures [122]. Despite the widespread use of CGE models, a spotlight on hydrogen-powered aviation is currently missing [59,64]. In contrast, CGE modeling has been frequently applied to hydrogen and aviation separately. Our study aims to build on this existing literature to lay a suitable foundation for macroeconomic analyses on hydrogen use in aviation. We therefore unveil the existing CGE literature on hydrogen and aviation separately to derive a macroeconomic research agenda for hydrogen-powered aviation. More precisely, this paper has three concrete research goals: (1) providing an overview of the existing literature dealing with CGE models in the context of (a) hydrogen and (b) aviation; (2) highlighting key insights and identifying research gaps in both fields; and (3) deriving implications to foster macroeconomic research on hydrogen-powered aviation. Our study applies the well-established method of a systematic literature review (SLR).

The remainder of this article is structured as follows: Section 2 describes the methodological approach of an SLR and the accompanying steps undertaken. Section 3 presents the results of our SLR and differentiates between the hydrogen- and aviation-related CGE literature. Key findings and research gaps from both fields are derived. Section 4 discusses the results and focuses on implications to foster a macroeconomic research agenda for hydrogen-powered aviation. Finally, Section 5 summarizes and concludes.

2. Methodology

This article employed a literature review as it aims to build on the knowledge from previous macroeconomic analyses of hydrogen and aviation. Literature reviews unveil the status quo in a specific academic field [123], enable researchers to derive insights from previous work [124] and identify research gaps for future studies [125]. As a structured and exhaustive way of reviewing the existing literature in an academic field, an SLR qualifies as a reliable scientific method [126,127]. In a nutshell, an SLR provides a comprehensive depiction of the state of research on a specific subject [123,128]. It follows a transparent procedure which can be reproduced by other researchers to validate the results [129]. Hence, the risk of personal bias affecting the review's outcome is minimized [123]. The application of an SLR ensures a scientifically sound procedure [129] and thus, it has already been applied to CGE models [130,131], hydrogen issues [132] and the aviation sector [133].

The SLR of this paper applied the well-established Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [134]. Figure 1 shows the general procedure of the review process. It incorporates multiple process steps as suggested in other reviews [131,135,136]. First, a preparation was carried out by clarifying the scope of the review [128]. This included the definition of suitable categories for analysis. Furthermore, formal and eligibility criteria were defined with respect to the research objective. This step also contained the decision on the literature databases. Second, the literature search was performed, which covered the formulation of search strings, paper screening and the selection of articles in scope [135]. Third, a detailed reading and analysis of the selected papers was conducted, followed by a description and interpretation of the results [128,136]. The steps of this review process are further explained in the remainder of this section.

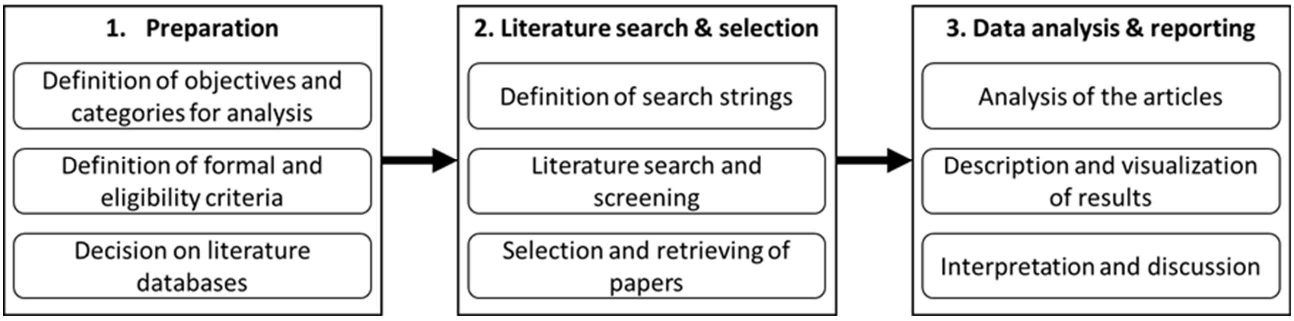

Figure 1. Overarching review process applied in this study (adapted from Verwiebe et al. [135]).

2.1. Preparation

This paper aims to foster macroeconomic research on hydrogen-powered aviation. We investigated the CGE literature on hydrogen and aviation separately by applying a two-sided review approach (see [137]). By doing so, our SLR intended to identify two types of studies: The first type employs the CGE method to hydrogen, including all types of technological or industrial applications. The second type contains CGE analyses covering the entire ATS. Oriented to this research scope, we defined various categories that fit our research objectives [129]. The main objectives included the derivation of insights about modeling features, the context of hydrogen and aviation in previous studies and a macroeconomic examination. Table 1 shows an overview of the predefined categories, including subcategories to concretize the categories and provide guidance during the analysis phase. Categories for both search strings covered general information, model characteristics, content-related focus topics and macroeconomic evaluation (see Section 2.3 for detailed information on the subcategories).

Table 1. Overview of categories and subcategories applied to analyze the articles included.

Applied to	Category	Subcategory
Hydrogen and aviation	General information	Year of publication Journal affiliation
Hydrogen and aviation	Model characteristics	Modeling framework Temporal dimension Geographical focus Data sources
Hydrogen	Hydrogen focus topics	Hydrogen type Production technology Application technology Sectoral application Hydrogen supply chain
Aviation	Aviation focus topics	Sectoral focus Type of disruption Fuel and propulsion technology Aviation supply chain
Hydrogen and aviation	Macroeconomic evaluation	Policy instruments Indicators

An application of formal selection criteria in the screening process is necessary to perform an SLR [123,129,138]. We focused on studies published in peer-reviewed journals and conference proceedings [123], which were available in English [128]. No other formal criteria (e.g., temporal restriction, affiliation to a certain discipline) were applied since we did not want to restrict the potential results. In addition, and oriented to our research objective, we only considered studies as eligible if they applied their own CGE analysis in the context of either hydrogen or aviation and generated quantitative results. The analysis used the well-established databases “Scopus” and “Web of Science Core Collection” as proposed in other SLR studies [123,139–141]. The platforms enabled the filtering of results by applying the intended selection criteria and provided a large accumulation of the scientific and interdisciplinary literature [136,142].

2.2. Literature Search and Selection

Figure 2 displays the two search strings for the CGE literature on hydrogen and aviation which covered the title, abstract and keywords. Both strings consisted of a content and a method part, which were connected by the Boolean operator “AND” to ensure results’ compliance with the eligibility criteria. Furthermore, the keywords within the content and method parts were connected by the “OR” operator. As a result, the SLR covered articles that matched at least one keyword from the content and one from the method part each. The content part of the search string considered any relevant content-related records. For hydrogen, the keyword focus was on application technologies, such as fuel cells and synthetic fuels [12]. For the content part of the aviation-related search string, we selected five keywords, namely “Aviation”, “Aircraft*”, “Airplane*”, “Air travel” and “Air transport*” to cover relevant aspects of the ATS. The use of “*” at the end of a term implied that any ending of that word was covered (e.g., “Airplane*” covered “Airplane” as well as “Airplanes”). The method part took into account the macroeconomic perspective, i.e., the application of a CGE model. This part was equivalent for both strings and contained any potentially relevant keywords for the identification of CGE studies. Besides the terms “CGE” and “General Equilibrium”, we included different versions of “Macroeconom*” to the search strings. By doing so, the SLR considered macroeconomic studies that comprised a CGE model not explicitly mentioned in the title, abstract or keywords. Three additional terms were added to cover the main data sources (i.e., SAM and IO tables) for CGE models (see [108–110]).

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TITLE-ABS-KEY ( ( ”Hydrogen” OR “H2” OR ”Fuel Cell*” OR “Synfuel*” OR “Synthetic fuel*” OR “Sustainab* fuel” )
AND ( “Macroeconom*” OR “Macro-econom*” OR “Macro Econom*” OR “CGE” OR “General Equilibrium” OR
“Social Accounting” OR “Input-output Table” OR “Input Output Table” ) )
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TITLE-ABS-KEY ( ( ”Aviation” OR “Air travel” OR ”Air transpor*” OR “Aircraft*” OR “Airplane*” )
AND ( “Macroeconom*” OR “Macro-econom*” OR “Macro Econom*” OR “CGE” OR “General Equilibrium” OR
“Social Accounting” OR “Input-output Table” OR “Input Output Table” ) )
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Figure 2. Search strings applied to the literature databases. The first string represents the search for computable general equilibrium models in the hydrogen context and the second one covers the search for computable general equilibrium studies related to aviation.

A PRISMA flow diagram illustrates the selection process of articles [131,136,143]. Figure 3 displays the process for hydrogen-related CGE studies and Figure 4 shows the one for the aviation-related CGE literature. Querying the search strings in the databases led to a total number of 419 hydrogen and 227 aviation articles. Two additional hydrogen studies and three aviation articles were added to the samples. These were found in previous literature search and complied with the SLR criteria but did not occur within the databases. The literature search was carried out on 10 June 2022.

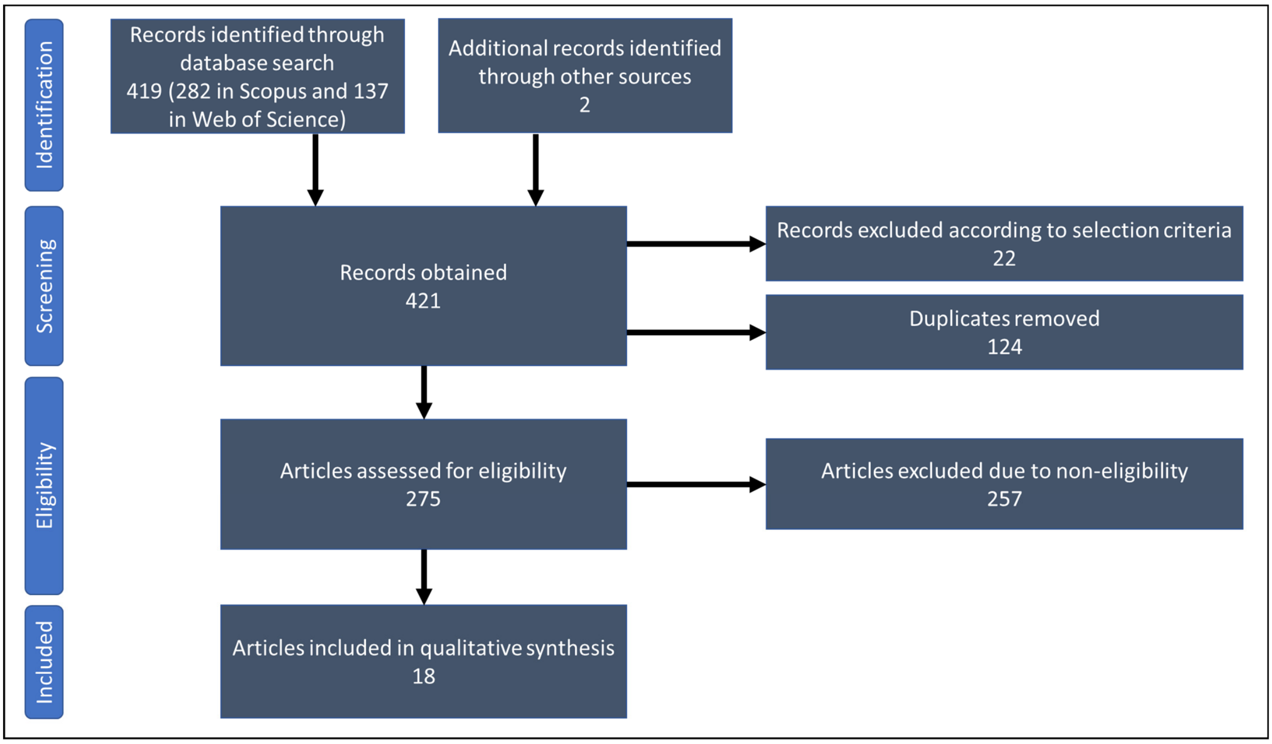

Figure 3. Search process for computable general equilibrium models dealing with hydrogen, designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (adapted from Moher et al. [134]).

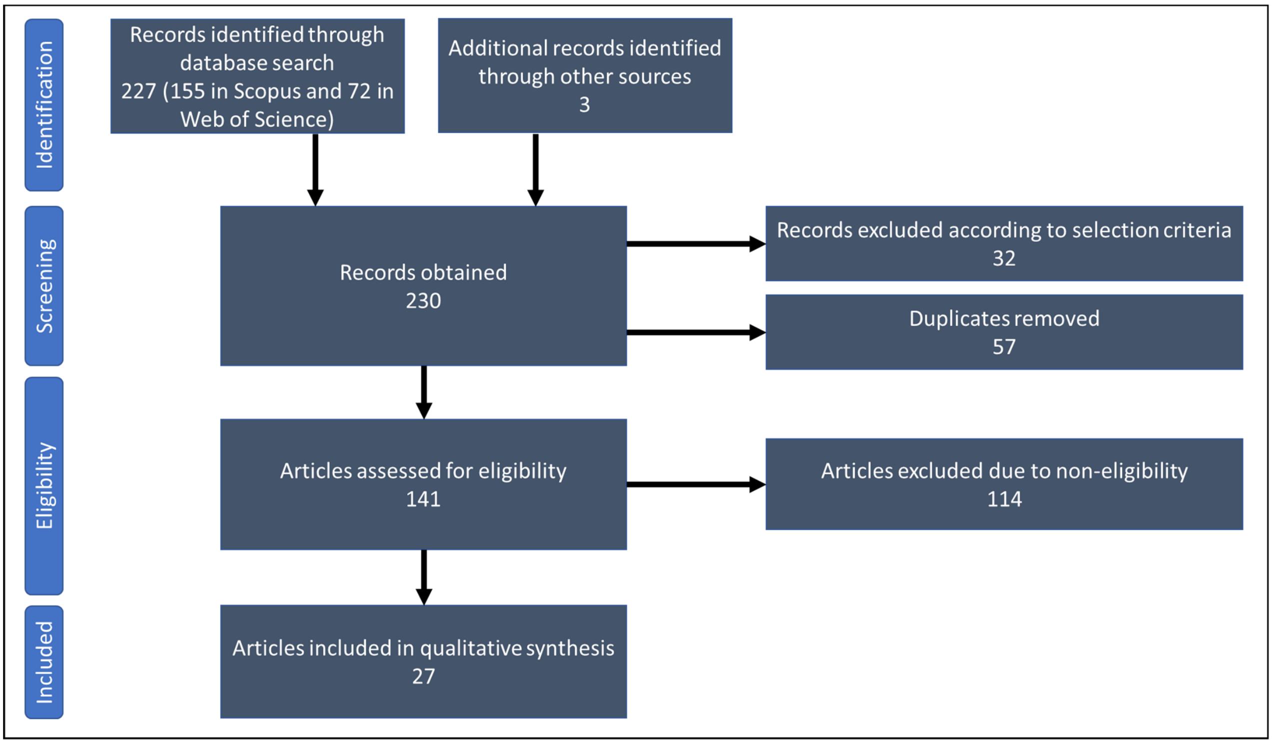

Figure 4. Search process for computable general equilibrium models dealing with aviation, designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (adapted from Moher et al. [134]).

In the hydrogen selection process, 18 relevant articles were identified out of 421 (Figure 3). Initially, formal criteria screening led to an exclusion of 22 papers and 124 duplicates were removed from the sample. The use of two large databases implied a significant intersection of articles. After performing this step, a number of 275 studies was obtained for the eligibility assessment: we first screened the titles and abstracts of the articles [128]. Papers that did not explicitly mention CGE models in the title or abstract were considered for full text screening if any kind of macroeconomic reference occurred in the abstract. At this step, papers were mostly rejected for being affiliated with other academic fields. For instance, papers from chemistry journals were covered by the strings because CGE is the abbreviation for a chemical parameter named cold gas efficiency (see [144]). Afterward, the full text versions of the remaining articles were examined for the application of CGE models in the context of hydrogen. In sum, 257 articles were excluded due to non-eligibility in the hydrogen selection process, leading to a total number of 18 hydrogen articles relevant for our analysis.

The aviation selection process revealed 27 relevant articles (Figure 4). Starting from a sample of 230 articles, 32 studies were excluded for not complying with the formal selection criteria and 57 duplicates were removed. Subsequently, we checked the remaining 141 papers for their eligibility with respect to the research objective. Our analysis focused on aviation, but also considered studies in other sectors as long as they had a particular spotlight on the ATS. The main requirement for inclusion was the CGE analysis of shocks affecting the ATS or policies with consequences to aviation. After excluding 114 records that did not meet this requirement, we ended up with a total of 27 aviation-related studies.

2.3. Data Analysis and Reporting

The final step of the SLR comprised an in-depth analysis of the selected papers [135]. All articles were studied based on the predefined categories and subcategories (see Table 1). In the remainder of this section, we briefly describe the subcategories and provide some explanations regarding their relevance with respect to our research objective.

The category *General information* contained two aspects: (1) The *Year of publication* was obtained in order to recognize the academic interest over the time. (2) The *Journal affiliation* served as an indicator for disciplines' focus on CGE models.

The group *Model characteristics* dealt with specifications of the CGE models employed in the literature and contained four subcategories: (1) We examined the *Modeling framework* itself to identify common approaches. More precisely, we investigated if the studies developed novel models or built on established ones. In addition, it was evaluated if a study solely used a CGE model or an integrated approach, i.e., a CGE model in combination with other methods or models. (2) The *Temporal dimension* revealed if models had a static, dynamic or recursive-dynamic character and examined which modeling class was dominant in the literature. When forward-looking models were applied, we further analyzed the timespan covered by the respective study. (3) The *Geographical focus* took into account the spatial coverage of a model. Moreover, we evaluated if a regional, single- or multiple-country model was used. By doing so, neglected countries could be identified. (4) The *Data sources* used for model construction were of particular interest for our study and considered the main database as well as additional data sources used.

The category *Hydrogen focus topics* consisted of five aspects: (1) We identified the *Hydrogen type* considered in the article. Our study applied a color-coding scheme to label the primary sources used for the hydrogen production (see [145]). (2) The *Production technology* considered the technological process of hydrogen generation [27,31]. (3) A further focus was set on the *Application technology* since hydrogen provides several possibilities [31]. (4) The *Sectoral application* shed light on the industries taken into account as hydrogen demanders since hydrogen is a promising fuel for several industries [33–42]. (5) Finally, papers were analyzed with respect to the *Hydrogen supply chain* components since the supply chain is a key driver for the successful realization of hydrogen applications [59]. The hydrogen type as well as the production technology were not always explicitly mentioned in the analyzed literature. However, we derived the element to the best of our knowledge when related indications were found in the respective study.

The category *Aviation focus topics* included four topics: (1) The *Sectoral focus* of CGE models evaluated if aviation occurred as a standalone industry or as part of aggregated sectors. (2) The *Type of disruption* considered changes or shocks to the aviation sector. (3) The *Fuel type and propulsion technology* provided insights about previously examined technologies. Particular attention was paid to sustainable technologies [12]. (4) The final subcategory took into account the *Aviation supply chain*. It particularly focused on the components of the ATS addressed in existing CGE studies.

Finally, the category *Macroeconomic evaluation* accounted for both samples and contained two aspects: (1) We analyzed *Policy instruments* tested in the respective studies as they are an important part of CGE analyses and relevant for practical implications [112,146]. (2) Another focus within the macroeconomic evaluation was set on *Indicators* that were analyzed in the included studies. We did not cover every single indicator due to the high number of different variables but focused on the most occurring ones and aggregated similar indicators. For instance, imports and exports were aggregated to trade effects. For a comparison, we aimed to keep consistency in the indicator definition for the hydrogen and aviation studies.

3. Results and Discussion of Hydrogen and Aviation in Computable General Equilibrium Models

This section differentiates between the hydrogen and the aviation sample. Each subsection has an identical structure, oriented to the categories presented before. Concretely, the results of the SLR are described along the presented categories, contributing the first research goal of this study. Subsequently, the second research goal is addressed by discussing the main takeaways from the analysis and deriving accompanied research gaps.

3.1. Hydrogen

3.1.1. General Information

The SLR revealed 18 hydrogen-related CGE papers. The earliest publication was from 2008 and the most recent papers were from 2021 (see Figure 5). Most studies were carried out between 2008 and 2012, after which research declined. In recent years, hydrogen has been gaining momentum, which is also reflected in the CGE literature. In 2021, there were three hydrogen-related publications [147–149]. Most journals combine economics and energy and thus have an interdisciplinary character. Overall, eight papers were published in “The International Journal of Hydrogen Energy” (e.g., [150,151]). Two journals stemmed from transportation research [152,153], which proves the application potential of hydrogen in this field. Table A1 provides an overview of the journal publications with a focus on hydrogen-related CGE studies.

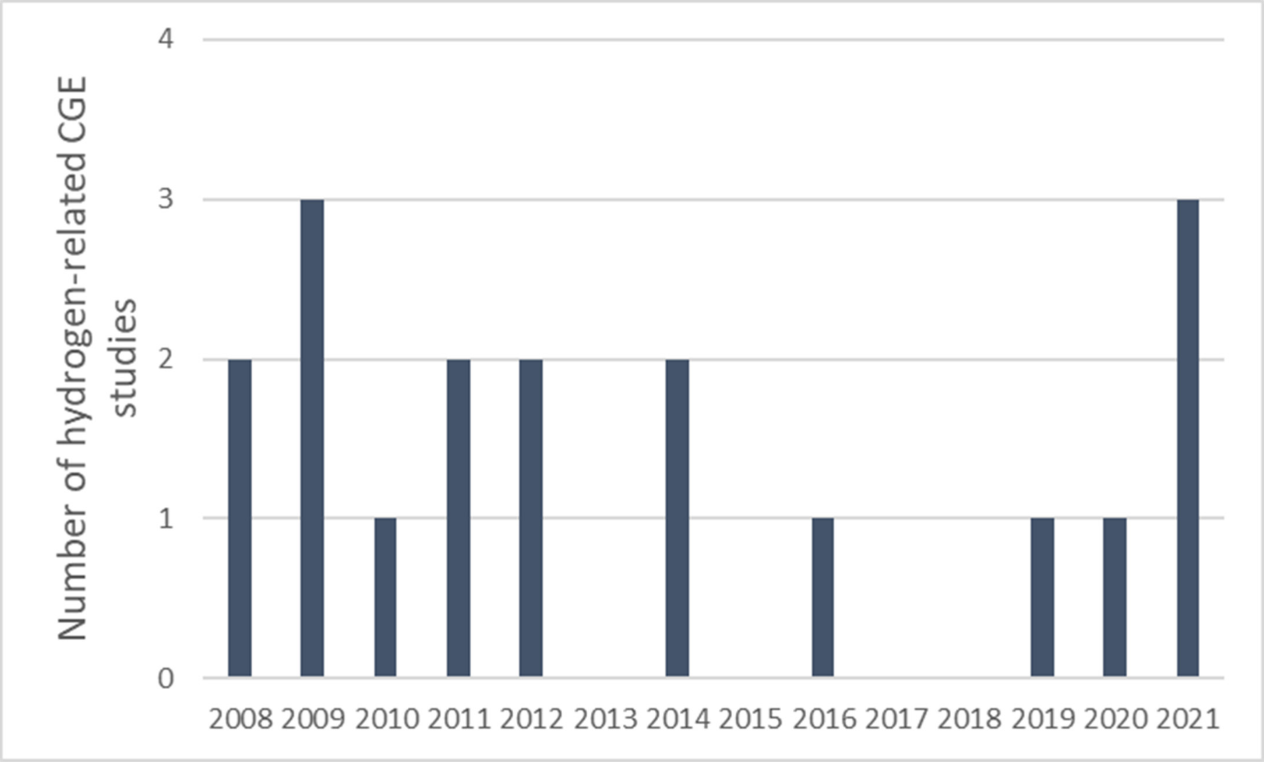

Figure 5. Number of computable general equilibrium models dealing with hydrogen, published per year.

3.1.2. Model Characteristics

Modeling Framework

In the CGE literature, it is generally common to build on already established models instead of developing completely new approaches [130]. The majority of hydrogen-related articles follow this procedure and use predeveloped models (e.g., [147,150,154]). For instance, the well-known Global Trade Analysis Project (GTAP) model was applied in three of the studies in our sample [151,155,156]. The GTAP model benefits from its focus on trade patterns and provides several options for modifications and extensions. The WEG-DYN model was employed in the work of Mayer et al. [157] and allows for investigating the macroeconomic effects of sectoral production changes. In addition, we found predeveloped models with a regional focus, such as the REMES model for Norway [148] or the TAIGEM-CE model for Taiwan [158]. These models are suitable for country-specific analyses. An environmental perspective (carbon leakage) is taken into account by the d-PLACE model [149] which makes it favorable for evaluating emission levels. The PACE-T model used in the work by Jokisch and Mennel [152] focuses on the passenger transport sector and provides a suitable choice for changes in this sector. Existing models are also modified in order to depict hydrogen-specific aspects. For instance, Lee and Lee [159] built on the energy-focused MONASH model and extended it by adding biohydrogen and hydrogen fuel cells. In contrast, Bae and Cho [160] sought their own CGE approach and provided a detailed mathematical description of the model features. A further characteristic is the combination of CGE models with other methods, which was found to occur in eight hydrogen-related CGE papers (e.g., [147,149,150,161]). For instance, recent work by Espegren et al. [148] applied a modeling framework that combined the CGE method with an energy system model for a holistic perspective on the energy transition. Jokisch and Mennel [152] integrated the energy system model MARKAL for data on hydrogen production technologies into their CGE study. This approach has also been applied in energy-related CGE studies (see [162,163]).

Temporal Dimension

Although hydrogen technology is available today, a large-scale utilization is unlikely before 2030 [32] or even 2050 [164] due to the lack of infrastructure [165] and hydrogen's price disadvantages [166]. These estimations are reflected in the analyzed papers. Four early studies applied a time horizon of 2030 [150,154,159,167] and only one study considered significant hydrogen use before 2030 [156]. Overall, a total of seven articles applied a time horizon of 2050 (e.g., [147–149,151]). We found similar time horizons of 2040 (e.g., [158,160,168]) and 2060 [155], whereas Sandoval et al. [153] ran long-term simulations up to 2100. Given this long-term time horizon in the hydrogen-related CGE literature, it is not surprising that dynamic models are the most common approach in our sample with a total of eleven studies (e.g., [148,151,152]). In addition, five studies applied recursive-dynamic CGE models (e.g., [153,161]). In particular, recent papers built on recursive-dynamic models [147,149,157], proving a growing trend toward this modeling type. Despite the dominance of dynamic and recursive-dynamic models, two studies proved that static models are also used for the simulation of future hydrogen scenarios [150,167].

Geographical Focus

CGE models are capable of examining different types of economies, from the global [169] to the regional scale [170]. In the hydrogen-related literature, a study by Sandoval et al. [153] applied a global CGE model, while two multi-country models dealt with hydrogen in the European Union [149,157]. Further multi-country models were found for Asia [151] and Europe [152]. However, the majority of ten papers employed a single-country model (e.g., [154,159,168]). Considering the geographical distribution of single-country models, a focus on hydrogen use in Asian countries has become obvious. For instance, we found articles applied to Japan [155], Korea [160], China [147] and Taiwan [158]. Two studies dealt with hydrogen in Europe on a country level. Espegren et al. [148] evaluated a hydrogen economy in Norway and Silva et al. [161] analyzed the introduction of hydrogen-powered cars in Portugal. Our analysis found no explicit hydrogen-related CGE study on a country level from the Global South. Interestingly, industrialized countries with a clear hydrogen agenda, such as Germany or Australia [171], were also missing. Finally, Wang [150] examined the economic impacts of hydrogen cars at the federal state level in the US.

Data Sources

Most hydrogen-related CGE studies make use of existing databases that contain comprehensive and detailed macroeconomic data about several countries. The most prominent example is the GTAP database, which was applied by eight papers (e.g., [147,149,151]), demonstrating its relevance to hydrogen-related CGE studies. National statistics about inter-industrial production patterns were another prominent data source (e.g., [154,160,168]). Around seven papers indicated the use of IO tables for a respective country as the primary data input including, for instance, Lee and Hung [158] for Taiwan and Bae and Cho [160] for Korea. Additionally, three studies used supply and use tables [148,150,167], which are similar to IO tables in terms of structure and data content. Apart from macroeconomic data, CGE modelers integrate additional information to illustrate viable scenarios. For instance, Bae and Cho [160] employed future energy demand estimations and Lee [156] considered different technological improvement rates in the production of biohydrogen. Similarly, the work of Jokisch and Mennel [152] assumed advancements in hydrogen technologies leading to decreased production costs. In addition to future scenarios, CGE studies integrate information about GHG emissions [149] as well as technoeconomic data on hydrogen (e.g., [155,157]).

3.1.3. Hydrogen Focus Topics

Hydrogen Type

Our analysis derived six different hydrogen types, namely orange, green, blue, purple, grey and brown. Seven studies focused on one specific hydrogen type (e.g., [153,158]) and seven articles took into account multiple alternatives (e.g., [155,160]). Only Ren et al. [147] applied a holistic approach and incorporated all six hydrogen types in their CGE model. Moreover, some papers could not be clearly assigned to specific hydrogen types [152,154,157,161]. The most prominent type (included in eight studies) was orange hydrogen (e.g., [147,156,158]), also known as biohydrogen from resources such as biomass. For instance, Lee [151] evaluated biohydrogen as an integral part of bio-based economies. Six articles had green hydrogen in scope (e.g., [147,148,168]). However, green hydrogen studies also considered other hydrogen types due to fossil fuel contribution in the electricity mix (e.g., [149,160]). In addition, four hydrogen-related CGE papers focused on blue hydrogen, which stems from fossil fuels with carbon capture and storage (e.g., [148,153]). Interestingly, recent papers considered blue hydrogen in combination with green hydrogen [147–149], underlining its role as an interim technology toward the scale up of electrolysis capacities. Purple hydrogen, generated from nuclear power, was included in five studies (e.g., [147,160,168]). Yet, it was not highlighted in the hydrogen-related CGE literature but included due to nuclear power's contribution to the electricity mix (e.g., [149]), which accounts for many countries worldwide (see [172]). Fossil-based hydrogen types are grey hydrogen, produced from natural gas, and brown hydrogen, generated from coal [145]. Grey hydrogen had a significant footprint in the CGE literature since it was included in six papers (e.g., [150,155,160]). Contrarily, brown hydrogen showed the lowest relevance among all hydrogen types with only two occurrences [147,160].

Production Technology

We derived five production technologies from the CGE literature, namely electrolysis, steam reforming, carbon capture and storage, biological production and coal gasification. The most relevant one in the CGE literature was electrolysis with eleven papers taking into account this technology (e.g., [148,161,168]). While most studies examined electrolysis in combination with other processes (e.g., [147,155,167]), two articles solely focused on this technology [149,157]. Steam reforming occurred with the second highest share, considered in nine articles (e.g., [155,167]). This technology emits significant amounts of carbon dioxide, but if combined with carbon capture and storage, the direct emissions decrease remarkably. CGE studies from Ren et al. [147], Espegren et al. [148] and Sandoval et al. [153] considered carbon capture and storage as carbon-mitigating technology for hydrogen production. Another relevant technology, examined in eight papers of the sample, was biological production (e.g., [156,158,159]). The remaining production process—coal gasification—had a lower significance within our sample and was only included in three papers. It was only considered in combination with steam reforming [147,153] or electrolysis [147,160]. Finally, the study by Ren et al. [147] took into account all of the five production technologies.

Application Technology

We detected four distinct technologies that applied hydrogen in the CGE literature: fuel cells, refueling stations, combustion and direct reduction. Fuel cell applications dominated the sample with eleven occurrences (e.g., [150,153,161]). Despite their large prevalence, the most recent CGE study including fuel cells was from 2014 [155]. Fuel cell technology also occurred in combination with other applications such as refueling stations [155,167]. In contrast, Tatarewicz et al. [149] focused on hydrogen combustion engines. Recent studies by Ren et al. [147] and Mayer et al. [157] examined the application technology of hydrogen-based direct reduction for steelmaking. Finally, four studies did not deal with a specific application technology for hydrogen but considered it as a general energy carrier within their macroeconomic model [148,151,156,159].

Sectoral Application

We identified four major fields of sectoral application: transportation, power generation/electricity, industrial processing and heating. The transportation sector was the most prominent field within the hydrogen-related CGE literature with a total of ten studies (e.g., [149,155]). More precisely, most studies evaluated the application of fuel cells for passenger cars (e.g., [153,161]), but the CGE focus on this sectoral application disappeared since 2014. More recent studies analyzed hydrogen rather as an option for heavy-duty transport (e.g., [148]). This is in line with IEA [32], suggesting hydrogen as more appropriate for heavy-duty transport, whereas passenger cars are rather seen as a field for battery electric propulsion [173]. Six papers examined power generation/electricity (e.g., [149,155,158]) and seven studies investigated industrial processes (e.g., [149,156,157]). While the consideration of hydrogen for power generation seemed more relevant in the early CGE studies (e.g., [160]), the use for industrial processes gained momentum (e.g., [148,149]). The five most recent CGE articles have in common that they took into account hydrogen application in industrial processes, such as in chemical manufacturing [156] and steelmaking [147,157]. The study from Tatarewicz et al. [149] was the only one that covered all four sectoral applications, including heating. Finally, three studies did not specify sectoral use but considered hydrogen as a general energy input for the entire economy [151,159,174].

Hydrogen Supply Chain

The supply chain is a critical driver to enabling the sectoral use of hydrogen [25]. Two supply chain components dominated the sample: On the one hand, generation was addressed in every paper (e.g., [156,158,174]). On the other hand, 15 of the 18 articles covered the final application (e.g., [148,149,157]). An examination of further hydrogen supply chain components was scarce in the existing CGE literature. Yet, refueling was taken into account by the work of Lee [155], Silva et al. [161] and Wang [150], who dealt with hydrogen use for passenger cars. Moreover, Jokisch and Mennel [152] and Sandoval et al. [153] illuminated the transport of hydrogen within their models. Hydrogen storage was only covered by one study [152].

3.1.4. Macroeconomic Evaluation

Policy Instruments

The simulation of different policy instruments played an important role in most hydrogen-related CGE studies. Our analysis revealed CGE models examining policies of carbon restrictions (e.g., [147,149,155]), the phaseout of fossil fuel sectors [148], the shutdown of nuclear power plants [155] and investments in hydrogen-related industries [158]. Given the lack of price competitiveness in comparison to fossil fuels [58], the investigation of policy price instruments seems reasonable. For instance, Espegren et al. [148] introduced additional taxes on coal and gas, whereas Mayer et al. [157] tested the impacts of carbon pricing. Furthermore, subsidies on hydrogen and renewable energy are an alternative instrument to compensate for cost deficits (e.g., [148,152]). For example, Bae and Cho [160] implemented different subsidy rates on the producer price of hydrogen.

Indicators

Within the hydrogen-related sample, we identified ten relevant indicators, namely GDP, welfare/consumption, carbon emissions, intersectoral effects, sectoral production quantities, price changes, employment effects, trade effects, hydrogen quantities and production/demand of energy/electricity. The most frequent indicator was hydrogen quantity, calculated in 14 studies (e.g., [147,149,154]). GDP was the second most relevant variable and computed in 13 papers (e.g., [148,151,157]). This is not surprising, given its high relevance for policy making and popularity among CGE modelers (see [175,176]). The welfare/consumption indicator appeared in eight articles (e.g., [155,157,161]), sectoral production quantities in nine (e.g., [147,157,158]) and price changes in ten (e.g., [155,160,167]). Intersectoral effects, which are an important aspect of adjusted supply chains, were found in only four papers (e.g., [147,150]). Moreover, five studies considered the employment effects of hydrogen introduction (e.g., [157,158]) and five papers investigated trade effects (e.g., [154,157]). For instance, Espegren et al. [148] concluded that Norwegian hydrogen export to European countries is a massive driver for its hydrogen economy and Lee [155] emphasized the positive impact of hydrogen exports for the Japanese economy. Another indicator with a high relevance among CGE modelers was carbon emissions, occurring in eight models (e.g., [149,153,155]). For example, Ren et al. [147] emphasized the emission reduction potential of hydrogen in the steel industry and Silva et al. [161] investigated the emission impact of hydrogen use in road transport.

3.1.5. Key Takeaways and Research Gaps

The following subsection represents the synthesis of the hydrogen-related studies. Main themes from the analysis of the studies are derived and discussed with respect to their relevance in the academic literature [129]. Moreover, identified research gaps are highlighted in this subsection.

Hydrogen Cost Competitiveness

The existing CGE literature emphasizes the lack of hydrogen's price competitiveness compared to conventional fuels [153]. The current cost deficit of hydrogen is a major issue in macroeconomic studies and thus, most studies applied long-term simulations including expected cost reductions (e.g., [148,152]). Still, according to the results of Mayer et al. [157], hydrogen will be even more expensive in the long term without massive decreases in electricity costs. These expectations are consistent with current cost projections from technoeconomic studies [58]. As a result, CGE scholars have proposed technology improvements as a necessity to achieve cost reductions in the hydrogen production and supply process [156]. Moreover, CGE studies have considered scaling up the infrastructure as a driver for a hydrogen economy [148]. This is in line with recent work from Hoelzen et al. [59] estimating liquid hydrogen for aircraft to be cost-competitive with kerosene in an optimistic case (including scaling effects and access to low-cost renewable electricity). CGE researchers should therefore consider such scenarios and compare the outcomes of different cost projections for hydrogen production and application technologies. In addition, policy instruments are required to compensate for the price deficit of hydrogen [58]. Existing CGE models test measures such as carbon cap targets (e.g., [147,149]) and fossil phaseout (e.g., [148]). Yet, we found that financial incentives such as taxes and subsidies were underrepresented in the current CGE literature (e.g., [157,160]), which makes their investigation a promising field for future studies. Scholars should therefore address this gap and put emphasis on taxes and subsidies to promote hydrogen supply chains. A comparison of different incentives would be particularly helpful to assess the effectiveness of policymaking since recent work has indicated that subsidies on hydrogen production and electricity are more effective than higher carbon tax rates [177].

Macroeconomic Contribution of Hydrogen

CGE models show ambiguous results regarding the effects of hydrogen use on macroeconomic indicators. Some scholars proposed negative effects on GDP or employment (e.g., [148,150]), whereas others reported positive outcomes (e.g., [154,161]). Contradictory results imply that the effects highly depend on the context of the study. For instance, Lee and Hung [158] showed positive effects on GDP and employment from hydrogen use for power generation, whereas Wang [150] proposed negative macroeconomic impacts from hydrogen introduction in the passenger car sector. However, the sectoral application is not the only context-specific parameter, as Silva et al. [161] and Wang [150] demonstrated. Both studies investigated hydrogen for passenger cars but obtained contrasting macroeconomic results. Furthermore, the existing CGE literature shows a fragmentation in terms of sectoral hydrogen applications and few works have taken into account hydrogen as an economy-wide energy carrier (e.g., [149]). Based on the current CGE literature, a reliable assessment of the overall macroeconomic effects induced by hydrogen is not possible, although many studies have indicated a positive influence on GDP (e.g., [154,158,160,161]). More research is therefore needed on hydrogen's macroeconomic contribution and the overall consequences of a hydrogen economy.

Hydrogen Applications

The CGE Literature has focused on a few sectoral use cases for hydrogen, whereas some promising application fields are currently missing. For instance, the recent literature proposes hydrogen use in shipping [34] and aviation [58], which were both neglected by the CGE studies, so far. Contrarily, the use of fuel cell vehicles is prevalent in the CGE research (e.g., [150,153,161]), although hydrogen is generally expected to be more relevant in fields where electrification is challenging [148,178]. Recent CGE papers from Ren et al. [147] and Mayer et al. [157] shed light on the steelmaking industry, which has also been addressed by other disciplines as a promising use case for hydrogen (see [38,179]). Modelers need to foster such sectoral deep dives and address promising applications based on the state of technological research. For instance, future studies should deal with hydrogen utilization in marine transportation or energy-intensive manufacturing industries, such as chemistry. Therefore, a close collaboration between CGE modeling and technological disciplines would be helpful.

Sustainable Hydrogen

The hydrogen production pathways in the existing CGE literature predominantly build on fossil technologies, while sustainable hydrogen is underrepresented. Many studies have taken into account carbon-intensive production methods, such as reforming natural gas (e.g., [153,155,160]) or brown coal gasification (e.g., [147,160]). Given the need for economy-wide decarbonization, hydrogen from fossil energy cannot contribute to a sustainable transition [157]. Among the low-carbon hydrogen types, biohydrogen dominated the existing CGE literature (e.g., [147,156,158]), but its use can lead to a lack of critical agricultural resources [180]. Therefore, green hydrogen, which was also addressed in the existing CGE papers (e.g., [148,160]), provides the most sustainable option. However, exclusive green hydrogen studies are currently missing due to the fossil fuel footprint in electricity generation (e.g., [147]). Consequently, the literature agrees on the need to decarbonize the electricity system as a prerequisite for green hydrogen (e.g., [147,160]). According to Lee [168], wind and biological energy are suitable for hydrogen production, but further renewable sources, such as photovoltaics or hydro power, should also receive attention in future macroeconomic studies. A CGE-based comparison of renewable electricity sources for green hydrogen production could help policymakers to assist in energy sector planning. For instance, renewable energy investment has induced varying job creation potential, depending on the different primary energy sources [181]. Additionally, multi-country CGE models can evaluate regional differences and trade flows with respect to renewable energy and hydrogen [182].

3.2. Aviation

3.2.1. General Information

The SLR revealed a total of 27 aviation-related CGE papers. The earliest studies were from 2009 [183,184], but the relevance of CGE modeling in aviation research increased over time, with a peak of six publications in 2021 [185–190]. Figure 6 shows the trend of growing CGE publications dealing with aviation. The aviation-related studies came from a broad range of 18 different journals and varying disciplines. For instance, the sample covered articles on tourism (e.g., [191,192]), the environment (e.g., [186,193]) and energy research (e.g., [188,194]). Still, the dominant discipline among the papers was transportation research, with a total of ten studies (e.g., [195,196]). Table A2 provides an overview of the journal publications.

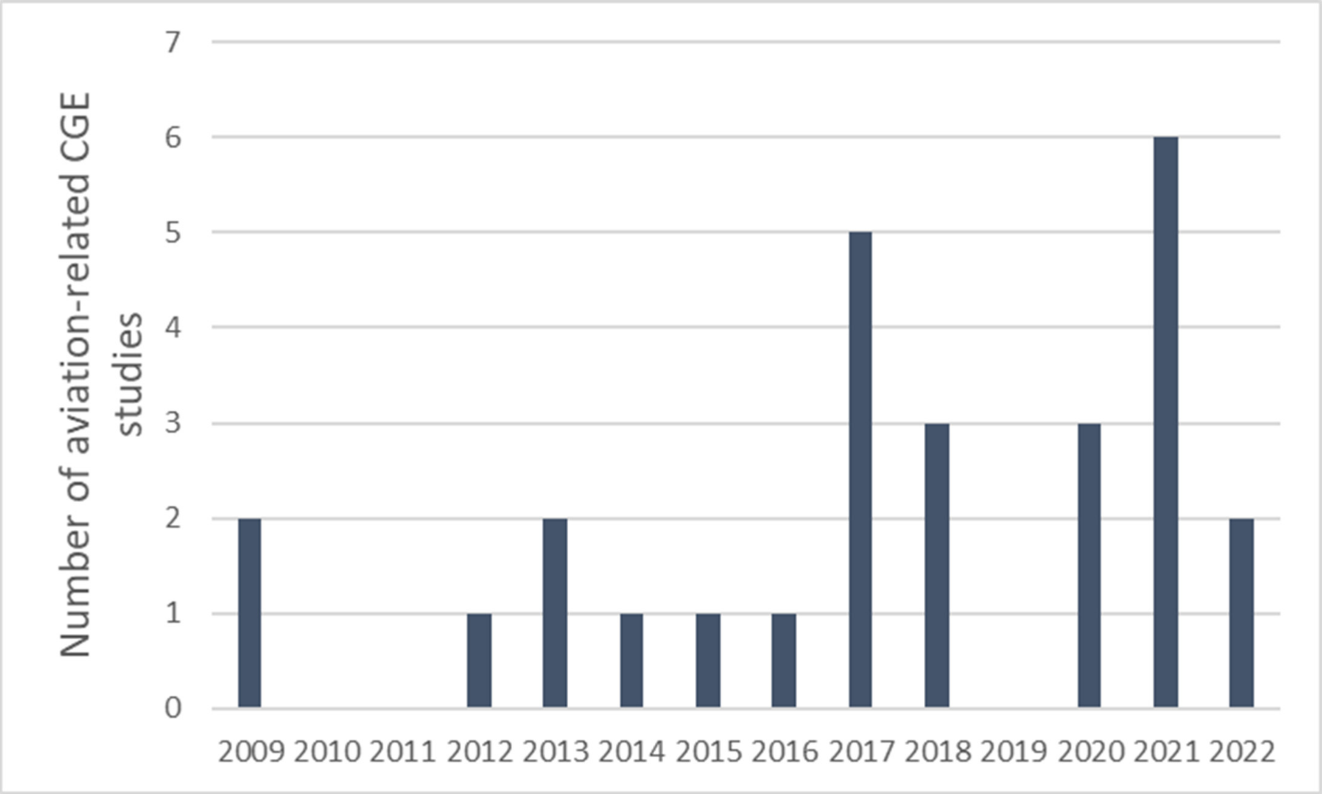

Figure 6. Number of computable general equilibrium models dealing with aviation, published per year.

3.2.2. Model Characteristics

Modeling Framework

In total, 24 analyzed papers indicated the application of predeveloped models (e.g.,[196,197]). The employment of universally applicable and established standard models is a common practice among CGE modelers in aviation research. We identified well-known frameworks from scientific institutions such as the GTAP [186,198] and the Partnership for Economic Policy [195,199]. The most prevalent framework in the sample was the standard CGE model from Lofgren et al. [106], which was adapted by three papers[185,196,200]. Besides the general standardized models, we found modeling specifications in terms of the country (e.g., [187,192,194]) and industry (e.g., [191,192]). For instance, tourism-focused models were applied in the aviation-related CGE literature [192,201]. Three articles provided no indications about the use of predeveloped models [183,202,203]. In addition, eleven papers within the sample incorporated a multi-modeling approach (e.g., [186,187,204]). The applied frameworks showed various approaches coupled with CGE models. Some scholars have integrated methods such as SAM models (e.g., [196]) and IO frameworks (e.g., [198,199]). Additionally, a combination of the CGE approach with econometric models (e.g., [188]) and the integration of environmental models (e.g., [186]) was found. Besides quantitative methods, Rose et al. [205] integrated qualitative survey results into a macroeconomic framework.

Temporal Dimension

The sample contained ten articles that took into account future simulations (e.g., [186,199,206]). Most models applied a short-term perspective. For instance, Some et al. [198] and Winchester et al. [204] employed a seven-year foresight up to 2020. Recent research has focused on scenarios up to 2030 (e.g., [193,199,206,207]). Still, future scenarios of early and recent studies have in common that their timespan does usually not exceed 15 years. An exception to this is the work of Broin and Guivarch [208], who ran simulations up to 2100. The remaining 17 aviation-related CGE publications neglected future scenarios and analyzed the immediate consequences of present shocks instead (e.g., [189,202,203]). The focus on short-term simulations and present shocks was not surprising, given that static models are the dominant approach in the aviation-related CGE literature. Overall, they were found in 18 publications (e.g., [185,188,203]). Early [183] as well as recent [196] works have built on static models to investigate macroeconomic aspects of the aviation sector, demonstrating the constant popularity of this approach. Recursive-dynamic models are also frequently applied to aviation issues and were identified in seven studies (e.g., [189,193,207]). Contrarily, the class of dynamic models was underrepresented in the sample with only two publications [184,187].

Geographical Focus

The aviation sample included five types of economic levels. First, cities as economic areas were subject to five publications (e.g., [183,206,207]). Second, the level of an entire region within a country was examined by Reimer and Zheng [200]. Third, the single-country level was the most considered type of economy within our sample with 17 occurrences (e.g., [187,196,199]). Fourth, a multiple-country analysis was conducted in two articles [186,198]. Finally, two papers in the sample considered a global perspective on macroeconomic aviation research [204,208]. The existing CGE literature concerning aviation is diverse in terms of geographical scope. We found aviation-related CGE models for Asia [194], Africa [195], Europe [186], North America [209], South America [189] and Australia [201]. Developing countries such as Egypt [199], Malaysia [188] and South Africa [196] were also investigated. Although each continent was included within the sample, academic interest was distributed unequally. European countries were only considered in multi-country analyses [186,198], though a single-country approach to a European state was missing. In contrast, the US was considered in five aviation-related studies (e.g., [183,200,209]) and seven CGE papers focused on China (e.g., [185,202,203]).

Data Sources

A remarkable number of studies utilized predeveloped databases provided by institutional sources such as the GTAP (e.g., [186,198,204]) and IMPLAN (e.g., [183,205,209]). Other papers made use of SAM databases generated by previous country-specific research (e.g., [196,199]). Moreover, we found the application of IO tables (e.g., [187,191,206]) and the derivation of elasticity parameters from the literature (e.g., [185]). Finally, aviation-related CGE studies supplemented the macroeconomic data with energy tables (e.g., [186,193,207]). An exception to this is the work from Straubinger et al. [190,197], who investigated the case of a hypothetical economy by using fictional data.

3.2.3. Aviation Focus Topics

Sectoral Focus

We identified four sectoral classifications with respect to studies on the aviation sector, namely an exclusive focus on aviation, aviation as part of transportation, the tourism sector and emission-intensive industries. First, eleven publications had an exclusive aviation focus (e.g., [183,196,199]). Second, eight studies considered aviation in the context of general transportation research (e.g., [185,187,203]). These works dealt with issues affecting the aviation industry as well as other transport sectors, such as passenger cars, heavy-duty transport and railways (e.g., [189]). Third, four studies in the sample assigned aviation to the tourism industry [191,192,195,201]). Aviation is particularly relevant in the case of inbound tourism countries that rely on air transportation [192]. Finally, four articles illuminated aviation-related aspects in the context of emission-intensive industries [193,194,206,207]. For instance, Dai et al. [193] included aviation in their research on the macroeconomic effects of carbon policies on emission-intensive sectors.

Type of Disruption

We identified various disruptions to the aviation industry. On the one hand, technological innovations linked to air travel included new aircraft designs [190,197], improvements in energy efficiency with respect to fuel consumption [195,203] and the introduction of alternative fuels or new propulsion technologies [186,200]. On the other hand, external factors influencing the aviation industry, such as oil price shocks [192], a rapid demand increase in air transportation [201] and terrorist attacks [183,209], were covered. In addition, recent studies have dealt with the consequences of the COVID-19 pandemic on aviation (e.g., [185,187,189]).

Fuel and Propulsion Technology

Despite the need for decarbonizing the ATS, the technological landscape is less diverse and reveals a clear dominance of fossil fuels in the existing CGE literature. Overall, ten studies explicitly indicated kerosene as an energy source for the aviation industry (e.g., [188,192,207]). Yet, some of these studies took into account the environmental impact of fossil-based jet fuel and considered kerosene-reducing policies (e.g., [194,202,206]). In contrast, sustainable technologies were barely addressed in the aviation-related CGE literature and only the subject of five publications in the sample. Concretely, biofuels have been evaluated as a kerosene substitute [186,198,200,204]. In addition, the CGE literature has evaluated battery electric aircraft as an option for urban traffic [197]. The majority of studies in the sample did not provide any indications about the considered type of aviation fuel or propulsion technology. However, a consideration of conventional fossil fuels seems more likely than the use of sustainable technologies in these cases.

Aviation Supply Chain

The SLR unveiled four elements with respect to the ATS supply chain. The dominant supply chain component within the aviation-related CGE literature was air transportation itself, which was addressed in 24 studies (e.g., [183,188,195]). Air transportation service is performed by airlines, which made them the most examined ATS actor in the sample (e.g., [195,205]). Air transportation infrastructure was detected in seven papers (e.g., [185,197,208]). For instance, Njoya and Ragab [199] highlighted airports as an essential part of the ATS and Betarelli Junior et al. [189] even integrated airports as a particular sector in their model. The fuel supply side was identified in five articles (e.g., [186,192,200]) and aircraft manufacturing was only investigated by one study [184].

3.2.4. Macroeconomic Evaluation

Policy Instruments

Policy instruments were frequently addressed in the aviation-related CGE literature. A total number of eleven studies dealt with policies addressing climate mitigation measures (e.g., [188,203,206,207]), which underlines the need for the decarbonization of the ATS. For instance, Choi et al. [194] and Dai et al. [193] implemented an emission trading system into their model. Additionally, carbon taxes [202] and subsidies for sustainable fuels [200] were discussed as policy instruments to reduce aviation's climate impact. Apart from climate mitigation measures, the CGE studies examined the macroeconomic consequences of other policy interventions, such as tariffs [191,195] and infrastructure investment [184,199] in the ATS.

Indicators

The SLR identified nine indicators within the aviation-related CGE literature: GDP, welfare/consumption, carbon emissions, intersectoral effects, employment effects, trade effects, aviation production/demand, aviation prices and energy demand. The most frequent indicator in the sample was the GDP, occurring in 23 publications (e.g., [187,196,208]). Welfare/consumption was detected in 16 articles (e.g., [191,201,203]) and carbon emissions were computed in eleven papers (e.g., [202,203,207]). Moreover, employment was considered by

15 articles (e.g., [185,196,199]) and trade effects by 13 studies (e.g., [187,189,196]). Furthermore, intersectoral effects played an important role in the aviation-related CGE literature with twelve occurrences in the sample (e.g., [185,195,206]). Concerning aviation-specific indicators, the supply of (or demand for) air transportation services was examined in 17 articles (e.g., [184,201,205]) and aviation price dynamics were computed in eight studies (e.g., [194,200,204]). The least frequent indicator in the aviation sample was energy demand (e.g., for jet fuel), which was considered by seven papers (e.g., [200,202,208]).

3.2.5. Key Takeaways and Research Gaps

Analogous to the hydrogen-related literature, we synthesize the aviation-related CGE studies. Concretely, we derive the main themes from the literature and discuss them. Finally, we propose research gaps in the following subsection [129].

Macroeconomic Relevance of Aviation

The macroeconomic relevance of the aviation industry has been emphasized in the CGE literature. For instance, changes and disruptions in the ATS have economy-wide impacts on macroeconomic indicators, such as GDP and employment [196,209]. Reductions in air travel can even cause negative consequences on economic prosperity [205]. Furthermore, disruptions to the ATS can affect other sectors due to inter-industrial dependencies and backward linkages [187]. For example, aviation plays a central role in the success of the tourism industry [195] and upstream sectors, such as mining [199]. However, CGE investigations often considered aviation as part of an aggregated transportation sector (e.g., [189,197]) and thus, the macroeconomic effects concretely induced by aviation-specific shocks remain unclear. The relevance of aviation and its macroeconomic contribution is even expected to rise, given the growing trend of globalization and increasing passenger numbers [6]. Thus, the ATS needs a particular macroeconomic consideration. Future CGE studies should therefore disaggregate aviation from other transport industries and examine its contributions to macroeconomic indicators and related sectors.

Sustainable Aviation Technologies

The need for the decarbonization of the ATS has been addressed in the CGE literature by climate policy analyses (e.g., [188,203,208]). Although carbon taxes and emission trading systems might have a considerable effect in terms of emission reduction [202], they seem insufficient to truly decarbonize the ATS [210]. Moreover, such policies often lead to a reduction in air travel, which is accompanied by negative macroeconomic consequences [193,207]. In addition, the large majority of CGE works have been built on conventional propulsion systems and fossil fuels (e.g., [192,202,207]) and few studies considered alternative technologies for aircraft (e.g., [200,204]). The current literature has only taken into account biofuels [186,198,200,204] and electric propulsion systems [197]. Moreover, these models have predominantly focused on environmental indicators (e.g., [186,198]) and thus, the macroeconomic effects of sustainable technologies are underrepresented [211]. A consideration of hydrogen-based propulsion or other synthetic fuels is missing in the aviation-related CGE discourse. Therefore, the investigation of sustainable technologies in aviation and their macroeconomic contribution represents a relevant future research direction in the CGE literature. Modelers need to address this gap in order to foster a true decarbonization of the ATS.

Long-Term Scenarios

The majority of aviation-related CGE studies dealt with short-term phenomena (e.g., [185,188,195,196]), while long-term investigations and future scenarios concerning the ATS have only been addressed by few scholars (e.g., [186,208]). Therefore, the aviation-related CGE literature is dominated by static modeling approaches (e.g., [185,186,203]), whereas dynamic modeling applications are scarce (e.g., [187]). However, the sustainable transition of the ATS requires a consideration of long-term consequences accompanied by new technologies or climate policies. CGE modelers should therefore put emphasis on long-term scenarios affecting the aviation sector, including the consideration of suitable modeling approaches.

Holistic Perspective on Air Transportation

Finally, a macroeconomic perspective on the entire ATS is underrepresented in the existing CGE literature. The majority of papers have dealt with issues concerning airlines (e.g., [188,203]), but the ATS is a complex system and incorporates further actors. For instance, aircraft manufacturing is an essential component of the ATS, but its footprint in CGE research is low [184]. Similarly, the fuel supply side as well as airport infrastructure are relevant elements of the aviation supply chain but were only covered by a few CGE studies (e.g., [192,199]). In addition, interrelations within the ATS are barely addressed in the macroeconomic discourse. However, Zhang and Tong [185] showed the dependency of airline business on airport infrastructure, which implies the relevance of ATS interrelations. A holistic consideration of the ATS becomes even more important with respect to the sectoral transformation toward sustainable technologies. The introduction of sustainable fuels and propulsion technologies requires adjustments in fuel supply, airport infrastructure and aircraft designs with macroeconomic implications [64]. CGE research should therefore focus more on all ATS components and their dependencies to evaluate disruptions to the ATS in a comprehensive manner.

4. Macroeconomic Research Agenda on Hydrogen-Powered Aviation

A perspective on hydrogen application in the ATS is neglected in the existing CGE literature [59,64]. However, our SLR on CGE models related to hydrogen and aviation represents a suitable foundation upon which future scholars can build. Based on the SLR analysis, we derived five major implications to foster macroeconomic research on hydrogen-powered aviation. By doing so, we addressed the third research goal of this study.

First, there is a variety of established macroeconomic models researchers can utilize and adjust to examine hydrogen-powered aviation. The use of predeveloped frameworks is a common approach in the general CGE literature [130] and neither hydrogen (e.g., [148,151,156,157]) nor aviation (e.g., [186,187,193,198]) is an exceptional field. However, we found more generic standard models in the aviation sample (e.g., [185,196,199]), whereas hydrogen analysis often applied customized models designed with respect to energy specifications (e.g., [149]). In addition, static approaches and short-term simulations were the main modeling type in the aviation studies (e.g., [183,189,199]), while the hydrogen context predominantly built on dynamic models (e.g., [147,148,157]). Given that large-scale hydrogen applications are expected by 2050 [164], the use of dynamic tools seems appropriate for hydrogen-powered aviation. Similar to the approach of Jokisch and Mennel [152], scholars can build on an established CGE model in order to design an individual approach that fits the concrete research objective for hydrogen-powered aviation. Finally, macroeconomic models have mainly involved hydrogen from natural gas (e.g., [155,160]) and coal gasification (e.g., [147,153]), which are not viable options for sustainable aviation. Future investigations should therefore adjust modeling approaches with respect to sustainable green hydrogen.

Second, appropriate data and viable scenarios are crucial prerequisites for the adequate macroeconomic analysis of hydrogen-powered aviation. Reliable and comprehensive data on green hydrogen costs and its supply chain are therefore inevitable [64]. Conventional energy carriers, such as oil or coal, are established in national economies and their supply chain and cost structure are incorporated in macroeconomic databases [64]. Contrarily, new energy sources are not represented in a disaggregated manner or even completely missing [212]. CGE modelers need to integrate the supply chain of green hydrogen for aviation. Existing hydrogen studies have provided some useful indications. For instance, Lee [155] disaggregated the cost structure of electrolysis with regard to macroeconomic categories. Still, more recent and comprehensive data are needed in order to cover the entire value chain. Such data are available in technoeconomic studies (see [58,59]), but need to be transferred into macroeconomic frameworks, such as IO tables or SAMs. For instance, Gronau et al. [64] provided a methodological procedure on the integration of green hydrogen into a macroeconomic framework for Germany. In addition, future scenarios and projections are relevant to the macroeconomic analysis of hydrogen use in aviation due to a realistic introduction of this technology by the midcentury [25]. For example, macroeconomic investigations should be combined with other approaches, such as energy system models, and their outcome used as input parameters for CGE models (e.g., [148,152,161]). Furthermore, researchers should take into account technological advancements in hydrogen and aircraft technology which might lead to price reductions in hydrogen-powered aviation [58]. Next to the quantitative aspects, modelers should consider the qualitative scenarios on future trends within the ATS (see [213]). For instance, air travelers have shown growing environmental awareness [214], which could increase their willingness to pay for sustainable aviation. The consideration of scenarios implies the need for interdisciplinary approaches and collaboration to evaluate hydrogen-powered aviation.

Third, modelers should critically assess the geographical scope of future studies on hydrogen-powered aviation. Hydrogen is gaining global momentum [215], which is underpinned by hydrogen strategies in a large number of countries [65]. Yet, the interest in scaling up a hydrogen economy differs among governments. For instance, Asian states are pioneers in terms of a hydrogen economy, which is reflected in the CGE literature, e.g., from Korea [160] and China [147]. In addition, Germany, Australia, the US and Japan are accelerating hydrogen infrastructure [65,171,216]. CGE scholars should recognize these political efforts and predominantly address countries with ambitious hydrogen strategies. Moreover, trade dependencies must be taken into account. Industrialized countries such as Germany and Japan plan extensive hydrogen utilization but are unlikely to meet their demand by domestic production [217,218]. Contrarily, countries such as Chile are expected to have better opportunities for green hydrogen production due to climate and topological conditions [76]. These regions could function as suppliers for states with a high potential for hydrogen-powered aviation. Cross-border trade activities will thus be of essential importance [77]. Scholars should analyze the most relevant suppliers of and demanders for hydrogen-powered aviation in order to illustrate these linkages in CGE models and evaluate the macroeconomic effects of such trade paths. For instance, recent hydrogen partnerships (e.g., between Germany and Canada [79]) could be depicted in those models. Furthermore, the relevance of the aviation industry in a respective country should be considered. Although the ATS connects countries worldwide and the decarbonization of this system must be realized on a global scale [219], some regions might be of higher interest for CGE studies on hydrogen-powered aviation. If air travel only plays a minor role in an economy, the macroeconomic effects associated with a new sector technology are less remarkable [195]. It might be valuable to focus on countries with a relatively high frequency of air transportation in order to report measurable effects.

Fourth, the investigation of policy interventions is relevant for hydrogen-powered aviation since hydrogen cost competition with kerosene remains questionable [59]. Following the existing CGE literature, climate mitigation measures could reduce the price gap between conventional and sustainable fuels. For instance, financial instruments, such as the taxation of fossil fuels [157,202] and subsidies on renewable energy [160,202], appear promising. In addition, market-based instruments such as emission trading schemes that are common in the aviation-related CGE literature [193,194,207] might be of interest for future studies on hydrogen-powered aviation. Finally, academics could examine how carbon restriction accelerates the adoption of hydrogen in the aviation industry. So far, CGE studies have tested carbon caps to foster hydrogen use in other applications, such as steelmaking [147]. Overall, the existing CGE literature on hydrogen and aviation offers a diverse toolbox of different policy instruments to be tested in future works on hydrogen-powered aviation.

Macroeconomic modelers could assess respective interventions and assist policymakers in fostering hydrogen use in aviation.

Fifth, future modelers should build on a holistic approach to investigate the macroeconomic aspects of hydrogen-powered aviation, including (a) the ATS as a comprehensive network and (b) sectoral competition for hydrogen resources. (a) The current discourse around aviation in the CGE literature mainly focused on airlines (e.g., [188,203]). Further supply chain components of the ATS, such as aviation infrastructure, aircraft manufacturing or fuel supply, were hardly addressed (e.g., [192,199]). Yet, the introduction of hydrogen in aviation affects the entire ATS, including changes to the airport infrastructure [56], new designs by aircraft manufacturers [51] and adjusted safety measures [57]. A holistic view of hydrogen-powered aviation requires the incorporation of all ATS components [64]. (b) The existing CGE literature considers hydrogen as a promising energy carrier in different sectors, such as heavy-duty transport [148], steelmaking [147] and power generation [160]. According to current expectations, hydrogen demand in these sectors will massively increase by 2050 [4]. CGE studies need to account for the potential competition between industries for hydrogen and avoid an isolated consideration of the aviation sector. In addition, macroeconomic studies should incorporate future projections on economy-wide hydrogen demand as well as the supply potential of green hydrogen in order to reveal potential shortages.

5. Summary and Conclusions

The ATS faces the crucial challenge of substantial decarbonization and hydrogen provides a promising opportunity to achieve this goal. As a result, hydrogen-powered aviation has gained increasing interest from scholars, policymakers, and practitioners. However, the scientific literature neglects a macroeconomic evaluation so far. Still, the introduction of hydrogen in the ATS has several macroeconomic implications and CGE modeling depicts a suitable approach for economy-wide analyses. This study therefore aimed to review the existing CGE literature dealing with hydrogen and aviation separately to propose a macroeconomic research agenda on hydrogen-powered aviation. More precisely, this paper had three research goals: (1) providing an overview of the existing literature dealing with CGE models in the context of (a) hydrogen and (b) aviation; (2) highlighting key insights and identifying research gaps in both fields; and (3) deriving implications to foster macroeconomic research on hydrogen-powered aviation. We applied the well-established method of an SLR.

First, this paper contributes by investigating the existing CGE literature on hydrogen and aviation. A total of 18 hydrogen-related and 27 aviation-focused CGE studies were gathered. In addition, these studies were analyzed with regard to meaningful categories.

Second, our study contributes key insights and critical research gaps identified in the existing CGE literature. (a) For the hydrogen-related CGE research, four major areas were found: (I) Hydrogen's lack of price competitiveness has been addressed in CGE studies, but the evaluation of taxes and subsidies as countermeasures is scarce. Future studies should give greater consideration to such financial policy instruments. (II) Hydrogen shows ambiguous effects on macroeconomic indicators. Future research needs to assess the overall impact of hydrogen in a more comprehensive and comparable way. (III) Hydrogen has been investigated in a few sectoral applications. CGE modelers need to identify and address promising fields of hydrogen application in future work. (IV) The current CGE literature is dominated by unsustainable hydrogen production, while green hydrogen is underrepresented. Future studies should focus on green hydrogen as a means toward a sustainable energy transition. (b) Concerning the aviation-related CGE literature, we revealed four key aspects: (I) The studies underlined the macroeconomic relevance of aviation, but its contribution was often unclear due to an aggregation of transport sectors. Future research needs to put more emphasis on the aviation industry and its macroeconomic role in a disaggregated way. (II) The need to decarbonize the ATS has been addressed via carbon policies in CGE analyses, but the consideration of sustainable technologies is underrepresented. In accordance with current net-zero ambitions, future studies should focus on sustainable alternatives to kerosene. (III) The CGE literature on aviation predominantly deals with short-term phenomena and the application of static modeling. In future research, scholars need to shed more light on long-term disruptions affecting the ATS and incorporate dynamic modeling. (IV) Aviation-related CGE studies mostly considered airline business, whereas a comprehensive investigation of the entire ATS is missing. Future modelers should consider multiple ATS components and unveil their interrelations.

Third, we contribute five implications for the macroeconomic evaluation of hydrogen-powered aviation, derived from the SLR: (i) The existing CGE literature provides a variety of predeveloped models upon which future studies can build. Scholars should modify existing models with respect to sustainable hydrogen incorporation. (ii) Data on hydrogen cost components and future supply scenarios are a prerequisite to evaluating hydrogen-powered aviation, but a comprehensive integration of green hydrogen supply chains is neglected in the CGE literature. Future modelers should therefore integrate data from technoeconomic studies into macroeconomic datasets. (iii) Hydrogen-powered aviation has a geographical dimension that requires consideration. Some countries position themselves as hydrogen suppliers while others show significant interest in hydrogen imports. In addition, the economic contribution of aviation varies among countries. Future research should take into account geographical discrepancies and identify suitable countries for macroeconomic analyses of hydrogen-powered aviation. (iv) The existing CGE literature provides a broad toolkit of policy instruments that can be applied to hydrogen-powered aviation. Financial incentives (e.g., carbon taxation) as well as market-based interventions (e.g., emission trading) were found in previous work and might be appropriate for future studies on hydrogen use in the ATS. (v) The ATS must be understood as a network of several actors that need to be addressed in a comprehensive manner. In addition, the economy-wide demand for hydrogen should be taken into account since different industries (e.g., aviation, steelmaking, heavy-duty transport) might compete for hydrogen supply in the future. Scholars need to apply a holistic perspective in order to gain an appropriate view on the macroeconomic dimension of hydrogen-powered aviation.

This study was oriented to scientifically sound principles, but still has some limitations. First, the SLR was limited to CGE models, although there are further macroeconomic methods that might have been applied to hydrogen or aviation in past studies. For instance, it could be beneficial to consider IO models or partial equilibrium models to receive a wider perspective on the macroeconomic aspects of hydrogen and aviation. Second, two databases, namely Scopus and Web of Science, which are recognized for covering the scientific literature to a large extent, were used. Yet, the consideration of further databases, such as Google Scholar, could increase the number of studies included. Future modelers should extend our review by incorporating additional databases. Third, this review was limited to scientific articles, but the so-called grey literature, such as industrial reports, might provide further insights. Fourth, this review was conducted in 2022, but the CGE literature on hydrogen and aviation is likely to grow in the upcoming years and the review should thus be updated constantly.

To conclude, our study serves as an appropriate foundation for ongoing macroeconomic research in the field of hydrogen-powered aviation. The growing interest in hydrogen application in the ATS requires macroeconomic evaluation to investigate issues such as sectoral linkages, welfare effects and suitable policy instruments. Our analysis provides a solid basis for macroeconomic studies on hydrogen-powered aviation and should be understood as a call for future scholars to explore the macroeconomic dimension of this novel technological field. This will not only be beneficial for the scientific discourse, but also for industrial players and policymakers. Enterprises are fostering hydrogen-powered aviation and will enable its practical realization. Macroeconomic elaborations will help these firms to identify economy-wide dependencies, sectoral beneficiaries, and potential bottlenecks. Moreover, macroeconomic studies can guide policymakers to implement the most efficient instruments for realizing hydrogen utilization in the ATS. A close cooperation between these stakeholders (i.e., science, industry, policy) will be inevitable to realize hydrogen-powered aviation and to eventually achieve a sustainable ATS.

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Appendix A

Table A1. Overview of studies applying computable general equilibrium models in the context of hydrogen.

Reference	Year of Publication	Journal Affiliation
Tatarewicz et al. [149]	2021	Energies
Ren et al. [147]	2021	Applied Energy
Espegren et al. [148]	2021	International Journal of Hydrogen Energy
Lee [156]	2020	International Journal of Hydrogen Energy
Mayer et al. [157]	2019	Journal of Cleaner Production
Lee [151]	2016	International Journal of Hydrogen Energy
Lee [155]	2014	International Journal of Hydrogen Energy
Silva et al. [161]	2014	Energy Procedia
Lee [168]	2012	International Journal of Hydrogen Energy
Lee and Hung [158]	2012	International Journal of Hydrogen Energy
Wang [150]	2011	International Journal of Hydrogen Energy
Wang [167]	2011	Journal of Power Sources
Bae and Cho [160]	2010	Energy Economics
Sandoval et al. [153]	2009	Journal of Transport Economics and Policy
Lee et al. [154]	2009	Renewable Energy
Jokisch and Mennel [152]	2009	Transport Reviews
Lee and Lee [159]	2008	International Journal of Hydrogen Energy
Lee and Lee [174]	2008	Energy and Fuels

Table A2. Overview of studies applying computable general equilibrium models in the context of aviation.

Reference	Year of Publication	Journal Affiliation
Njoya and Ragab [199]	2022	Sustainability (Switzerland)
Straubinger et al. [197]	2022	Transportation Research Part D: Transport and Environment
Betarelli Junior et al. [189]	2021	Transport Policy
Solaymani [188]	2021	Energy
Zhang and Tong [185]	2021	Transport Policy
Zhao et al. [186]	2021	Science of the Total Environment
Cui et al. [187]	2021	Transport Policy
Straubinger et al. [190]	2021	Transportation Research Part C: Emerging Technologies
Njoya and Nikitas [196]	2020	Journal of Transport Geography
Du et al. [203]	2020	Journal of Management Science and Engineering
Njoya [195]	2020	Research in Transportation Economics
Dai et al. [193]	2018	Renewable and Sustainable Energy Reviews
Zhou et al. [202]	2018	Resources, Conservation and Recycling
Liu et al. [207]	2018	Applied Energy
Reimer and Zheng [200]	2017	Renewable and Sustainable Energy Reviews
Chen et al. [209]	2017	Transportation Research Part A: Policy and Practice
Choi et al. [194]	2017	Energy Policy
Rose et al. [205]	2017	Risk Analysis
Broin and Guivarch [208]	2017	Transportation Research Part D: Transport and Environment
Wu et al. [206]	2016	Applied Energy
Pham et al. [201]	2015	Tourism Management
Forsyth et al. [191]	2014	Tourism Management
Winchester et al. [204]	2013	Transportation Research Part A: Policy and Practice
Some et al. [198]	2013	SAE Technical Papers
Lennox [192]	2012	Tourism Economics
Harback et al. [184]	2009	9th AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Aircraft Noise and Emissions Reduction Symposium (ANERS)
Rose et al. [183]	2009	Peace Economics, Peace Science and Public Policy

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