MACROECONOMIC EFFECTS OF SUSTAINABLE AVIATION – A MULTIPLIER ANALYSIS OF POWER-TO-LIQUID JET FUEL IN GERMANY

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Abstract

Hydrogen is a promising fuel to decarbonize the air transport system and offers different options for application in aircraft. For instance, hydrogen-based Power-to-Liquid (PtL) fuel represents a viable pathway for the aviation sector. Currently, the academic discourse around PtL fuel focuses on technological or techno-economic issues, while macroeconomic analyses lack behind. However, the introduction of new technologies has numerous implications on sectoral and economy-wide level. To estimate potential macroeconomic effects of PtL jet fuel production in Germany, this paper builds on a Social Accounting Matrix (SAM) – and applies the well-established method of multiplier analysis. Our results indicate economic benefits from PtL fuel on both sectoral and economy-wide level. Compared to mineral oil products like kerosene, PtL jet fuel can generate superior contribution to the domestic economy as well as increased labor demand and production output in multiple sectors. Despite its advantages, the multiplier approach has some limitations. Therefore, our paper also discusses the need to apply more advanced methods, such as equilibrium models, to fully understand the macroeconomic impact of PtL jet fuel production and use.

Keywords

Power-to-Liquid; SAF; Supply chain; Macroeconomics; Social accounting matrix; Multiplier analysis

1. INTRODUCTION

Climate change represents one of the most urgent challenges of humanity, mainly driven by escalating fossil fuel emissions [1]. Amidst this crisis, the aviation sector plays a crucial role in the international economy, yet its emissions significantly contribute to global warming [2]. New technologies are inevitable to achieve the sector's climate goals. While electric propulsion has significant climate mitigation potential [3], battery-powered aircraft lack the required energy density to go beyond short distances [4]. Contrary, biofuels are suitable for long-haul flights and are already used as drop-in fuels for conventional aircraft [5]. However, biofuels have high demand for land and water [6] which can jeopardize food security in regions with limited resources [7].

Given the shortcomings of battery-electric aircraft and biofuels, hydrogen emerges as a potential game-changer for aviation and can be used in various ways [8]. First, by using fuel cells, hydrogen can power electric aircraft which significantly reduces the on-board emissions [9]. Still, fuel cell-powered aircraft are likely to be limited to short-haul flights since they have a relatively low power density [10]. Second, hydrogen can be directly combusted in aircraft turbines in its liquid state. Liquid hydrogen outperforms fuel cell-powered systems in terms of flight distances [11]. However, a large-scale use is unlikely in the short-term [12] as several technological bottlenecks need to be overcome, such as novel aircraft designs, storage technology advancement and a modified on-ground infrastructure [8],[13]. Third, hydrogen can serve as a feedstock for sustainable aviation fuels (SAF) [5]. Hydrogen-based SAF, better known as Power-to-Liquid (PtL) fuels have recently attracted growing interest from practitioners and researchers [14],[15],[16]. Due to several advantages over other technologies, PtL fuels are considered as most realistic way to decarbonize aviation in the short term [17]. Although economy-wide impact of alternative fuels has been shown for the case of biofuels in previous studies [18],[19], a macroeconomic assessment of PtL fuels in aviation is currently neglected [20].

Our paper addresses this gap and aims to unveil potential macroeconomic effects induced by an introduction of a PtL jet fuel supply chain in Germany. We employ an extensive empirical dataset for the German economy – a national social accounting matrix (SAM). A detailed analysis of the PtL fuel supply chain is then conducted and subsequently, the cost components of PtL jet fuel are integrated into the SAM framework. To analyze the potential effects of PtL fuel supply chain introduction in Germany, a multiplier analysis is applied. The impacts on sectoral as well as on economy-wide level are presented and discussed.

The paper is structured as follows: In section 2, the potential of PtL jet fuels is illustrated. Moreover, we review the macroeconomic literature on alternative fuels. Section 3 outlines the method, including a description of the data. Subsequently, section 4 presents the results. Finally, section 5 discusses the findings and limitations.

2. LITERATURE REVIEW

2.1. Power-to-Liquid Fuels in Aviation

The use of PtL fuels in aviation holds promises due to several advantages. First, PtL technology allows the transformation of renewable electricity into synthetic hydrocarbon fuels, offering a sustainable supply chain [21]. Second, PtL fuels exhibit high energy density, overcoming limitations associated with electric or fuel cell-powered aircraft [17]. Third, PtL fuels can utilize existing infrastruc-

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ture, diminishing the need for extensive modifications to aircraft and refueling systems [15],[22],[23]. In terms of climate mitigation potential, PtL fuels show promising results and thus, are suitable for reducing emissions in aviation [24]. Finally, PtL fuels make better use of scarce environmental resources, e.g., land and water, than biofuels [15]. Despite the potential benefits, PtL fuels face cost disadvantages compared to kerosene and most biofuels [25],[26]. Although recent studies expect immense cost reductions for PtL fuels due to efficiency gains, technological advancements, and economies of scale [16],[27], PtL fuels are likely to remain more costly than fossil fuels, even in the long term [26].
The growing interest in PtL jet fuels is also reflected by an increase in industrial projects [23] and by growing policy ambitions [28]. For instance, the European Union has recently announced obligatory blending quotas to foster the application of PtL fuels in aviation [29]. Studies indicate that blending quotas represent a suitable approach for implementing PtL fuel in aviation [26],[30].
So far, macroeconomic analyses on PtL fuels are scarce, although the introduction of a new fuel supply chain is expected to have various macroeconomic effects. First, a shift from fossil to PtL fuel alters intersectoral relationships due to the more complex supply chain [15]. Second, unlike fossil fuel production, PtL involves labor-intensive steps, potentially creating new jobs [31],[32]. Third, PtL's domestic production, in contrast to kerosene imports, may enhance local value creation and national welfare [33],[34]. Fourth, renewable electricity expansion for PtL fuel could further stimulate economic growth [35],[36]. Fifth, even PtL imports might reshape trade dynamics towards regions with favorable production conditions [37]. Understanding such macroeconomic effects from a supply chain shift requires suitable analysis tools.

2.2. Macroeconomic analysis of new fuels

Two main techniques have evolved for the macroeconomic analysis of new technologies – input-output (IO) / multiplier analysis and general equilibrium modelling [38]. IO and multiplier analysis follow the same approach, but multiplier analysis builds on a more comprehensive data framework [39]. In contrast, equilibrium modelling incorporates further features, such as price-sensitivity and individual behavior of economic agents [38]. Due to its straight-forward procedure, IO analysis is frequently applied to new technologies, such as smart ports [40], coal-to-liquids [41] or photovoltaics [42].
Furthermore, IO analysis is the dominant approach for estimating macroeconomic effects of biofuels [38]. One of the first studies stems from Van Dyne et al. [43] who build on IO modelling to evaluate the macroeconomic effects of biodiesel production in a regional context. A later study applies IO analysis to the case of biofuel sectors in Canada [44]. The authors extend the existing database by new sectors for biofuel production. In addition, Yang et al. [45] use IO modelling for quantifying the socio-economic impact of biodiesel production in China. Their findings indicate that the magnitude of economic and employment growth depends on the structure of the regional economy. More recent studies deal with macroeconomic implications of biofuel production in South America. For instance, Lechón et al. [46] use an IO analysis to show that biofuel integration in Uruguay brings socio-economic benefits. Another recent work by Wang et al. [19] applies a scenario-based IO approach to analyze aviation biofuel production in Brazil. The authors show that aviation biofuel production leads to positive net socio-economic effects, but the magnitude depends on the chosen supply chain design and technological assumptions. In addition, Sievers & Schaffer [18] use the IO approach for the investigation of biofuel quotas, i.e., the authors examine the effects of biofuel quotas on the sectoral domestic production and imports in Germany. They show that domestic production of biofuels contributes positively to the German economy. However, when accounting for constraints in agricultural land availability, the positive effects are clearly smaller since more biofuel is imported. Besides biofuels, IO analysis has also been applied to hydrogen-based technologies [47],[48]. However, the application of this method to the promising technology of PtL fuels is lacking behind.

3. METHODS AND DATA

3.1. Macroeconomic database

Our analysis is applied to the case of Germany for several reasons. First, Germany has a clear agenda for PtL jet fuel use, aiming at a minimum of 300,000 tons annual use by 2030 [49]. Second, Germany has been examined in feasibility studies, estimating domestic production potential and costs of PtL supply chains [34],[37]. Finally, Germany provides macroeconomic data following international standards of national accounts [50].
The SAM is used as macroeconomic database in our study. In general, a SAM is the representation of an economic system in matrix format, covering all the transactions among economic agents within a certain period, typically one year [39]. More precisely, a SAM contains information about production, consumption, and trade of different products and services [51]. It further illustrates investment patterns, tax earnings and the distribution of income and is therefore an extension of the production-focused IO tables [38]. A SAM consists of six main accounts: (1) commodities, representing products and services, (2) activities of production which reflect the technology base of economic sectors, (3) factors of production, (4) economic agents (e.g., households, firms, and a government), (5) a capital component, accounting for savings and investment, and (6) the rest of the world to incorporate cross-boundary trade activities. The general structure of the SAM is illustrated in FIG 1.

ACCOUNT			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	TOTALS
Production	Commodities	(1)		Intermediate consumption		Household consumption		Government consumption	Fixed capital formation and change in stocks	Exports	Demand for products
	Activities	(2)	Domestic sales								Sales of commodities
Factors of production		(3)		Gross value added payments to factors						*Net* factor income from RoW	Factor income receipts
Institutions (Current accounts)	Households	(4)			Labour and mixed income	Inter-household transfers	Distributed profits to households	Current transfers to households	Labour and mixed income	*Net* current transfers from RoW	Current household receipts
	Corporate enterprises	(5)			Operating surplus			Current transfers to enterprises	Operating surplus	*Net* current transfers from RoW	Current enterprise receipts
	Government (&NPISHs)[1]	(6)	*Net* taxes on products			Direct taxes	Direct taxes			*Net* current transfers from RoW	Current government receipts
Combined capital accounts		(7)				Household savings	Enterprise savings	Government savings	Capital transfers	*Net* capital transfers from RoW	Capital receipts
Rest of World (combined account)		(8)	Imports						Current external balance		Aggregate receipts from RoW
TOTALS			Supply of products	Costs of production activities	Factor income payments	Current household outlays	Current enterprise outlays	Current government outlays	Capital outlays	Aggregate outlays to RoW	

Notes: NPISH: Non-profit institutions serving households

FIG 1. General SAM structure [39].

The structure allows for disaggregation of the accounts, depending on the available data and the research aim. The SAM framework follows the double-entry system of national accounts, with each component represented as a row and a column [39]. The rows show the incomes of each account, whereas the columns represent expenditures. The total of each row must equal the total of the corresponding column, ensuring the double-entry accounting principle [52]. German supply and use tables represent the main data source for our SAM [53]. The complete SAM, which is based on 2017 data, consists of 63 production sectors and 85 commodities (for a detailed version of the SAM, see [54]).

3.2. Supply chain analysis

German supply and use tables do not provide specific data on PtL fuel. In order to apply multiplier analysis, we need to integrate PtL fuel as a novel account into the SAM. For the integration of the PtL fuel into the SAM framework, we use a supply chain-based approach that has already been applied to the case of liquid hydrogen [54]. This approach builds on a detailed analysis of the fuel supply chain, analyzing its single production steps and identifying the cost components and their contribution to the overall production costs. Subsequently, and based on the classification of product groups in the national accounts, the cost components are translated into the data framework which conforms to the SAM structure.
The PtL supply chain consists of four main process steps: (1) renewable electricity generation, (2) hydrogen production, (3) circular carbon dioxide (CO_2) supply and (4) fuel synthesis. The PtL production process is shown in FIG 2.
At each stage of the supply chain, several technological options are feasible, leading to a broad range of potential supply chain designs [23]. The ideal supply chain depends on local production conditions, regulatory barriers, and assumptions about the increase of technological maturity in the future. Our analysis follows a supply chain design for Germany, incorporating offshore wind energy, proton exchange membrane (PEM) electrolysis, direct air capture (DAC) and Fischer-Tropsch (FT) synthesis [55].
In the following, we provide a detailed description of the supply chain steps and the techno-economic studies that we used to identify the individual cost components at each stage of the supply chain.

Renewable electricity generation. For the production of renewable electricity, different options are available, such as photovoltaics [56] and wind energy [33]. In accordance with the literature [33],[37], the supply chain used here assumes offshore wind as economically most viable choice for PtL production in Germany [55]. Based on techno-economic studies [57],[58], we obtained the cost allocation for offshore wind energy on a component level.

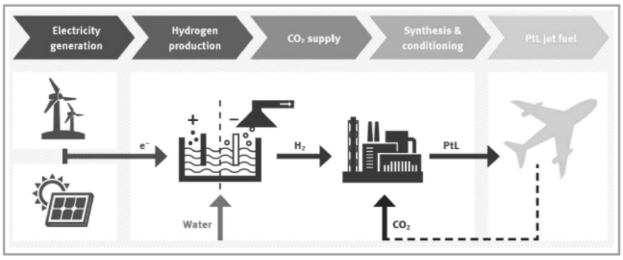

FIG 2. Schematic procedure of the PtL supply chain [15].

Hydrogen production and storage. Electrolysis produces hydrogen from electricity and water. Three electrolysis technologies are mainly discussed in the PtL literature. Alkaline electrolysis is the most established technology, but PEM and solid oxide electrolyzer cell (SOEC) show better efficiencies [24]. The supply chain design used here assumes PEM as most realistic long-term technology for German PtL fuel [55]. It is also assumed that compression and storage are part of the supply chain. We calculate the contribution of the individual cost components based on several techno-economic studies [54],[59],[60].

Carbon dioxide supply. The integration of a CO_2 source is inevitable to produce a hydrocarbon drop-in fuel [15]. However, to effectively reduce the climate impact of the fuel, a circular CO_2 source is a prerequisite. The literature considers biogenic material, industrial process emissions or DAC as potential CO_2 sources [27]. Despite its lack of technological maturity, DAC is seen as the only long-term option to effectively support a decarbonization pathway [33]. Consequently, DAC is assumed as CO_2 source for PtL in the supply chain design used here [55]. The allocation of the macroeconomic cost components is based on recent techno-economic analyses on DAC [61],[62].

Fuel synthesis. Using hydrogen and CO_2 as feedstock, a synthetic hydrocarbon fuel is produced. Two major technologies are feasible to synthesize the fuel: methanol synthesis and FT synthesis [16]. Despite its technological potential, methanol synthesis still lacks an approval for the aviation sector [17]. Hence, FT synthesis is mostly considered in the PtL literature and therefore integrated in the cost projection used here [55]. The cost allocation of FT synthesis to macroeconomic accounts is computed based on a techno-economic study [63].

As an additional cost component, the distribution by truck transport is considered in the PtL supply chain [55]. An overview of the process steps along the supply chain and their contribution to the total PtL supply costs is obtained from Kutz et al. [64] and provided in TAB 1.

Process step	2030 setup	2040 setup
Renewable electricity	0.1579	0.1472
Hydrogen production	0.0200	0.0123
Hydrogen storage	0.0115	0.0115
CO_2 supply	0.0281	0.0281
Fuel synthesis	0.0270	0.0270
Transport and distribution	0.0044	0.0044
Total supply costs	0.2490	0.2306

TAB 1. Cost assumptions for PtL fuel in EUR/kWh [64].

3.3. Multiplier analysis

Multiplier analyses extend traditional IO models as they build on the more comprehensive SAM data framework which includes further macroeconomic information [65]. By doing so, multiplier analyses are suitable to quantify the impact of new technologies to an existing economic system [66]. In the model, technological changes are represented by exogenous demand-side shocks [67], leading to direct and indirect effects, as shown in FIG 3.

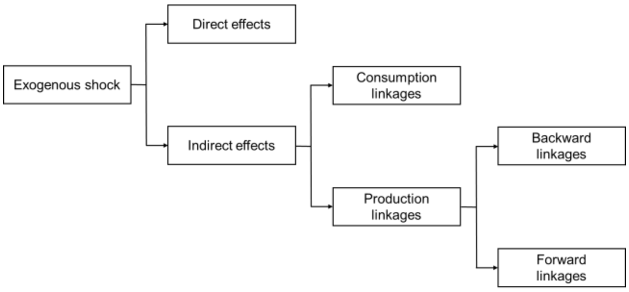

FIG 3. Economic effects in multiplier analyses [67].

One advantage of multiplier over IO analysis is the consideration of consumption linkages which trigger additional demand induced by growing income after a sector's production increases [67]. Similar to IO models, the multiplier analysis is a computation method based on linear algebra. Certain steps are necessary to perform a multiplier analysis. First, it needs to be decided which accounts are assumed exogenous. At least one account must be set exogenously to meet the mathematical requirements of the matrix-based calculations [39]. Generally, the government account, the capital account and the rest of the world are assumed as exogenous [39],[67]. In our case, we follow this established approach. The exogenous accounts are separated from the remaining SAM. Second, the endogenous part of the SAM is used to compute a coefficient matrix. Thereby, the column entries are divided by each column's total to calculate the relative expenditures of each account [67]. Third, the coefficient matrix is used to calculate the multiplier effects, defined by

$$Z = (I - M)^{-1}E, \tag{1}$$

where I is the identity matrix, M the coefficient Matrix, E represents the exogenous demand vector and Z the resulting multiplier matrix [67].
For the simulation of new technology introduction, two different approaches are feasible: (1) the final demand approach and (2) the modification of the technical coefficient matrix [65]. The final demand approach illustrates the new sector as composition of its inputs and thus, considers the new sector only as demander for existing sectors' outputs. Contrary, the latter method does not only include the production inputs of the new sector, but also its use as intermediate input in other sectors or as consumption good [65]. Many studies on alternative fuels apply the final demand approach (e.g., [18],[19]). We follow this approach since the application of PtL jet fuel in sectors apart from aviation is beyond the scope of this study. Based on the final-demand approach, we compute the multipliers of the PtL jet fuel supply chain. The multipliers illustrate the relative effect on different indicators per cost unit PtL produced. As PtL is currently not available at large scale, we simulate the supply chain introduction for a 2030 and 2040 setup and cost breakdown. Due to cost reductions and the EU blending quotas, this time horizon is more realistic in terms of a large-scale use in aviation [33]. The remaining economic structure of our data framework remains the same. A modification of the SAM for the years 2030 and 2040 would require forecasting the development of the entire economic structure in Germany. However, this is beyond the scope of this study.

4. RESULTS

4.1. Power-to-Liquid fuel cost breakdown

As there is no existing PtL account in the SAM, we use the final-demand approach to illustrate PtL as composition of its inputs. The cost breakdowns for 2030 and 2040 are shown in TAB 2. An explanation of the accounts is given in the Appendix (TAB 4 and TAB 5).

Input	**2030 setup**	**2040 setup**
c_chem	0.0518	0.0559
c_iron	0.0019	0.0013
c_met	0.1680	0.1692
c_eod	0.0013	0.0008
c_eleq	0.1142	0.1052
c_mach	0.1936	0.1829
c_mntg	0.0808	0.0858
c_elec	0.0086	0.0093
c_wat	0.0026	0.0029
c_con	0.0187	0.0173
c_trd	0.0022	0.0023
c_tran	0.0177	0.0191
c_infr	0.0446	0.0476
c_cnst	0.0040	0.0043
c_arch	0.0199	0.0189
c_rd	0.0106	0.0104
c_renm	0.0098	0.0096
c_cser	0.0191	0.0206
c_pser	0.0088	0.0095
Labor	0.0952	0.1012
Capital	0.1266	0.1260
Total	**1**	**1**

TAB 2. Relative allocation of PtL jet fuel production costs to macroeconomic accounts.

The input structure is calculated from the cost contribution of the process steps displayed in TAB 1 [64] and several techno-economic studies (see 3.2). The results show involvement of 21 macroeconomic accounts in the PtL fuel supply chain, including 19 commodities and the production factors labor and capital. A broad variety of input products reflects the complex supply chain of PtL fuels. For a 2030 setup, dominant inputs are machines with 19.36%, metal products with 16.80% and electrical equipment with 11.42%. These products are crucial for the setup of facilities along the supply chain, including wind turbines, electrolyzers and synthesis plants. As the renewable electricity part is the dominant process step in terms of cost, its cost structure contributes the most to the total fuel cost structure. The analysis shows that wind turbines, which are part of the machines in the commodity classification, make up a large share of the total costs. Moreover, TAB 2 also illustrates the relevance of services for PtL fuel supply chains in Germany. For instance, maintenance accounts for 8.08% of the fuel costs, while 4.46% are contributed by infrastructure services. Further services, such as architecture, research and development or business services make up a small share of the total costs. Besides manufactured products and services, labor and capital are identified as relevant cost components since they account for more than 20% of the total costs. The analysis reveals that renewable electricity and synthesis in particular are relatively labor-intensive production steps. Furthermore, capital cost represents a significant part of the supply chain which is particularly explained by the project risks of technologies with a low technological maturity, such as DAC.

4.2. Multiplier effects of Power-to-Liquid fuels

We compare PtL fuel multipliers to those for mineral oil, which contains kerosene in the SAM. For our analysis, we did not separate kerosene from the remaining mineral oil products. The introduction of the PtL jet fuel supply chain affects the economy in several dimensions. A closer look at the production multipliers reveals strong linkages of the PtL fuel supply chain to other sectors. Various manufacturing industries benefit from the introduction of a PtL supply chain in Germany. As displayed in 4.2, the metal products and machines sector show the largest multipliers among the manufacturing industries. A large direct effect on these sectors results from the PtL production since metal products and machines appear among the most relevant components in the PtL fuel supply chain (see TAB 2**).**
However, the multiplier effect also incorporates the indirect impact which is caused by the additional production in other industries, re-creating demand for inputs and income for households. Therefore, many sectors that are not directly involved in the PtL supply chain show multiplier effects, such as the motor vehicles production.
In addition, the manufacturing aggregate shows a high multiplier of 0.11. This account is a composition of several manufacturing industries that are not directly involved in the PtL production process, such as food processing, clothes, and plastic products. In all manufacturing industries, except from the mineral oil sector, the multiplier for PtL fuel is higher than for kerosene. Interestingly, the multiplier effect on electrical equipment industry is lower than the share of the corresponding product group in the PtL fuel supply chain. This can be explained by leakages from a relatively high import share in this product group. Thus, the effect on the domestic production (0.092 for 2030) is much lower than the effect on the commodity group (0.1521 for 2030).

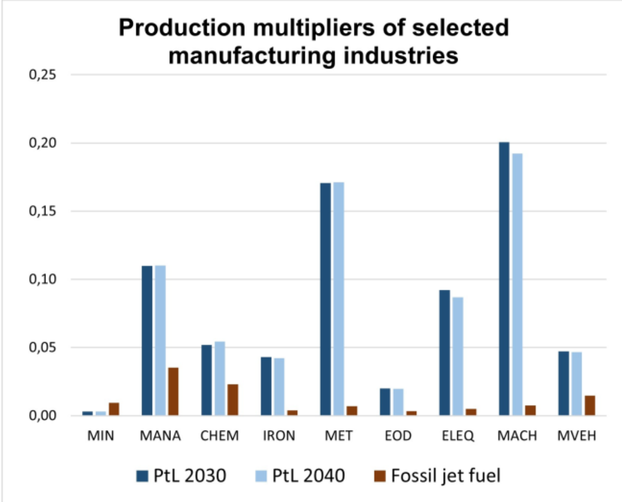

FIG 4. Multiplier effects on production levels of manufacturing sectors.

For infrastructure industries, we see similar results. The PtL fuel multipliers are higher than for kerosene (i.e., mineral oil products) in every sector. One the one hand, many infrastructure industries, such as maintenance and construction are directly part of the PtL supply chain. On the other hand, indirect effects of PtL production further trigger several infrastructure sectors. Some sectors experience their highest multiplier in the 2030 PtL setup, while others have their peak for the 2040 cost breakdown. Overall, the sector “Warehousing and infrastructure services” has the highest multiplier among the infrastructure industries (FIG 5). This multiplier is mainly induced by indirect ripple-through effects since it is much larger than the direct contribution to the PtL supply chain (see TAB 2).

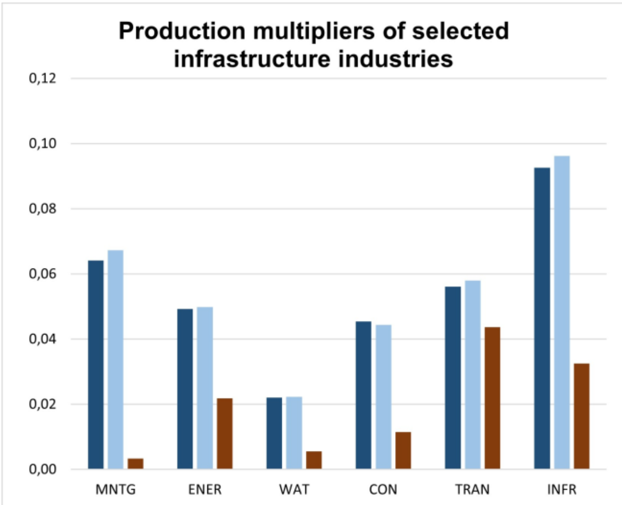

FIG 5. Multiplier effects on production levels of infrastructure sectors.

Looking at the multipliers in service industries reveals linkages of PtL fuel production to several services. Although most service sectors have lower multipliers than manufacturing industries, they benefit from indirect effects. Thus, the service sectors prove that the introduction of new technologies in the domestic market leads to effects that go beyond the product's supply chain. As shown in FIG 6, the service aggregate, a composition of several service industries, benefits most from the supply chain as it has the highest multiplier among all sectors in the SAM. However, it must be noted that this composition account consists of around 20 single sectors on which the effect is distributed. Interestingly, the trade sector is a profiteer from the PtL fuel introduction although its direct impact in the PtL fuel supply chain is relatively low, indicating a large indirect effect through production and consumption linkages.

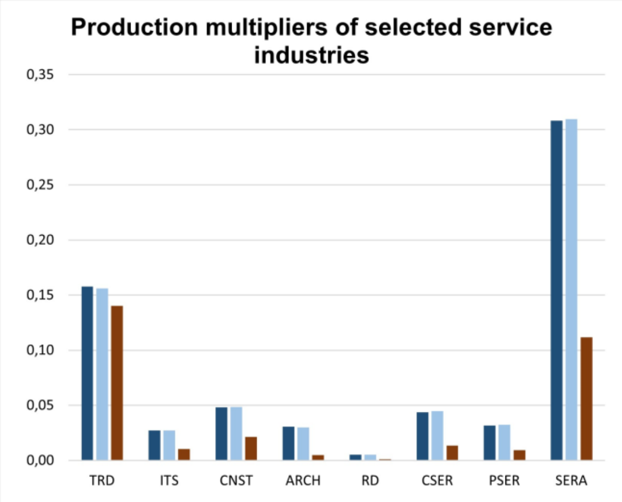

FIG 6. Multiplier effects on production levels of service sectors.

In addition to sectoral production increase, economy-wide indicators are affected by an introduction of PtL jet fuel in Germany. TAB 3 provides an overview of some relevant macroeconomic indicators.
In comparison to the use of petroleum-based fuels, we see superior multipliers for several economy-wide indicators. As the sectoral linkages indicate, the domestic production benefits significantly from a PtL fuel supply chain in Germany. The aggregated output in established sectors is more than 1.8. In addition, the labor demand is positively affected as a demand increase of 1 EUR in PtL fuel production leads to approximately 0.6 EUR growth in labor demand. This linkage is the main reason for the high multiplier in household incomes as labor represents the main income source for households in Germany. Furthermore, the effect on the gross domestic product (GDP) at factor cost, i.e., GDP adjusted for net taxes on products, exceeds the demand increase by more than 6%. Moreover, savings show a higher multiplier in comparison to kerosene which is mainly a result of the household income increase. An indicator that has a higher multiplier in the case of kerosene demand increase is the trade volume. This is not surprising since mineral oil products are imported to a large extent. Additional demand for kerosene therefore stimulates trade activities. In addition, the multiplier for government income is higher for mineral oil. Since kerosene is exempt from commodity taxes in Germany, this is primarily a result of the aggregation of mineral oils in our SAM. Assumptions about future taxation of PtL fuel and kerosene are beyond the scope of this study.

Macroeconomic indicator	PtL 2030	PtL 2040	Kerosene (2017)
Total production	1.832	1.831	0.919
GDP (factor cost)	1.064	1.069	0.324
Labor demand	0.602	0.607	0.176
Household income	0.874	0.879	0.263
Government income	0.371	0.373	0.482
Trade volume	0.391	0.389	0.445
Total savings	0.238	0.239	0.073

TAB 3. Multiplier effects on macroeconomic indicators.

5. DISCUSSION AND CONCLUSION

This paper investigated potential effects of PtL jet fuel introduction on the German economy. First, a supply chain analysis was conducted to identify relevant inputs to the PtL fuel supply chain and to integrate them into the SAM framework. The findings revealed strong linkages of PtL fuel production within the German economy and identified various inputs. From 85 commodity groups in the initial SAM, 19 are directly involved in the PtL fuel supply chain. In particular, products from the manufacturing industries, such as metal products, machines, and chemical products contribute significantly to the total PtL fuel production.
Second, a multiplier analysis was employed to estimate the total impact of PtL fuel introduction on the German economy. This method extends the supply chain analysis as it also accounts for indirect effects caused by production and consumption linkages. The results from the multiplier analysis emphasize the potential of PtL fuel production on both sectoral and economy-wide level. On a sectoral level, production activities in several sectors are triggered by an introduction of PtL fuel in Germany. The total domestic production multiplier exceeds the direct effects from PtL fuel production as the supply of PtL fuel inputs re-creates demand in further industries as well as income from labor and capital which stimulates consumption. The magnitude of this ripple effect varies among industries, depending on their production structure and the dependence on imports. For instance, when the import share for a certain product group is relatively high, the domestic production in the corresponding sector benefits less from a demand increase. These leakages become, for instance, evident in the case of electrical equipment (see FIG 4). On the other hand, several sectors that are not directly involved in the PtL fuel supply chain show notable production multipliers as a result from indirect effects. In particular, service sectors have low import dependencies and benefit via indirect effects (see FIG 6).
Next to sectoral effects, our findings underline the influence of PtL fuel supply chains on an economy-wide level (see TAB 3). The analysis also proved that domestic PtL jet fuel production has superior multiplier effects compared to kerosene. The total production multiplier and multipliers for different macroeconomic indicators are higher than for

mineral oil products. Despite the comprehensive analysis, our work has some limitations. First, by using the final-demand approach in our multiplier analysis, we only considered PtL fuel as demander for production inputs. Therefore, our analysis focused on the backward linkages of the PtL fuel supply chain. However, PtL fuel is expected to serve as a crucial input for several applications in the future. While this study dealt with PtL jet fuel, further industries are likely to create demand for PtL fuel. For instance, PtL fuels might play an important role in the decarbonization of maritime and heavy-duty transport [37]. PtL fuel use in these fields would require a modification of the technical coefficient matrix, implementing PtL fuel as intermediate input to several sectors. This procedure could further amplify the multiplier effect of PtL fuel in the economy as it accounts for stronger forward linkages.
Second, we assumed a fully domestic supply chain for PtL jet fuel in Germany and did not consider any capacity constraints with regards to the production of PtL fuel. It is debated if Germany could deploy the renewable electricity to generate PtL fuel on a large scale. For instance, it is estimated that a 10% PtL fuel quota for aviation in 2030 would require the total electricity that was generated from solar energy in Germany in 2018 [33]. Therefore, a rapid increase in the expansion of renewables, particularly offshore wind energy, is inevitable to establish a domestic PtL fuel industry. Still, it is unlikely that Germany will meet its entire PtL fuel demand by domestic production. Thus, imports from regions with more suitable conditions might play a key role in the decarbonization of the German aviation industry. The literature shows that the fuel supply from imports reduces the benefit to the domestic economy [18]. Thus, a pure domestic production, as simulated in our work, might overestimate the multiplier effects.
Third and last, the general limitations of multiplier analysis should be taken into account when interpreting our findings. This method assumes a constant return of scale and neglects price-responsive behavior [38]. These assumptions are simplifications since it is undeniable that prices affect the decision making of individuals and the substitution among different products. This aspect might overestimate multiplier effects to a certain extent. An established approach to overcome the limitations of multiplier analysis is the use of computable general equilibrium (CGE) modelling [67]. This class of models builds on the same empirical data as multiplier analysis. In contrast to IO and multiplier analyses, CGE models incorporate price-driven behavior and substitution effects within an economic system. Given these benefits, CGE models have already been used in the context of new aviation technologies, such as electric aircraft [68] and biofuels [69],[70]. However, the application to PtL jet fuels is scarce [20]. Therefore, the use of CGE models represents a promising research direction to extend the multiplier analysis presented here.

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APPENDIX

Code	Description
c_chem	Chemical products
c_iron	Iron and steel products
c_met	Metal products
c_eod	Electronic and optical devices and data processing equipment
c_eleq	Electrical equipment
c_mach	Machines
c_mntg	General maintenance services
c_elec	Electricity
c_wat	Water and disposal services
c_con	Construction services
c_trd	Trade services
c_tran	Transport services (land and shipping)
c_infr	Warehousing and transport infra-structure services
c_cnst	Consultancy services
c_arch	Architecture and engineering services
c_rd	Research and development ser-vices
c_renm	Renting of movables
c_cser	Corporate services
c_pser	Public services

TAB 4. Description of commodity groups involved in the PtL fuel supply chain.

Code	Description
a_min	Mining and quarrying
a_mana	Manufacturing aggregate (sever-al manufacturing industries)
a_chem	Chemical industry
a_iron	Manufacturing of iron and steel
a_met	Manufacturing of metal products
a_eod	Manufacturing of electronic and optic devices and data pro-cessing equipment
a_eleq	Manufacturing of electrical equipment
a_mach	Manufacturing of machines
a_mveh	Manufacturing of motor vehicles
a_mntg	General maintenance
a_ener	Energy supply
a_wat	Water supply and disposal
a_con	Construction
a_tran	Transport (land and shipping)
a_infr	Warehousing and infrastructure
a_trd	Trade
a_its	IT services
a_cnst	Consultancies
a_arch	Architecture and engineering
a_rd	Research and development
a_cser	Corporate services
a_pser	Public services
a_sera	Service aggregate (several ser-vice industries)

TAB 5. Description of activities (industries) considered in the multiplier analysis.