Modelling road transport technologies in future scenarios: theoretical comparison and application of Well-to-Wheels and Input-Output analyses

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Abstract

According to IEA projections, the penetration of electric vehicles in the world transportation sector is expected to increase in the next decades to comply with the future GHG emissions policy targets. The change in transport technology mix will cause a change the environmental and economic impacts of the transportation sector, switching it from flows to funds, that is, from the production and use of the fuel to the production of the fuel pathway and powertrain infrastructures. Therefore, due to their comprehensiveness, the use of Life Cycle Assessment models will be increasingly important with respect to Well-to-Wheels ones in assessing the impact of future transport technologies.

In this paper, the Hybrid Input-Output analysis is proposed as the appropriate framework to assess the impact due to a change in transport technology mix from a LCA perspective. First, LCA and WTW approaches are theoretically compared. Secondly, the LCA model is applied for the analysis of the economic and environmental impact caused by the prospected penetration of Fuel Cell Electric Vehicles (FCEV) based on Proton Exchange Membrane Fuel Cell (PEMFC) for Germany in 2050. In addition to the production of the vehicles, the LCA model includes the infrastructures for hydrogen production and distribution and the prospected change in the national electricity production mix.

Significant discrepancies have been found by comparing results of LCA with the ones obtained by well-established WTW models already available in the literature. It is found that the impact caused by infrastructures and production of vehicles could significantly offset the expected reduction in CO2 emissions and primary non-renewable energy consumptions.

Keywords: Life Cycle Assessment, Input-Output analysis, Well-to-Wheels, Transport sector, Fuel Cells electric vehicles, Energy modelling.

Highlights:

- Input-Output analysis is proposed to perform LCA of future automotive technologies;
- Input-Output analysis and Well-to-Wheels methods are theoretically compared;
- Penetration of fuel cell vehicles in Germany in 2050 has modelled and analyzed;
- Results of Input-Output analysis are significantly different compared to Well-to-Wheels;

1. Introduction

Among all the human productive activities, the energy-related activities represent by far the largest source of pollutants and greenhouse gases (GHG) emissions. In particular, CO2 emissions from energy-related sectors account for the largest share of global anthropogenic GHG emissions [1]. According to IEA data, fossil sources still accounted for 82% of the global TPES in 2015, playing a key role in the upward trend of CO_2 emissions [2]. Among other sectors, production of energy utilities (electricity and heat) and transport activities account respectively for the 42% and the 24% of the total CO_2 emissions. Despite the growth of renewable energy deployed in developed countries, the share of fossil energy sources in the world electricity and heat supply has slightly changed over the past four decades, and it is dominated by coal and natural gas (Figure 1, right side). On the other hand, considering the world emissions by sector (Figure 1, left side), it can be inferred that the transport sector has the highest share of world oil consumptions (49.7% in 2015); moreover, the road transport sector accounted for three quarters of world transport GHG emissions [3].

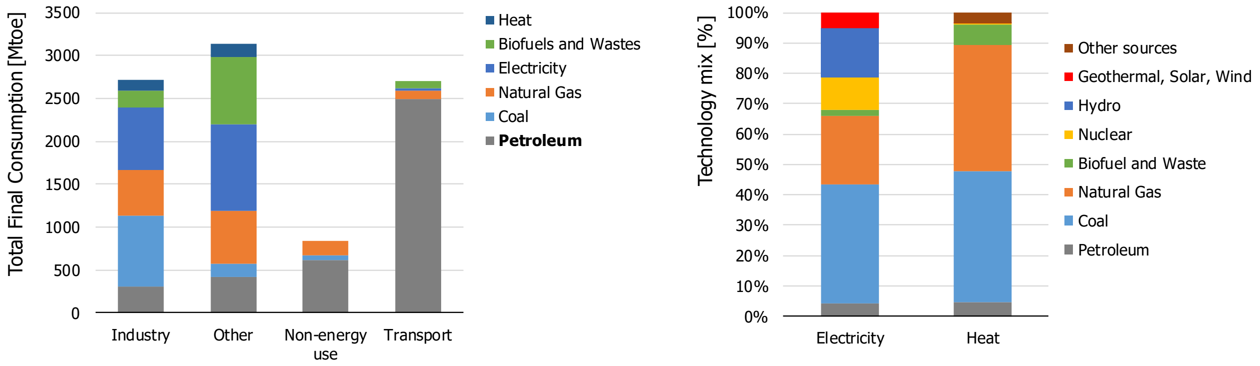

Figure 1. World Total Final Consumption (TFC, left side) and technology mix for electricity and heat production, year 2015 [2].

According to the IEA future Sustainable Development scenario, to complain with the world long term emission reduction commitments defined by the COP21 Paris agreements, emissions mitigation actions must be undertaken by all the participant countries and by acting in both energy production and transport sectors. According to IEA scenarios, the adoption of electric transportation modes may play a crucial role in achieving the 2°C target and for reducing oil dependency: among others, Fuel Cells Electric Vehicles (FCEV) appears as the most promising systems for future generation vehicles with the potential of competing with Internal Combustion Engines vehicles (ICE) [4]. Indeed, while electric vehicles based on batteries (BEV) are economically competitive for small travel distances and small vehicles, FCEV performances, driving range and refueling time are expected to be competitive with ICE [5,6]. Among the various type of fuel cells, the Proton Exchange Membrane Fuel Cells (PEMFC) fueled by hydrogen seems to be the most suitable technology for road transport applications, due their high power density, quick start-up time and rapid response to load change. Recently, the so-called *hydrogen economy* has received particular attention in literature, since hydrogen characteristics makes it an ideal candidate for a future sustainable energy system using renewable energy as primary source and hydrogen and electricity as energy carriers for a variety of purposes [7]. Despite such positive aspects, there are technical and economic barriers to overcome before FCEV will achieve significant shares:

- First, the cost of them is still not competitive with those of ICE: total cost of FCEV are dominated by materials, stemming from the special polymer required and the platinum-based catalyst layer [8].
- Secondly, PEMFCs adopt platinum as catalyst, which is a rare and precious metal characterized by an energy intensive and expensive production process, and literature argues that it may have a non-negligible environmental impact in terms of GHG emissions [9].
- Finally, the development of hydrogen generation and distribution infrastructures need to be established, hence requiring strong initial investments [10]: currently, infrastructure suppliers await market developments before investing in an extensive roll-out [11]. This mutual interaction has been a field of research for several years and a variety of modelling approaches has been applied. Some authors suggest a simultaneous development of market and infrastructures [12], others believe that a preliminary realization of infrastructures will provide stimulus to the penetration of alternative vehicles in the market [13].

The most important initiative for promoting FCEV in the European Union is represented by the *Hydrogen Mobility for Europe* (H2ME), a flagship project giving FCEV drivers access to the first European network of hydrogen refueling stations. The H2ME project will significantly expand the European hydrogen vehicles fleet and in doing so, aims to confirm the technical and commercial readiness of vehicles, fueling stations and hydrogen production techniques. Even if there is uncertainty regarding the future development pathway, many automotive industries are active in programs of development of transport means powered with fuel cell systems and they are allocating significant investments to drive the technology towards commercialization.

1.1. Literature review

Due to the increased policy interest raised by the role of hydrogen in the transport sector, several studies have been published in the past years in the attempt to assess the environmental impact associated to FCEV technology. The most relevant scientific studies published between 2001 and 2018 are collected in Table 1, and classified based on the following categories: the object of the analysis (type of light duty vehicle and, in case of fuel cells, type of fuel used); the country of analysis and the considered temporal scope; the phases of the vehicle life cycle included in the analysis (production, operation and disposal) and the type of impact addressed (environmental, economic, human health). Due to the variability in methodology and scope of the analysis, the researches lead to contrasting results that cannot be coherently compared: for such reason, the methodological approach is the main concern of this review.

Among the LCA studies, Garrain et al. [14] and Penth [15] investigated the production process of PEMFC, identifying the ecological contributions of various components and materials. Additionally, Penth compared the obtained results with the impact due to utilization of the stacks in a transport vehicle. Simons and Bauer [16] studied the production and the end-of-life of PEMFC systems for road passenger vehicle applications, including sensitivity analysis on crucial parameters and performing an impact analysis looking at the environmental burdens associated to the hydrogen use in the vehicle. Sorensen [17] and Hussain et al. [18] analyzed the overall fuel cell vehicle in LCA perspective, attempting to include operation of the vehicle on the road and production and distribution of both the vehicle and the fuel for the evaluation of energy consumptions and GHG emissions. Ahmadi and Kjeang [19] performed an LCA of FCEV focusing on the vehicle operation phase and providing a detailed analysis of the hydrogen production phase, comparing different production processes (electrolysis, water splitting, steam reforming) in Canada. Differently, Lombardi et al. [20] performed a detailed LCA analysis of different electric powertrains, focusing on the production and use phases. In two similar works, Miotti et al. [21] and Evangelisti et al. [22] apply LCA for assessing the environmental impact of PEMFCs considering future technical development scenarios and comparing results with traditional ICE powertrains.

On the other hand, looking at the WTW studies, Rousseau and Sharer [23] compared traditional ICE engines with FCEV: because of the high efficiency and lower direct emissions of FCEV compared to ICE, a complete assessment of the fuel pathway is claimed by the authors. The other WTW researches reported are always focused on the environmental impact associated to FCEV but differs in the primary energy source considered for hydrogen production. Hekkert et al. [24] evaluated CO_2 emissions and energy efficiencies of alternative automotive fuel chains, using natural gas as an alternative primary energy source to replace crude oil. Felder and Meier [25] conducted a WTW analysis for solar hydrogen production, transport and usage in passenger car transportation, examining solar hydrogen production through a LCA approach and revealing a significant environmental impacts associated with the construction of the fuel production infrastructures. Ramachandran and Stimming [26] compared the use of alternative fuels (electricity, hydrogen and bio-ethanol) in combination with battery and fuel cells electric vehicles based on WTW analysis. Likewise, Li et al. [27] apply WTW analysis for comparing BEVs and FCEVs operating with different energy resource and technology pathways in China. Yazdanie et al. [28] and Sharma and Strezov [29] applied WTW for the economic and environmental comparative assessment of conventional ICE and electric vehicles (including battery and hydrogen types). Among all the studies cited above, Bauer et al. [30] performed a comprehensive LCA analysis of different passenger vehicles, focusing on a detailed vehicle simulation model and including both the vehicles and the fuel production chain, emphasizing the importance of carrying out complete LCA instead of often performed WTW studies. However, since this study assumes the km traveled as the functional unit, the proposed methodology is unable to assess the global economy-wide consequences of the analyzed scenarios (e.g. the overall impact of a deep penetration of new vehicles in the national transport mix). More recently, in a similar fashion, Bicer and Dincer [31] apply LCA for assessing the impact on environment and human health of hydrogen, methanol and full electric vehicles, covering all the life cycle phases.

Table 1. LCA and WTW studies related to light-duty Fuel Cell Electric Vehicles (FCEV). (*If Operation phase is included, the fuel production processes and the related vehicle driving cycles are included in the analysis' scope).

Year	Authors	Ref.	Analysis' object	Country	Temporal scope	Vehicle LC phases			Impact indicators		
						Production	Operation	Disposal	Environmental	Economic	Human health
2001	Penth	[15]	PEMFC (with hydrogen and methanol)	Germany	Contemporary years	x	x		x		
2004	Sorensen	[17]	PEMFC (with hydrogen)	EU	Contemporary years	x			x		
2004	Rousseau, Sharer	[23]	PEMFC	US	Contemporary years		x		x		
2005	Hekkert, Hendricks, Faaij, Neelis	[24]	ICE, PEMFC (with natural gas and hydrogen)	EU	Contemporary years		x		x		
2007	Hussain, Dincer, Li	[18]	PEMFC	US	Contemporary years	x	x		x		
2008	Felder, Meier	[25]	PEMFC, ICE	Spain	Contemporary years	x			x		
2011	Garrain, Lechon, de la Rua	[14]	PEMFC	EU	Contemporary years	x			x		
2015	Simons, Bauer	[16]	PEMFC	EU	Near future (2012-2020)	x	x	x	x	x	
2015	Ramachandran and Stimming	[26]	BEV, FCEV (with hydrogen and bioethanol)	EU	Contemporary years		x		x		
2015	Ahmadi, Kjeang	[19]	FCEVs, with different hydrogen production modes.	Canada	Contemporary years	x	x		x		
2015	Bauer et al.	[30]	Conventional and hybrid ICE, BEV, PBEV, HEV (with different hydrogen production modes)	EU	Future scenarios (2012-2030)	x	x	x	x	x	x
2016	Li et al.	[27]	ICE, BEV, FCEV (with hydrogen and natural gas)	China	Future scenarios (2012-2030)		x		x		
2016	Yazdanie et al.	[28]	ICE, BEV, FCEV	Switzerland	Future scenarios (2012-2030)		x		x	x	
2017	Lombardi, T	[20]	Conventional and hybrid ICE, BEV, HEV (with	EU	Contemporary years	x	x	x	x		

			different hydrogen production modes)								
2017	Sharma, Strezov	[29]	ICE, BEV, FCEV	Australia	Contemporary years		x		x	x	x
2017	Bicer, Dincer	[31]	BEV, ICE (fueled with methanol and hydrogen)	n.d.	Contemporary years	x	x	x	x	x	x
2017	Miotti et al.	[21]	ICE, BEV, FCEV	EU	Future scenarios (2030)	x	x	x	x	x	x
2017	Evangelisti et al.	[22]	FCEV, BEV, ICE	EU	Contemporary years	x		x	x		x

The following fundamental elements have emerged from the literature review:

- In general, while WTW models are focused on the analysis of fuel pathways and powertrains operation, LCA models are generally focused on the construction of the PEMFC and FCEV, representing in detail all the materials involved in their manufacture and the related energy requirements. However, due to the difficulties in compiling LC inventories in LCA studies, there are only few attempts to include in the analysis the operation and the end use phases.
- The source of environmental impact of new transport technologies seems to be shifted from the fuel use to the production of increasingly complex vehicles and powertrains: since this latter factor may be quantitatively relevant, it should be considered for a comprehensive and meaningful impact assessment of the vehicle. Indeed, stocks and flows should be both included in the modeling framework adopted for the study, and this is one of the major claims in the recent Industrial Ecology literature [32].
- The scope of all the analyzed studies is restricted to the sole automotive sector supply chain, without considering the whole economic context in which the technology operates. Even the more extensive and comprehensive LCA studies disregards the indirect effects related to: (1) all the LC phases of the vehicles; (2) the industrial infrastructures required to support the production and distribution of the fuel, and the production of all the vehicle components different than the powertrain; (3) the effects associated to the prospected changes in the national electricity mix, which may be very important since manufacture of both vehicles and fuels are strongly related to the national electricity sector.
- The reviewed LCA approaches are based on commercial databases (i.e. Ecoinvent): these detailed models are usually referred to defined economies and hardly customizable, and this could limit the usefulness of the model in analyzing country-specific policies.
- Both WTW and LCA studies are focused on the environmental effects of the analyzed automotive technologies assessing a variety of impact indicators. However, little attention has been devoted so far to the overall economic implications of the prospected transport policies, which are equally or even more relevant with respect to the environmental ones for the policy makers.

1.2. Aim of the work

Based on the outcomes of the literature review, it can be inferred that none of the reviewed researches have been able to assess the economic and environmental consequences due to the implementation of FCEV transport technologies through a standardized, fully integrated and holistic approach, able to include the indirect effects of changes in the national electrical energy mix as well as the interrelationships of the transport sector with other producing sectors of the country.

Based on the background information and the research needs emerged from the literature review, the objectives of this study are:

- First, to propose a framework for the assessment of the economic and environmental impacts of future technological scenarios in a LCA perspective. The proposed approach is based on *Hybrid Integrated Input-Output analysis* (IOA), that are widely recognized as the computational structure of

LCA analysis [33]. The scope and the capabilities of the proposed LCA approach are finally compared to the WTW analysis.

- Secondly, the proposed LCA method is employed to assess the economic and environmental impact related to the prospected diffusion of FCEV in the German road transport sector in 2050, used as a case study. The economic impact is evaluated as the expected changes in national value added, while the environmental impact as the change in primary non-renewable energy consumptions and greenhouse gases (GHG) emissions.
- Finally, results of the developed LCA model are normalized to be consistently compared with results of well-established WTW studies available in the literature, hence leading to a fair comparison and discussion.

The developed LCA model aims at filling the gaps emerged from the literature review, assessing the effects of the prospected powertrain transition encompassing the fabrication of vehicles, the fuel production pathways, the physical infrastructures required and the indirect effects due to changes in the national electricity energy mix.

The rest of the paper is organized as follows: section 2 describes the proposed LCA model based on IOA, and then compares the LCA and WTW methods. Section 3 sets the scenario analysis and describes how the LCA model has applied the case study, presenting and discussing the obtained results. In section 0, results obtained for the same scenario based on standard WTW models are then presented and compared with results of the LCA model. Concluding remarks and future research directions are collected in section 4.

2. Materials and Models

This section introduces and explains the proposed LCA approach, and then compare its features with the ones of traditional WTW models.

2.1. LCA based on Input-Output models

LCA models are adopted for the evaluation of the overall environmental impact embedded into the goods and services production, including the entire life cycle of the product: extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal [34]. LCA analysis can be performed based on two main approaches: *process-based models* and *Input-Output based models* (IOA) [35]. The former approach (also defined as *bottom-up approach*) consists in the detailed definition of the production process of the analyzed system, while the latter (also defined as *top-down approach*) assesses the impact of average products of national sectors based on empirical models of the whole economy (i.e. the Monetary Input-Output Tables, MIOT). Process-based models are focused on the impact assessment of detailed products, and are characterized by a greater detail of the analyzed system with respect to IOA; however, they strongly depend on data availability (especially for new technologies, for which the model must be defined from scratch), and they provide models that can be hardly customized and adopted as references to assess technological changes in defined economic contexts [36]. On the other hand, IOA relies on freely available and constantly updated data sources (i.e. the MIOTs), it enables to comprehensively include the direct and indirect contributions of all the economic activities in the impact assessment, and it can be more easily adopted as a base to assess the effects due to the prospected changes in technology in one defined economic system [37]. Because of its features, the Author will refer to the IOA model as the preferred approach to perform LCA in the following.

The IOA model will be either used for *Attributional* and *Consequential* LCA applications. Notably, Consequential LCA is strongly debated in literature, and it includes a variety of modeling approaches that can be retrieved in the literature [38].

2.1.1. The basic IOA model: Attributional LCA

In its most basic form, the IOA model represents one or more national economies in one given time frame (usually one year), based on empirical observations of the economic transactions of goods and services among sectors collected in the so-called Monetary Input-Output Tables (MIOTs). One given economy is represented by its MIOT as a network of *n* productive processes, each producing and exchanging one single type of product with all the other sectors and providing a certain amount of goods and services for households' final demand, collected in vector $\mathbf{f}(n \times 1)$. The technical coefficients matrix $\mathbf{A}(n \times n)$ represents the quantity of input produced by *i*th sector and consumed by *j*th sector to deliver one unit of its product, hence it is a numerical representation of the national production technology. Moreover, each sector of the economy causes consumption of factors of production (i.e. labor, capital, others) per each unit of their product, collected into the value added coefficients vector $\mathbf{v}(1 \times n)$. Likewise, each sector relates to the environment through a number *m* of exogenous transactions (resources consumption or waste emissions), collected into the exogenous transactions coefficients vector $\mathbf{b}(m \times n)$. The core of IOA model is represented by the *Leontief production model*, shown by equation (1): it enables to account for the national economic production by each sector $\mathbf{x}(n \times 1)$ once the technology and the final demand level are known.

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{1}$$

Once the total production level is derived, is it possible to assess the total economic and environmental impacts of goods and services, respectively $\mathbf{V}(1 \times n)$ and $\mathbf{B}(1 \times n)$ caused by each economic sector, defined respectively by relations (2) and (3), known as the *Leontief Impact models*. Noteworthy, economic and environmental impact can be assessed according to a *Production-based* (subscript PB) or a *Consumption-based* (subscript CP) paradigm: the former reflects the impact directly caused by each sector (e.g. the direct GHG emissions of a given sector), while the latter reflects the impact embedded in products of each sector (e.g. the GHG emissions embedded into one specific product delivered for final uses, also known as the environmental *footprint*). Similarities and differences between the two approaches in an IOA framework have been recently investigated by the Author [39], investigating the energy metabolism of world economies through the joint application of PB and CB paradigms. Since the Consumption-based paradigm represented by equation (3) fits and reflects the purpose of LCA analysis, it will be adopted in the following as the reference for the application of IOA.

$$\mathbf{PB} \rightarrow \begin{cases} \mathbf{B}_{PB} = \mathbf{b} \cdot \hat{\mathbf{x}} \\ \mathbf{V}_{PB} = \mathbf{v} \cdot \hat{\mathbf{x}} \end{cases} \tag{2}$$

$$\mathbf{CB} \rightarrow \begin{cases} \mathbf{B}_{CB} = (\mathbf{b} \cdot \mathbf{L}) \cdot \hat{\mathbf{f}} \\ \mathbf{V}_{CB} = (\mathbf{v} \cdot \mathbf{L}) \cdot \hat{\mathbf{f}} \end{cases} \tag{3}$$

National economies are not closed clusters due to international trades of goods and services: therefore, it is fundamental to define suitable assumptions to treat flows of imports and exports flows before applying Leontief models. If Multi-Regional tables (MRIO) are adopted no assumptions are needed to treat imports and exports; on the other hand, Single-Region models (SRIO) usually assume exports as part of the households' final demand, while imports are assumed as *competitive* or *non-competitive*. An extensive discussion on this topic has provided by the Author [37]; other authoritative references can be found in literature [40].

2.1.2. Applying shocks in IOA model: Consequential LCA

Leontief Production and Impact models (1), (2) and (3) can be adopted to perform *Attributional LCA*, accounting for the impact of existing products in a given technological context. On the other hand, the IOA model can be also adopted to perform *Consequential LCA* assessments, evaluating the prospected impact due to future changes in technology, production levels, or other kind of shocks exogenously imposed to the model. Consequential LCA can be performed in several ways, mainly classifiable depending on the complexity of the market mechanisms included in the model and the types of variables endogenized by the model: *partial/general equilibrium models* [41,42], models based on *Comparative Advantage principle* [43] or *linear models* [44]. All these models may be used in two main ways: the *comparative statics* analysis simply assess the effects of a future shock as if it happens overnight, thus without considering the path required to implement such change and the related consequences; on the other hand, the *dynamic* analysis takes into account such path over future years, hence providing a more realistic picture at the expense of a greater effort required for implementing and calibrating the model.

Considering, for the sake of simplicity, a comparative statics approach based on a linear IOA framework, the impact caused by a shock can be modeled in the following ways, depending whether the shock is related to existing sectors, or if it implies the deployment of new technologies:

- Change in *existing* sectors/technologies: this shock consists in a change in technology and/or final demand level between two time frame 0 (before the shocks) and 1 (after the shocks). IOA models are defined for the two time frames by modifying coefficients of $\mathbf{A}$, $\mathbf{v}$, $\mathbf{b}$ or $\mathbf{f}$ according to process-specific data collected through a life cycle inventory process, and results of the Leontief models (1), (2) and (3) are simply subtracted, deriving the change in total production, total value added generation and environmental transactions.

$$\Delta\mathbf{x} = f\,\Delta_{0\to1}(\mathbf{A},\mathbf{v},\mathbf{b},\mathbf{f}) \quad \rightarrow \quad \Delta_{0\to1}(\mathbf{V},\mathbf{B}) \tag{4}$$

- Implementation of *new* sectors/technologies: this approach can be implemented with the purpose of increasing the accuracy of the analysis decoupling one specific technology from an aggregated sector (e.g. an existing coal power technology from a generic and aggregated energy sector). Alternatively, the same approach may be used to model the introduction of a novel technology in the country (e.g. the introduction of fuel cells vehicles in the transport sector). In both cases, the basic Leontief production model (1) is modified according to equation (5), usually defined as an *hybrid* IOA model, and the impact assessed through the Leontief Impact model, with the same approach as in equation (4). In the hybrid model, the subscript 1 refers to the shocked economy, while S refers to the detailed system or technology to be analyzed. Notice that technical, input and exogenous transactions coefficients of the basic economy should be properly corrected to avoid double counting issues (highlighted with the ~ hat). Also, in this case, the IOA model is characterized by process-specific data collected through a life cycle inventory process. Flows of products produced by the economy and consumed by the analyzed process are collected in the *Upstream Cutoff matrix* $\mathbf{C_U}$, while the opposite flows are collected into the *Downstream Cutoff matrix* $\mathbf{C_D}$. More technicalities related to the application of the hybrid IOA are available in the literature [45,46].

$$\begin{cases} \mathbf{x}_1 = \left(\begin{bmatrix} \mathbf{I} & 0 \\ 0 & \mathbf{I}_S \end{bmatrix} - \begin{bmatrix} \tilde{\mathbf{A}}_0 & \mathbf{C}_U \\ \mathbf{C}_D & \mathbf{A}_S \end{bmatrix} \right)^{-1} \cdot \begin{bmatrix} \tilde{\mathbf{f}}_0 \\ \mathbf{f}_S \end{bmatrix} \\ \mathbf{v}_1 = \begin{bmatrix} \tilde{\mathbf{v}}_0 & \mathbf{v}_S \end{bmatrix}; \ \mathbf{b}_1 = \begin{bmatrix} \tilde{\mathbf{b}}_0 & \mathbf{b}_S \end{bmatrix} \end{cases} \tag{5}$$

Notably, the two approaches introduced above can be applied together, if several shocks related to existing and new technologies need to be simultaneously implemented: this will be the case treated by this research. representing the joint implementation of a variety of exogenously defined policy/technology shocks.

2.2. Well-to-Wheels models

WTW models can be defined as engineering models that combines different fuel pathways (e.g. gasoline, hydrogen, electricity, etc.) and powertrains (e.g. internal combustion engine, fuel cell, etc.), assessing their environmental impact mainly expressed as energy use and GHG emissions related to 1 km traveled [47,48]. WTW models are based on a widely agreed and standardized methodology and data-set, in which the scope of the analysis is limited to the fuel pathways and the powertrains, while the construction of infrastructures and vehicles are excluded. WTW models are composed by two distinct models: *Well-to-Tank* (WTT) and *Tank-to-Wheels* (TTW): WTT includes the full details of the defined fuel production pathways, focusing on the process of producing, transporting, manufacturing and distributing a number of fuels suitable to be used in road transport powertrains, and covering all steps from extracting, capturing or growing the primary energy carrier to refueling the vehicles with the finished fuel [49]. On the other hand, TTW includes vehicle technology details, accounting for the energy expenditures and the associated GHG emissions directly caused by the vehicle operating with a reference driving cycle (such as, for instance, the *New European Driving Cycle* – NEDC) [50].

In the literature, the Argonne National Laboratory (ANL) developed the Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) model for Well-to-Wheels calculations. In GREET models, WTT fuel economy and GHG emissions estimates are based on the U.S. Environmental Protection Agency's (EPA's) National Emissions Inventory (NEI) database. The TTW vehicle fuel economy analysis used a General Motors (GM) proprietary modelling tool to estimate fuel consumptions on the U.S. urban and highway driving cycles. Additionally, EUCAR, CONCAWE and JRC have evaluated the WTW energy use and GHG emissions for a wide range of future fuel and powertrains options: the main calculations in WTT analysis have been carried by a software program developed by LB Systemtechnik in Germany, while TTW figures refers to vehicle and fuel combinations in the reference NEDC driving cycle.

2.3. LCA and WTW models: methodological comparison

Even if both LCA and WTW models can be adopted to assess the impact due to future technology scenarios in the transport sector, the two approaches are characterized by several methodological differences that must be known and properly considered.

Functional unit definition. The most important difference is related to the definition of the functional unit, which is defined by the WTW model as the km traveled in a country in one given time frame, disregarding its final purpose (transport services are used by both production or leisure activities). On the other hand, due to the nature of the IOA model, a distinction is made among the goods and services required by each production activity (intermediate consumptions) and by households (final demand). This aspect is particularly relevant, since this feature makes the impact of the transport sector of the LCA model a function of the changes in technology and production level of all the other industrial sectors of the country and vice-versa.

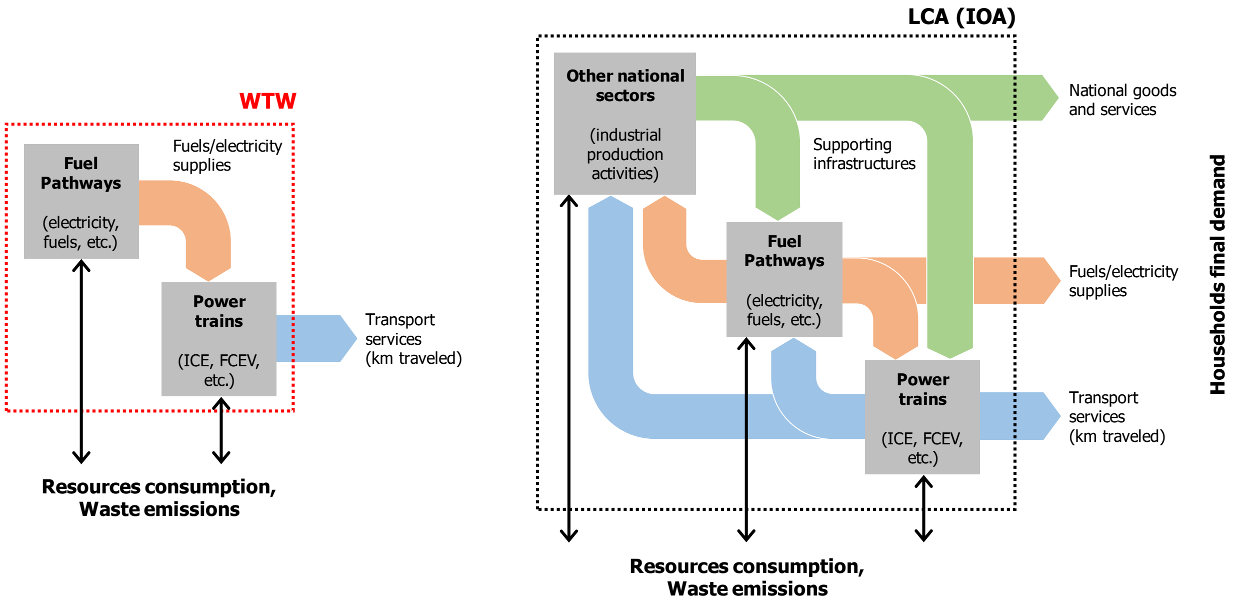

Figure 2. Graphical representation of the comparison between WTW models (left side) and LCA models based on IOA (right side).

Goal and Scope definition. System boundaries of WTW and LCA models significantly differs, as can be inferred from their graphical comparison presented in Figure 1. System boundaries of the WTW models are limited to the fuel pathways (fuel production activities) and the powertrains (the use of the fuels in vehicles), neglecting the interactions among these sectors and – more important – all the two-ways interactions of these sectors with all the other sectors of the country. Therefore, the indirect impact caused by the infrastructures and ancillary activities that support the fuel pathways and powertrains production and operation are neglected by WTW models, while their impact may be relevant for novel stock-based renewable technologies and its inclusion in the assessment is strongly advocated by the recent literature [32]. Beside this, it is impossible for WTW models to account for the benefits provided by a change in transport technology in specific sectors or processes of the country. Noteworthy, according to the WTW model, one specific fuel pathway and powertrain will have the same impact, disregarding the country of operation. The aforementioned drawbacks are partially balanced by the less amount of data required to setup and calibrate the WTW model compared to the LCA one.

Modeling approach. WTW models are usually based on an aggregation of engineering models of detailed processes (chemical models for fuel production, driving cycles models for powertrain operation, and so on), hence being able to provide great details related to the analyzed transport supply chain. Conversely, the proposed hybrid IOA models are based on empirical economic models (MIOTs) integrated with information provided by engineering models or life cycle data inventories. Therefore, it can be concluded that WTW models provide accurate but non-comprehensive results, while LCA models based on IOA return less accurate but comprehensive results.

Impact assessment methods. WTW models are mainly adopted to assess the environmental impact (namely, primary energy requirements and pollutants and GHG emissions) related to the transport services only. On the other hand, LCA models based on IOA provide a multiplicity of quantitative economic and the environmental impact indicators not limited to the transport service, but also related to all the production activity of the analyzed country.

The impact assessed by the proposed Hybrid Input-Output model, defined by relation (4) as the difference between the shocked system 1 and the baseline system 0, includes the effects that the modeled shocks have on the *whole economy*. Therefore, as an instance, the impact due to the prospected changes in the national electricity production mix are reflected in *all the production activities*, not only on the transport sector. Conversely, the impact assessed by the WTW model caused by the same shock is related to the *transport sector only*. For such reason, it can be concluded that results of WTW and the proposed LCA model cannot be coherently compared, and this especially because of the differences in the definition of the boundaries of the system and the related functional unit. Therefore, to compare results of WTW and LCA models, it is required to *normalize* the results of LCA model by subtracting the results of the analyzed scenario with the results obtained by the same scenario where changes in transport technologies are not implemented. In this way, it is possible to observe the impact related to the change in transport technology only, hence enabling a coherent comparison among WTW and LCA models.

3. Case study: definition and analysis of future German automotive scenario

In this section, the analyzed scenario and the related assumptions are introduced and justified. Then, the scenario is introduced as a series of integrated shocks in the Hybrid Input-Output model model based on the approaches described in subsection 2.1, and the economic and environmental impacts are assessed.

Likewise, results of the same scenario are assessed based on the reference *JRC WTW model* [51]. Results of both the models are finally compared and discussed.

3.1. Scenario definition

Many authoritative public institutions and private companies identify Germany as the most favorable European context for the development and large scale deployment of fuel cell technology for road transport, and several technology forecasts are available for years 2050 [10]. Moreover, a wide and comprehensive literature and data bank required to characterize the LCA model are currently available for Germany. For such reasons, Germany in 2015 is here selected as the baseline economy to conduct the analysis, and it will be compared with a scenario defined based on technology shocks implemented according to 2050 forecasts. The analyzed scenario assumes a change in the portfolio of powertrains, the type of fuel pathways and the electricity technology mix based on 2050 forecasts: these shocks are descripted in the following and resumed in Table 2.

A *comparative statics* approach based on a *linear Hybrid Input-Output model* is adopted, where the shocks are exogenously imposed in the model, and implemented as both changes in existing technologies (such as the prospected changes in the energy mix) and changes due to the introduction of new technologies (such as the introduction of FCEV vehicles). Technology changes are assumed to be implemented *overnight*, without considering the time needed for the construction of the infrastructures. Moreover, it is assumed that in 2050 the hydrogen production technologies and PEMFC are mature and competitive with respect to conventional technologies, then no incentives or other fiscal instruments are required to support their penetration in the market [10,52].

Table 2. Summary of exogenous parameters considered in the case study.

Area of intervention	Type	Baseline (2015)	Scenario (2050)
Powertrain technology	Internal Combustion Engine (ICE)	98%	70%
	Fuel Cell Electric Vehicles (FCEV)	-	30%
	Other powertrains	2%	-
Hydrogen production	Natural gas steam reforming	-	70%
	Water electrolysis (centralized)	-	15%
	Water electrolysis (on-site)	-	15%
Hydrogen distribution	Pipelines	-	85%
	Trucks (liquid H_2)	-	15%
Electricity production mix	Coal	44%	10%
	Natural gas	10%	14%
	Oil	1%	0%
	Nuclear	14%	0%
	Wind	12%	42%
	Solar	6%	11%
	Biomass	9%	16%
	Geothermal	0%	1%
	Hydro	4%	6%

Other basic assumptions are related to the nature of the defined Hybrid Input-Output model, which assumes constant return to scale, no price elasticities, no market equilibrium mechanisms and no constraints on exogenous resources availability. Even if these assumptions may be seen as too strong to derive reliable results, this choice has been made to reduce the amount of exogenous parameters required to set and calibrate the model, and it is strongly supported by several recent studies in the field of impact assessment [53].

Starting from the baseline economy, assumed as Germany in 2015, the implemented scenario is defined as the mix of the following described shocks.

Powertrain technology. According to Eurostat statistics, the number of road vehicles was about 49.6 million, the 91% of which are represented by passenger vehicles (http://ec.europa.eu/eurostat/data/database). In the *IEA ETP 2DS high H_2* scenario, the provisioned share of FCEV in passenger cars fleet will reach the 30% in 2050, assuming a Proton Exchange Membrane Fuel Cells (PEMFC) technology. Three different PEMFC technology standards are assumed, corresponding to different platinum load for the cell manufacture. The reference cell type has a platinum load of 0.142 mg_{pt}/cm^2 and represents the most advanced technological standard proposed by the Department of Energy (DOE) in 2015 [54]. The other cells have respectively a load of 0.3 and 0.4 mg_{pt}/cm^2, representing a medium technology and a well-established standard. For the evaluation of the quantity of hydrogen consumed by a stack during its operations, the *New European Driving Cycle* (NEDC) defined by the *Joint Research Centre* (JRC) has been considered. Results for the best technological standard will be reported, while sensitivity analysis will be performed to test the incidence of platinum load. Noteworthy, it is assumed that there are no changes in the number of circulating transport vehicles between 2015 and 2050, while their technology mix is changing.

Hydrogen production. Within the *IEA ETP 2DS High H_2* scenario, the hydrogen generation pathway for the year 2050 shows that almost 70% of production comes from natural gas reforming. Other studies considers a similar share for natural gas production [55], and the main reason is that natural gas reforming is more competitive with respect to other technologies. Therefore, the implemented scenario assumes 70% of hydrogen production from natural gas, while the remaining 30% is produced through water electrolysis. The choice of considering water electrolysis in the production mix reflects the penetration of renewable energy sources in the energy sector, according to the *IEA New Policies* and *450* Scenarios [4]. Finally, only centralized production is considered for natural gas reforming, while for water electrolysis centralized and on-site production are represented, each one accounting for 15% of the total production.

Hydrogen distribution. The case study assumes that, due to a significant diffusion of FCEV, the expected demand of H_2 is high, so the defined scenario considers 85% of pipeline distribution. The remaining 15% is based on liquid hydrogen truck transport, which is needed to satisfy the lower H_2 demand of less densely populated areas. This choice may not be the most cost-effective solution for the considered geographical area, but it is forced by the need to provide high quantities of fuel to final consumers. Other studies assume similar shares for the distribution method in the same geographical context [56].

Electricity production mix. According to *IEA New Policies* and *450* scenarios, a shift from conventional ICE to FCEV is justified if accompanied by the exploitation of renewable primary energy resources for electricity production, since the manufacturing of the fuel cell system and the hydrogen production are both energy-intensive. Additionally, in a future perspective, water electrolysis is considered competitive only in those cases in which renewables are integrated into power generation, hence allowing hydrogen to be used also for energy storage purposes [10]. Since the impact of the technology introduced is strictly dependent on the electricity production mode, a change in the electricity mix must be introduced in the scenario based on IEA projections [57].

3.2. Scenario analysis: shocks implementation, and results

The structure of the developed Integrated Hybrid IOA model is graphically represented by Figure 3. Data required for setup and calibration of the model have been retrieved from the following sources: macroeconomic and environmental accountings from the *Exiobase v.2* MRIO database [58,59] while data required to characterize the implemented shocks have been derived from the *European Life Cycle Database* (ELCD), the *New Energy Externalities Developments for Sustainability* (NEEDS), *Ecoinvent v.2.2* database, Yang and Ogden research [60], and results of the ongoing research of the *MRT Fuel Cell Laboratory* of Politecnico di Milano. Notably, since this analysis is focused on the domestic German economy, the Leontief models have been applied through a single-region approach, assuming imports as non-competitive and then not including them in the assessment of the environmental footprint.

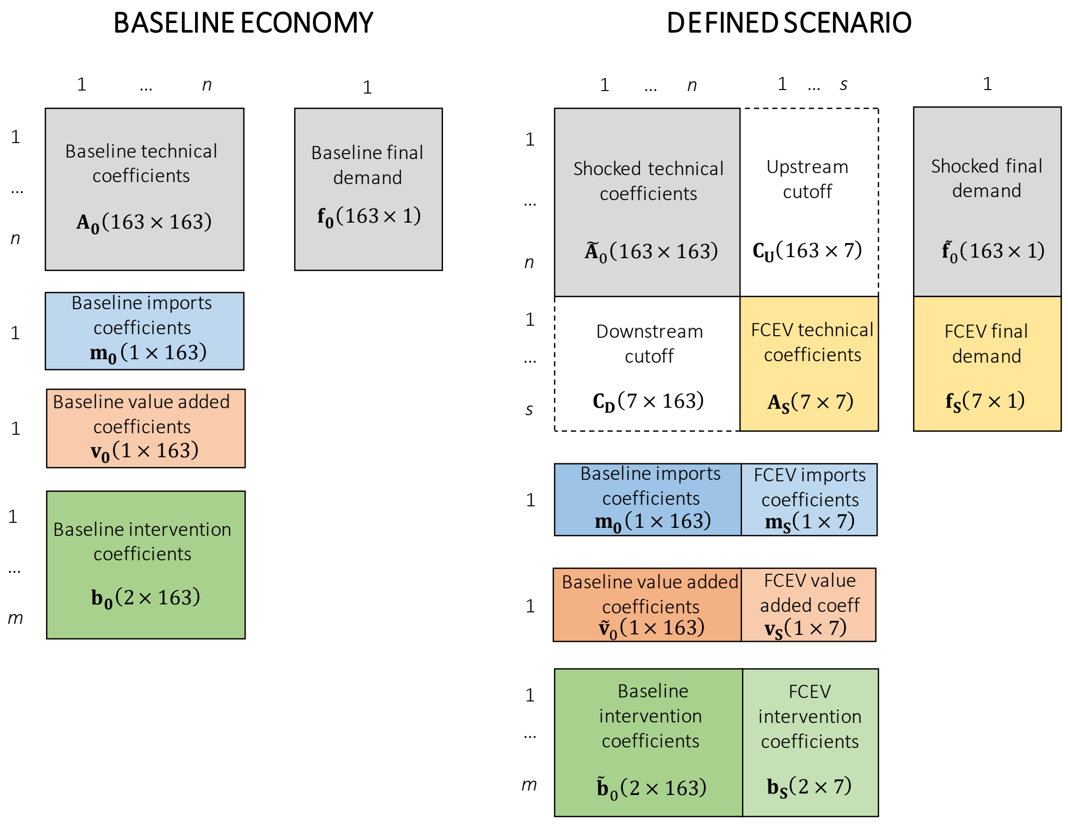

Figure 3. Graphical representation of the IOA model in the baseline economy (left side) and in the defined scenario (right side).

Consistently with the comparative statics nature of the analysis, it is assumed that there are no changes in the transport services delivered to final consumers, but only in the technology adopted to deliver such services. Modifications in already existing technologies have been implemented in the IOA model by modifying the *background system* (baseline economy 0), while the introduction of novel technologies have been defined in the *foreground system*. Notice that the *cutoff matrices* collect the products inventories related to such novel processes. With reference to Figure 3 (right side), the implementation of the 2050 scenario (subsection 3.1) is described in the following (detailed information are provided in Appendix 1). The major limitations and assumptions of the defined model are following listed:

- Germany is considered representative of forecasts on FCEV diffusion and hydrogen production pathways; however, several data source adopted to characterize costs and performances of technologies are based on the average EU context.
- The scenario analysis is limited to FCEV, and their diffusion is limited to light-duty passenger vehicles. Additionally, no distinction among vehicle segments in the car fleet is considered.
- Due to the comparative statics nature of the analysis , the implemented shocks are assumed to occur overnight, without taking into account any dynamics and transition pathway. Therefore, such shocks are the only changings occurring in the national technology mix.
- The analysis assumes that hydrogen production and distribution (as well as the required infrastructure) and FCEV technology have both reached maturity: FCEV are costs and performances are then competitive with conventional ICE vehicles cars.
- The proposed model accounts for the impact of the modelled scenario through indicators able to quantify the nation-wide economic impact and the GHG emissions: other relevant aspects such as the human health or other types of environmental impacts are not considered here.

3.2.1. Background system

The following modifications have been introduced in the background system 0:

- *Reduced demand for conventional ICE vehicles and fuels*. Services activities related to conventional transport vehicles are collected in the "*Other Land Transport"* sector. Technical coefficients and final demand for such sector in matrices $\tilde{\mathbf{A}}_0$ and $\tilde{\mathbf{f}}_0$ are modified to represent the 30% reduction in use of conventional ICE vehicles. The consumption of retail sales of conventional fuels represented by "*Retail sale of automotive fuel*" sector is reduced accordingly.
- *Change in the national electricity mix*. Considering electricity production technologies, the relative proportions of the values of electricity production related to all the industrial sectors and final demand have been changed in both $\tilde{\mathbf{A}}_0$ and $\tilde{\mathbf{f}}_0$ in order to represent the new electricity production mix (see Table 2).

All the technical, imports, value added and exogenous transactions coefficients of the baseline economy 0 that are not interested by any of the following shocks remained unchanged.

3.2.2. Foreground system and Upstream/Downstream Cutoffs

The foreground system represents all the activities required to support the introduction of FCEV in the transport mix and its core is represented by the technical coefficients matrix $\mathbf{A_S}$ (Figure 4). The characterization of coefficients matrices and Cutoff matrices is based on the introduction of the following seven new processes:

- *FCEV in the transport technology mix*. Two new sectors have been introduced: the "*Other land transport via FCEV*" sector, which reflects the average performance of such vehicles and is characterized by zero direct GHG emissions, and the "*Manufacture of FC system*", which resumes the average production process of fuel cells.
- *Hydrogen production processes.* Three new sectors have been introduced: the "*H2 production via natural gas reforming*", which represent large centralized hydrogen production facilities; the "*H2 production via centralized water electrolysis*" and the "*H2 production via on-site water electrolysis*", both assuming to exploit mainly renewable electricity to sustain the hydrogen production. Hydrogen produced by such processes is all delivered to distribution activities (final demand of it is assumed as zero).
- *Hydrogen distribution processes and retail activities*. Two new processes have been introduced: the "*H2 distribution via pipelines*", mainly adopted for transport and retail distribution of large quantities of gaseous H2 distributed in densely populated areas and the consequent retail; and the "*H2 distribution via trucks*", referring to the distribution of liquid H2 though trucks for long distance delivery and moderate demand.

For all the new introduced processes, it is assumed that materials/energy inputs are domestically produced, with the exception of platinum, imported from abroad. In absence of further detailed information, other data such as value added and exogenous transactions coefficients for all the new processes have been assumed as equal to existing sectors producing similar products.

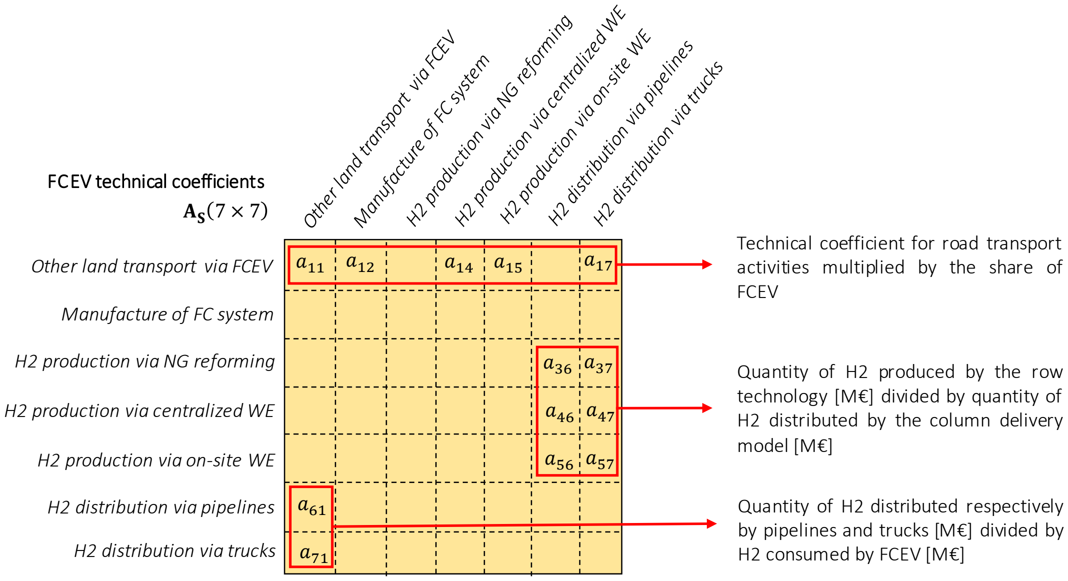

Figure 4. Foreground technical coefficient matrix.

The “*Upstream cutoff matrix*“ $\mathbf{C_U}$ collects the results of the Life Cycle Inventory Analysis for the new seven processes previously introduced. Product inventory for fuel cell manufacturing are related to a PEMFC stack with a nominal power of 100 kW (disposal phase is not considered), and inventories for three different technology levels – corresponding to three different performances and material inputs – have been considered (see Appendix 1 for further details). Every input employed in the manufacture of the stack is associated to a specific sector of the supply chain to determine the quantity of inputs that sectors already existing in German economy must provide for the manufacture of the fuel cell. The same process has done for hydrogen production (both based on steam reforming and water electrolysis) and delivery modes. Finally, the “*Dowstream cutoff matrix*“ $\mathbf{C_D}$ collects the amount of product flowing from each process of the detailed system to one or more sector of the background economy, and it reflects the change in technology mix due to the technology substitution.

Finally, inventory data have been collected by considering three different platinum concentration levels in the catalyst, corresponding to different performances, size and weights of the FCEV. Indeed, the extraction, concentration and refining of platinum is a capital, energy and labor-intensive process. The high footprint of primary production of platinum can have a significant impact on primary non-renewable energy consumptions and GHG emissions. Results of the LCA model presented in the next paragraph are related to a platinum load of 0.142 mg_{pt}/cm^2, assumed as the most advanced technological standard. To investigate the role of platinum used as a catalyst in the automotive sector two other technological standards with a higher load have been tested: respectively 0.3 mg_{pt}/cm^2 and 0.4 mg_{pt}/cm^2.

3.2.3. Results of the Input-Output model

Results of the Hybrid Input-Output model have been accounted through equations (4) and (5), and conveniently aggregated according to the ISIC rev.4 classification to ease their representation. The economic impact of the analyzed scenario is assessed as the change in the national *imports* and *value added* creation due to the modeled technology shocks, and graphically presented in Figure 5. Economic impact on imports results as a reduction of about 4400 M€ (-0.9%) compared to the baseline economy: most of this reduction comes from the “*Electricity, gas, steam and air conditioning supply*” sector, and this can be associated to the lower amount of electricity produced from natural gas and coal sources due to a change in the electricity mix. Even if the provisioned penetration FCEV imply a massive production of fuel cells, with a related significant increase in platinum imports, results show a reduction of the overall imports for the manufacturing sector, which is covered by the imports reduction for the energy sector. National value added is expected to increase by about 7200 M€ (+0.3%): this reflect the increased contributions of production factors (capital, labor, rents, etc.) that are expected due to the implementation of new technologies in the national mix. An increase in value added can be interpreted as a higher quantity or quality of the required factors of production, hence an increased economic effort required to deliver the same services. Value added increase is associated only to the contribution of manufacturing sector and comes from manufacturing of fuel cell system, while a reduction in costs is due to a change in the electricity mix and other ancillary activities.

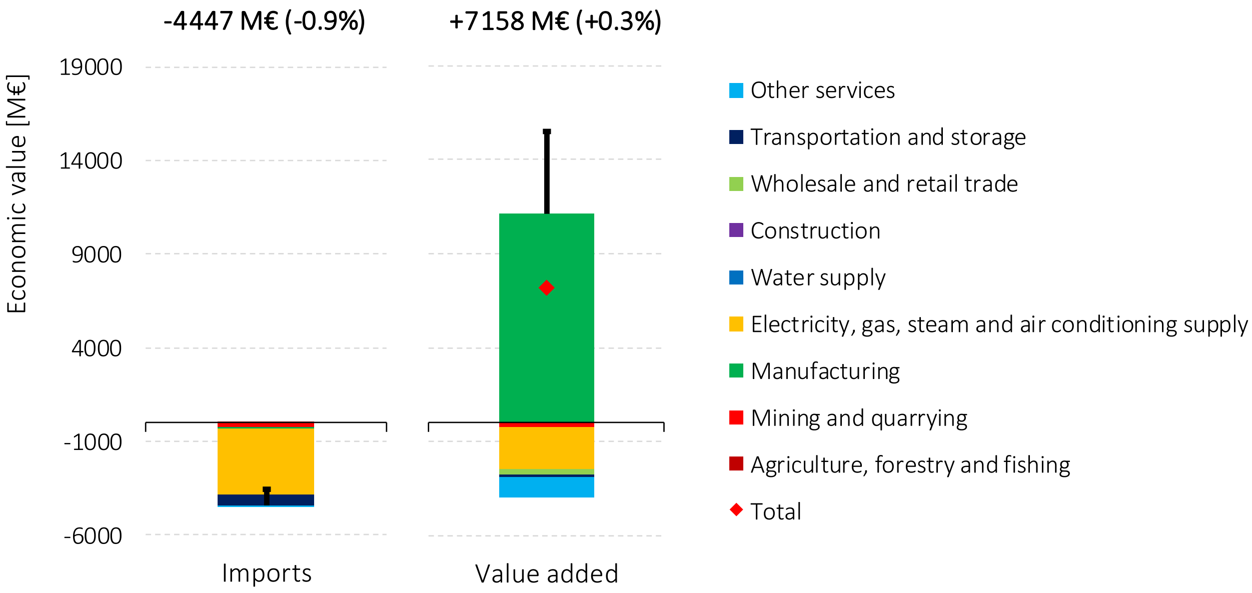

Figure 5. Economic impact caused by the 2050 scenario assessed through the LCA model.

On the other hand, the environmental impact resulting from the LCA model is quantified through changes in national *primary non-renewable energy consumptions* and *GHG emissions*, represented in Figure 6. Results show a reduction in primary non-renewable energy use by about 40 Mtoe (-18% compared to the national TPES): 85% of such decrease is related to the "*Electricity, gas, steam and air conditioning supply*" sector, hence in the increased renewable penetration in the electricity mix, while the rest is related to ancillary activities. Manufacturing sector also contributes in reducing energy consumptions, including both the production of the automotive fuel (gasoline and diesel as well as hydrogen) and the manufacture of traditional and fuel cell vehicles. Furthermore, the applied technological shocks contribute to a decrease of about 214 Mton (-30%) of GHG emissions: crucial for the achievement of such result is the transformation of the electricity sector that represents the 60% of the overall reduction. Moreover, manufacturing sector contribute to the overall GHG mitigation by 22%. This sector includes the manufacture of vehicle but also the production of automotive fuel and this means that FCEV and the use of hydrogen in the transport sector offer an important contribution in emissions reduction. The reduction in GHG emissions of the transportation and storage sector is very limited and this seems to be in contrast with the modelled scenario: 30% of passenger cars are FCEV and they can be considered as zero emission vehicles but there is no relevant reduction in emissions compared to the baseline scenario. The reason behind this result is related to sector classification: transportation and storage includes all kind of transportation modes (land, air and water), and it represents the transport service offered by the considered economy. As an example, this class includes land transport of passengers by urban transport system, but the road transport of citizens is not represented: since the latter is classified as final demand, its contribution is embedded in other production activities.

Finally, sensitivity analysis of results with different platinum concentrations in the catalyst has been performed, and results are expressed as uncertainties in energy use and GHG emissions in Figure 6. The augmented platinum load partially offset the reduction in both primary non-renewable energy use and GHG emissions compared with savings achievable with a load of 0.142 mg_{pt}/cm^2: a higher amount electricity for platinum primary production in 0.4 mg_{pt}/cm^2 standard leads to a relative increase in fossil energy use of +23% and a relative increase in GHG emissions of +8% compared to savings achievable with the best technological standards. Efforts for platinum load reduction in PEMFC are not only determined by the scarcity of this precious material but are fundamental to reduce the environmental burden associated to its use in FCEV.

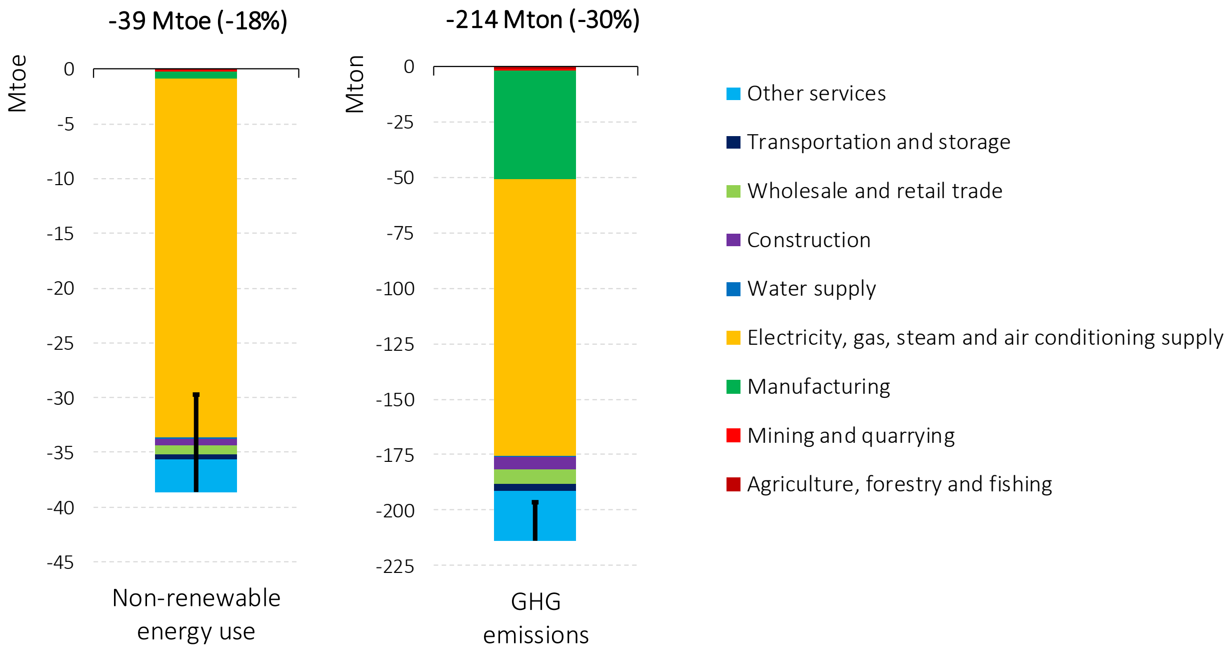

Figure 6. Environmental Impact in LCA model accounted through primary non-renewable energy requirements and GHG emissions. Notice that uncertainties are related to different platinum content in the PEMFC.

3.3. Comparison of WTW and LCA: results and discussion

The WTW model introduced in subsection 2.2 have been applied by introducing the same transport and electricity mix of the LCA model, hence comparing results of the baseline economy and the 2050 scenario, reported in Figure 7.

Significant discrepancies between results of WTW and LCA models emerge. Results of the 2050 scenario in the WTW model show a decrease in primary non-renewable energy consumptions of about 10 Mtoe (-5%), and a reduction of 35 Mton in GHG emissions (-5%). These results are related to a change in powertrains and fuel pathways only, disregarding the interrelations with the background economy, as described by section 2.3. FCEV fueled with hydrogen produced from NG reforming have lower primary non-renewable energy use and GHG emissions compared to gasoline and diesel vehicles. However, in case of water electrolysis, production of hydrogen from natural gas results in higher non-renewable energy consumptions and comparable GHG emissions, while the latter are doubled if coal is assumed as the primary energy source. Relying on biomass and wind as primary energy sources, a significant reduction in both fossil energy use and GHG emissions could be achieved.

WTW model provides detailed information related to the fuel supply chain and on the efficiency of the use of the fuel coupled with the vehicle, characteristics that make WTW analysis worthy for comparisons between different technologies. However, the main limitation is that such approach does not consider the manufacture of the fuel cell system and the FCEV, as well as the construction of facilities needed for the hydrogen energy system, that may influence fossil energy consumptions and GHG emissions. Additionally, the evaluated environmental burdens only refer to the automotive sector and an evaluation of the impact of alternative vehicles overall national economy is not feasible. A changed electricity mix can be considered only in the production of the automotive fuel but the effects on other sectors due to changes in the national energy mix are not considered.

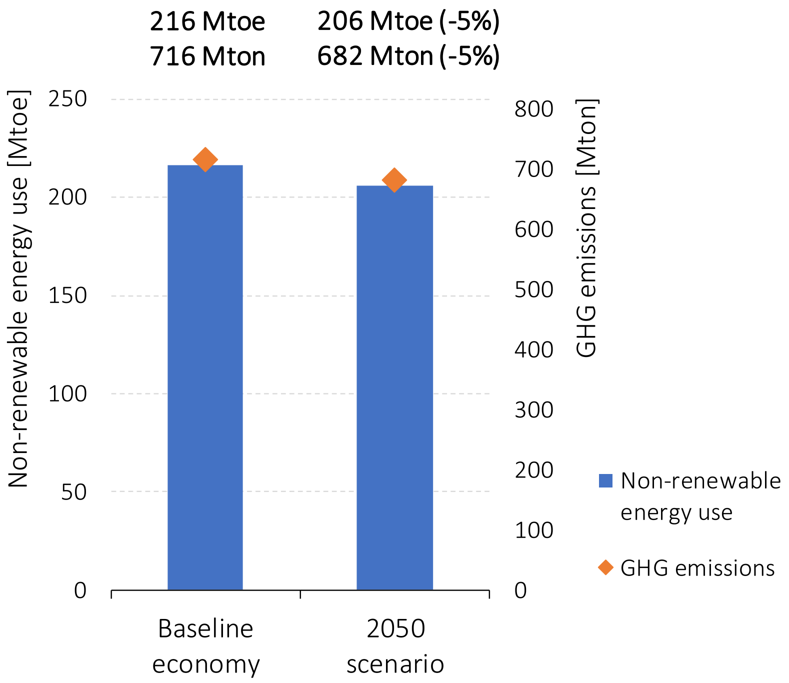

Figure 7. Primary non-renewable energy use and GHG emissions for baseline scenario and FCEV shocked scenario in WTW.

According to the methodological differences between the LCA and WTW models, analyzed in subsection 2.3, results of the two approaches cannot be compared. Even if both models apply the same shocks on the same economy, the shocks imposed in the proposed LCA model affects all the other sectors of Germany, while they affect only the primary energy sources used for hydrogen production in the WTW model. In order to provide correct and consistent comparisons of the results of the two approaches, results of the LCA model have been normalized according to the procedure described in subsection 2.3: another shocked scenario has been created, in which the unique change with respect the baseline scenario consist of the variation in the electricity mix, and the result of this scenario have been subtracted to the LCA results of the 2050 scenario. The obtained LCA results are visualized and compared with WTW ones in Figure 8, resulting in an overall decrease in primary energy use of 11 Mtoe (-5%) and GHG emissions of 5 Mton (-1%). Reduction in fossil energy use obtained through LCA model is comparable with the WTW model, while significant discrepancies holds for GHG emissions. To explain the origin of such difference, results of LCA are disaggregated into two major contributions:

- *Vehicle manufacture and Infrastructures.* This contribution refers to the environmental impact associated to the production of FCEV and the supporting infrastructure and ancillary activities needed to support the whole fuel pathway. These contributions result as relevant in this case, and they are usually neglected in WTW models.
- *Fuel pathway*. This contribution represents the impact due to the production and distribution of the fuels for automotive use, including also the effects associated to other ancillary activities that are enclosed in the LCA scope (again, these latter contributions are neglected by WTW models).

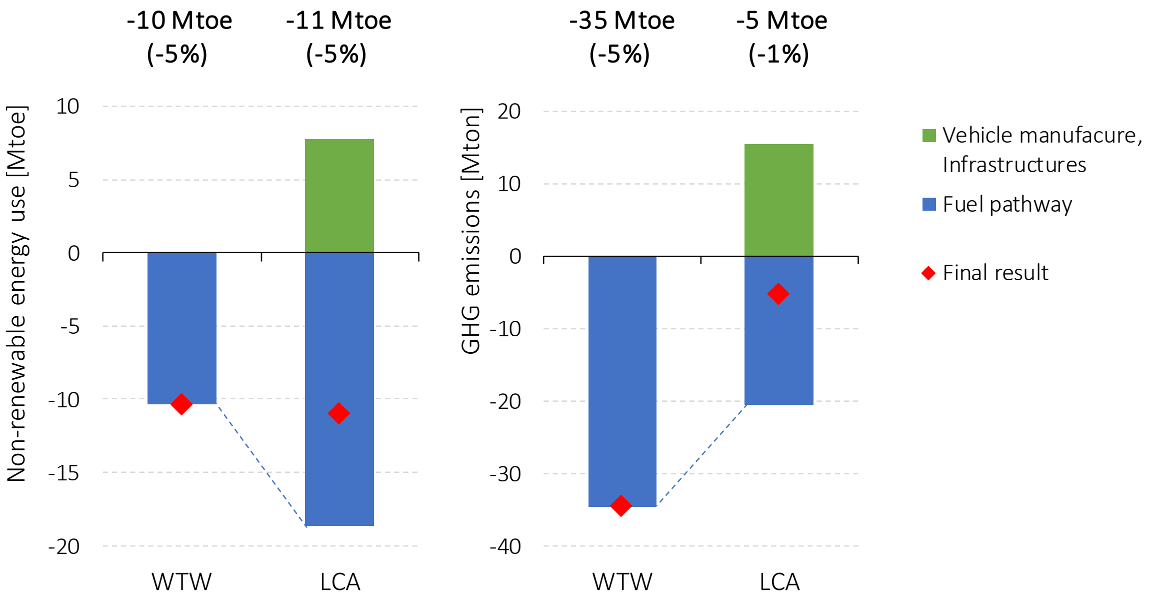

Figure 8. Primary non-renewable energy use and GHG emissions reduction in WTW and LCA models.

The change in national fuel pathway alone is expected to cause a reduction in primary energy use of 19 Mtoe, but this is compensated by an increase in energy use of 8 Mtoe due to the manufacture of FCEV and the related supporting infrastructures: in particular, this is due to the fuel cell stack (PEMFC), which requires large amount of energy due to the presence of platinum as a catalyst.

Regarding the GHG emissions, the contribution of the fuel pathway contributes by reducing them or about 21 Mton, which is significantly offset by the increased emissions of 16 Mton due to vehicles manufacture and infrastructures. Notice that reduction of the fuel pathway contribution in the LCA model are higher than WTW model for energy use, while are lower for GHG emissions: such difference can be explained as to the indirect effects in ancillary activities that are neglected by traditional WTW models, and such activities usually rely on primary energy sources with high GHG emissions intensity. Therefore, not only the manufacture of the vehicle and infrastructures becomes more emission intensive, but also ancillary activities may use emission relevant energy carriers.

4. Conclusions and future works

Based on the outcomes of the methodology analysis (section 2) and numerical results (section 3), it can be inferred that traditional WTW models provides detailed information for a comparison between different technologies, but they seem to be not fully appropriated for the evaluation of the overall impact of structural technology changes applied to the transport sector of one generic national economy. Therefore, integrated approaches based on LCA frameworks are needed to capture the real complexity of modern productive systems.

From a methodological perspective, impact assessment in LCA models is not limited to the sector where the shock is actually applied, but the scope of the analysis is extended to the whole national supply chain, enabling to assess the economic and environmental impacts in a holistic perspective, considering also how such structural changes affect directly and indirectly all the sector of the economy, hence revealing unexpected sources of impact that may be hidden in the upstream production processes. Therefore, due to the increasing complexity and interrelation of technologies and national supply chains, a paradigm shift is claimed. This result is supported by the obtained quantitative results, from which the following concluding remarks can be derived and summarized:

- The contributions to the environmental impact due to the penetration of FCEV vehicles manufacture and the related supporting infrastructures in the transport mix significantly offset results of traditional WTW models: an integrated and comprehensive approach is then required to include such contributions in future analyses. In this perspective, the Hybrid Input-Output model can be considered as the suited methodology to analyze the effects due to high penetration of new technologies in the national economy.
- The holistic approach to economic and environmental impact assessment is also motivated by the fact that the environmental impact of future energy technologies based on renewables is mostly due to the system production (e.g. the production of the capital stock, which is characterized by a greater impact than the related material/energy throughput). This is essential to assess unexpected source of environmental impact that may be hidden in the upstream production processes.
- The penetration of FCEV in the German context has relevant economic impact, since it requires a higher quantity of factor of production: compared to traditional powertrains, higher expenses are need to deploy and support FCEV in the transport mix.
- In the analyzed 2050 scenario, most of the reduction in energy use and GHG emissions are caused by a change in the electricity mix, while the contributions of transport and manufacturing sectors are less relevant.
- Beside a material scarcity issue, reduction in platinum load of PEMFC is also justified because it overall causes a reduction in the environmental burdens associated to its use in FCEV.

One of the main limitations of the adopted LCA methodology is related to the use of several assumptions for the description of the fuel cell technology and hydrogen production and distribution routes. Also, the description of the hydrogen delivery mode needs to be improved: the model assumes that a high quantity of hydrogen must be delivered and mainly pipelines are adopted for this purpose. However, delivery mode is strongly related to specific geographical conditions, thus an optimization of this aspect of the hydrogen supply chain is fundamental. Moreover, the impact assessment presented in this study is restricted to few impact categories, while multiple other types of impact should be taken into account for a comprehensive and meaningful assessment.

Looking at further development, an Integrated Hybrid Input-Output analysis of a diversified portfolio of powertrains could be performed to include Battery Electric Vehicles (BEV) and Plug-in Hybrids (PHEV). Such alternative vehicles have an important role in automotive scenarios and in the displacements of traditional ICE. Moreover, a more reliable scenario analysis could be performed by implementing the IOA model with more sophisticated market mechanisms, such as rebound effects, comparative advantage principle or price equilibrium.

Appendix 1

This section provides all the numerical information required to setup the hybrid integrated IOA model, hence ensuring the reproducibility of the results presented in the article. The authors are willing to provide further support and reply to eventual enquiries related to the data and assumptions required to characterize the model.

Table 1. Inventory analysis for materials employed in the manufacture of the analyzed FC stacks.

		0.142 [mg_{pt}/cm^2]	0.3 [mg_{pt}/cm^2]	0.4 [mg_{pt}/cm^2]
Components	**Materials**	**Weight [g]**	**Weight [g]**	**Weight [g]**
Membrane	Nafion xl	739.2	499.4	563.2
Diffusion layer	PTFE	620.9	419.5	473.1
	Carbon fiber	1 930.5	1 304.3	1 470.9
Microporous layer	PTFE	89.6	60.5	68.3
	Vulcan xc-72	268.8	181.6	204.8
Catalyst layer	Platinum	19.1	27.2	41.0
	Vulcan xc-72	95.4	136.2	204.8
	Nafion xl	143.1	204.3	307.2
Bipolar plates	Stainless steel	31 418.4	21 216.0	23 930.4
Manifolds	Alluminium alloy	2 168.0	2 168.0	2 168.0
Tie-rods	Stainless steel	4 862.9	3 475.4	3 844.6
	Total	**42 356.0**	**29 692.4**	**33 276.1**

Table 2. Performances of the analyzed FC stacks.

Name	**Unit**			
Platinum content	mg_{pt}/cm^2	**0.142**	**0.3**	**0.4**
Average power	kW	30.2	30.4	30.4
Average efficiency	%	55.7	55.0	55.3
Hydrogen consumption	kg	9042	9190	9145

Table 3. Reference data used for the WTW analysis.

Time horizon	Fuel pathway		Non-renewable energy use [MJ/100km]	GHG emissions [g CO2eq/km]
2010	Conventional gasoline from crude oil		240	178
	Conventional diesel from crude oil		195	145
2020+	Conventional gasoline from crude oil		168	125
	Conventional diesel from crude oil		142	106
	H2 from centralized NG reforming + pipelines		90	56
	H2 from centralized NG reforming + road		93	58
	H2 from on-site electrolysis	Natural gas	237	110
		Biomass	61	12
		Coal	285	244
		Electricity nec	194	122
	H2 from centralized electrolysis + pipelin	Natural gas	230	108
		Biomass	66	13
		Coal	274	231
		Electricity nec	198	125
		Wind	62	7

Nomenclature, Subscripts

Symbol	**Quantity**	**Unit**
A	Technical coefficients matrix	M€/M€
b	Exogenous transactions coefficients vector	Mtoe/M€ or Mton/M€
B	Exogenous transaction matrix	Mtoe or Mton
C	Cutoff matrix	M€/M€
f	Final demand vector	M€
L	Leontief inverse matrix	M€/M€
m	Imports coefficients vector	M€/M€
v	Value added coefficients vector	M€/M€
V	Value added matrix	M€
x	Total production vector	M€

CB	Consumption Based
D	Downstream
PB	Production Based
S	Detailed system

U	Upstream
0	Baseline economy
1	Defined Scenario

Acronyms

ANL	Argonne National Laboratory
BEV	Battery Electric Vehicle
CB	Consumption Based
DOE	Department Of Energy
ELCD	European Life Cycle Database
EPA	Environmental Protection Agency
ETP	Energy Technology Perspective
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicles
GHG	Greenhouse gases
GM	General Motors
GREET	Greenhouse gases Regulated Emissions and Energy use in Transportation
H2ME	Hydrogen Mobility for Europe
ICE	Internal Combustion Engine
IEA	International Energy Agency
IOA	Input-Output Analysis
ISIC	International Standard Industrial Classification
JRC	Joint Research Centre
LC	Life Cycle
LCA	Life Cycle Assessment
MIOT	Monetary Input-Output Table
MRIO	Multi-Regional Input-Output
NEEDS	New Energy Externalities Developments for Sustainability
NEDC	New European Driving Cycle
NEI	National Emissions Inventory

NG	Natural Gas
PB	Production Based
PEMFC	Proton Exchange Membrane Fuel Cell
PHEV	Plug-in Hybrids Electric Vehicle
SRIO	Single-Region Input-Output
TPES	Total Primary Energy Supply
TTW	Tank-to-Wheels
WTT	Well-to-Tank
WTW	Well-to-Wheels
2DS	2°C Degrees Scenario

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