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Original research article

Decoding the transport policy maze towards climate neutrality: Cross-sectoral policy landscapes

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ABSTRACT

Making transport sustainable is one of the grand global challenges. Numerous policies are currently underway, particularly in the European Union, to mitigate greenhouse gas emissions substantially. Germany has set ambitious targets, aiming for a 65% reduction in emissions by 2030 and becoming climate neutral by 2045. Unlike other sectors, Germany and the European Union have struggled to reduce emissions in the transport sector. Thus, the effectiveness of the current policy framework has been questioned. This study presents the outcomes of a comprehensive policy review across multiple sectors with direct or indirect implications for the sustainable transition in the transport sector. For this purpose, 44 policies were identified in the fields of transport, energy, agriculture, bioeconomy, and climate change. A mixed method content analysis approach was used to scrutinize policy documents, examining targets, fuel alternatives, transport modes, and coherence among policies. The findings underscore Germany's commitment to meet the climate targets through different pathways regulated by national and European policies. Electrification has been the predominant pathway for the decarbonization of the transport sector, followed by renewable fuels, e.g., Power-to-X fuels. Although well-designed plans exist for the electrification of road passenger transport, findings indicate low policy support for renewable fuels, especially for parts of the transport sector not well-suited for electrification, e.g., aviation and maritime.

1. Introduction

The United Nations (UN)'s Sustainable Development Goals (SDGs), the Paris Agreement, or the European Union (EU)'s Green Deal and the Fit for 55 package reflect the strong intention with which international governmental institutions intend to reduce greenhouse gas (GHG) emissions in all sectors including the transport sector. The EU and its member states have set the target of becoming a leader in the transformation to a net-zero economy [1,2]. In line with the introduced legislation, the EU also aims to reduce its heavy dependence on imported crude oil and its derivatives [3]. Despite efforts by the EU to decrease emissions, the transport sector has so far failed to meet the previous reduction targets, thus casting doubt on whether it will be possible to reduce emissions to achieve carbon neutrality by 2050 [4–6]. According to a recent report of the International Energy Agency (IEA), after a temporary decline by 5.8% in 2020 due to the COVID-19 pandemic, global CO_2 emissions increased again noticeably such that the transport sector currently accounts for roughly 23% of the total EU GHG emissions [7,8].

The EU is one of the major contributors to GHG emissions worldwide. In the EU, Germany has a long history in the governance of the energy transition ("Energiewende") dating back to more than three decades [10]. In 2016, Germany intensified its efforts for achieving climate neutrality by setting the target of reducing emissions by 55% until 2030 and becoming climate neutral by 2050 — targets aligned with the corresponding EU targets for the same years. In 2021, the German Government made amendments to the national targets, tightening the targets to 65% by 2030, 88% by 2040, and climate neutrality by 2045 (five years earlier than the EU's 2050 target). However, the transport sector is of great concern. According to the German Environment Agency (Umweltbundesamt) [9], the transport sector accounted for roughly 20% of the total emissions of Germany in 2021. Fig. 1 presents an overview of emissions in different sectors. Despite a substantial decrease of sixteen million tonnes in GHG emissions in 2021 compared to the base year, only a marginal reduction has been achieved in the transport sector since 1990.

To provide a better overview of the German transport sector, Fig. 2 shows the fuel consumption in the transport sector categorized by

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A list of abbreviations

AFIR	Directive on the Deployment of Alternative Fuels Infrastructure	FQD	Fuel Quality Directive
BEV	Battery Electric Vehicle	GHG	Greenhouse Gases
BEHG	Fuel Emissions Trading Act	GL	Global
BioKraftQuG	Biofuel Quota Act	IEA	International Energy Agency
BiomasseV	Biomass Ordinance	IF	Innovation Fund
BioSt-NachV	Biomass Electricity Sustainability Ordinance	LNG	Liquefied Natural Gas
Biokraft NachV	Biofuel Sustainability Ordinance	LPG	Liquefied Petroleum Gas
BImSchG	Federal Immission Control Act	LULUCF	Land Use, Land-Use Change and Forestry
CAP	Common Agricultural Policy	MFS	Mobility and Fuel Strategy
CBA	Carbon Border Adjustment	NPE	National Platform for Electric Mobility
CEAP	Circular Economy Action Plan	NPM	National Platform for Future Mobility
CNG	Compressed Natural Gas	NZIA	Net-Zero Industry Act
CORISA	Carbon Offsetting and Reduction Scheme for International Aviation	PEV	Plug-in Electric Vehicle
DE	Germany	PtG	Power-to-gas
EEG	Renewable Energy Act	PtL	Power-to-liquid
EED	Energy Efficiency Directive	PtX	Power-to-X
ESR	Effort Sharing Regulation	RED	Renewable Energy Directive
ETD	Energy Taxation Directive	RFNBOs	Renewable Fuels of Non-Biological Origins
ETS	Emission Trading System	SCF	Social Climate Fund
EnergieStG	Energy Duty Act	SDGs	Sustainable Development Goals
EU	European Union	SNG	Synthetic Natural Gas
EVs	Electric Vehicles	SSMS	Sustainable and Smart Mobility Strategy
EnWG	Energy Industry Act	TENT-T	Trans-European Transport Network
FTIP	Federal Transport Infrastructure Plan	UN	United Nations
ZPAP	Zero Pollution Action Plan		

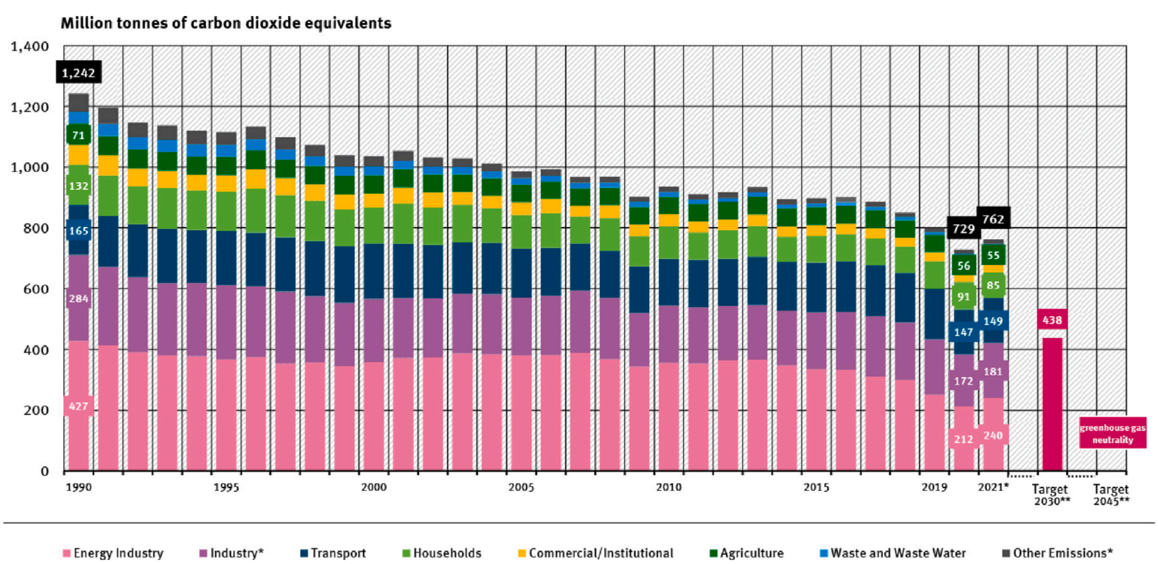
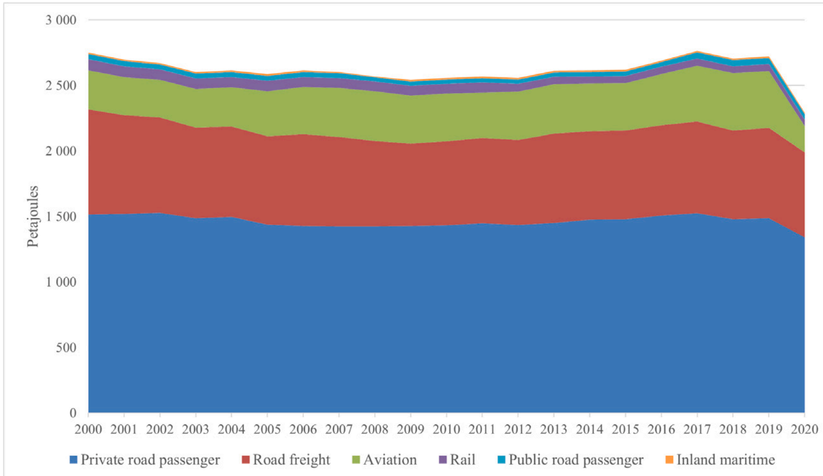


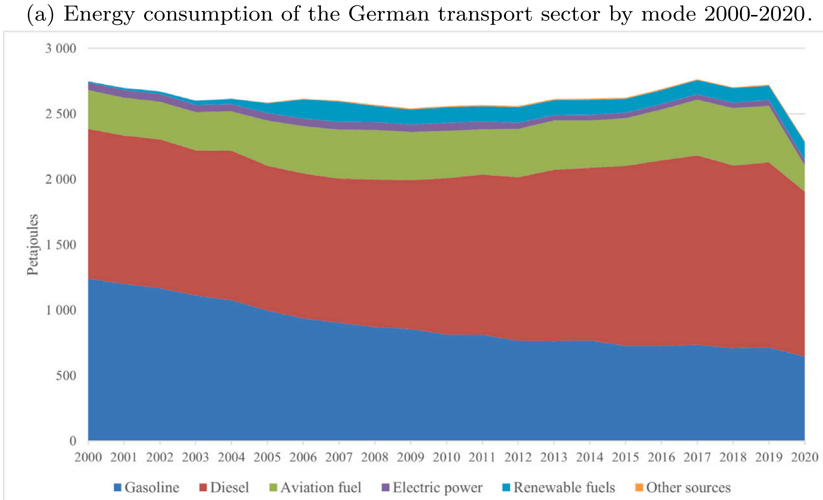
Fig. 1. GHG emissions in Germany by sector [9].

transport modes in Fig. 2(a) and fuel type in Fig. 2(b). According to Fig. 2(a), more than half of the energy consumption in each year and over 55% in total is related to private road passenger transport, accounting for 83% of the total energy consumption over the last two decades. Road freight transport is the second mode with high consumption and emission, where, compared to 2000, energy consumption has only slightly decreased. Considering the key role of aviation in recent decades, energy consumption in this sector has increased noticeably, accounting for over 13% of total energy consumption for two decades. In 2020, energy consumption in rail transport was successfully reduced through technological advances and electrification (roughly by 41% compared to 2000) as well as a likely impact of the pandemic. Energy consumption by public road travel and inland maritime have stayed roughly steady over the last two decades.

Similarly, Fig. 2(b) shows the share of energy sources in energy consumption. Gasoline and diesel have been the main energy sources, accounting for 33% and 47% of the total consumption. Moreover, jet fuel, electricity, and renewable fuels are further sources that were subject to an increasing trend towards 2020. Aviation jet fuel, which had accounted for a share of only 10% in 2000, increased to 16% in 2019. Conversely, the minor share of renewable fuels in the year 2000 (0.4%) has increased significantly, by 6% by 2020. According to the German Agency for Renewable Energy, in 2021, diesel and gasoline still accounted for over 93% of total fuel consumption [12]. Biofuels,



(a) Energy consumption of the German transport sector by mode 2000-2020.



(b) Energy consumption of the German transport sector by source 2000-2020.

Fig. 2. Status quo of energy consumption in the German transport sector (see [11]).

specifically biodiesel, bioethanol, and biomethane accounted for 4.2%, 1.4% and 0.1% of the total fuel consumption [12]. The remaining shares were divided among liquefied petroleum gas (LPG), compressed natural gas (CNG) and liquefied natural gas (LNG) [12]. The statistics indicate that the German transport sector is still dominated by fossil fuels, and the implemented policies have not led to a sufficient change in the fuel mix and corresponding emissions.

Over the past years, Germany has explored different pathways to mitigate its emissions through sustainable and cleaner alternatives such as hydrogen [13], electricity, [14], biofuels [15], or power-to-x (PtX) fuels [16,17]. However, the challenges related to production and efficiency, costs, and potential for meeting the targets of the national and EU regulatory frameworks have raised questions. For example, for road passenger transport, low- and zero-emission vehicles such as electric vehicles (EVs) (plug-in: PEV, battery: BEV) are currently considered the most promising alternatives to combustion engines [18,19]. However, their emission reduction potential significantly depends on the share of renewable electricity in the electricity mix [20–22]. In addition, battery price, battery capacity, charging time, and the availability of charging stations are remaining challenges hindering public acceptance [23,24].

In the case of biofuels, first generation biofuels continue to face challenges in terms of feedstock availability, food competition, land requirement, deforestation, and pollution [25,26]. To address these challenges, second- and third-generation biofuels, derived from non-edible resources and feedstock, are developed [27,28]. These fuels, however, have not yet reached market readiness. Moreover, hydrogen has long been discussed as a reliable and potential fuel for future transport systems; nevertheless, hydrogen energy intensity, hydrogen storage, hydrogen delivery, and hydrogen infrastructure build-up are considered its main challenges [29,30]. In addition to hydrogen, PtX fuels, also known as electricity-based fuels, renewable fuels of non-biological origins (RFNBOs) or e-fuels, have also been considered as potential alternatives to fossil fuels; however, they also face various technical and economic challenges [31–33]. Considering the dynamics in the transport sector and the complexity of market developments for new fuels, a sustainable transition in the transport sector requires well-designed and comprehensive policies which not only address technical aspects but also consider sustainability (economic, environmental and social) principles [34–36]. Various policies exist in the EU and Germany supporting the different fuel alternatives.

Both the EU and Germany have made serious efforts to implement policies that directly or indirectly address the defossilization in the transport sector. Given the complex nature of the policy landscape across multiple sectors, the establishment of a robust regulatory framework demands a meticulous strategic planning. This entails achieving coherence among a diverse set of policies. Such an ambitious endeavor necessitates a comprehensive evaluation of both current and proceeding policies for effective policy design based on a profound understanding of both the direct and indirect effects of policies.

The existing literature has aimed to address specific regulatory challenges regarding the sustainable transition of the transport sector through different fuel alternatives across different countries. However, most of these studies have addressed regulatory challenges from a very specific point of view such as the policy paradigm governing the diffusion of EVs [37], transport mode-specific analyses [38–40], specific policy-based impact assessment [41], or modern concepts in transport, e.g., policy analysis for carsharing [42]. However, no study has comprehensively investigated the structure of the regulatory framework relevant to the transition in the transport sector, considering direct and indirect effects across different policy fields. This, however, is urgently needed to increase policy effectiveness for the sustainable transition of the transport sector.

Using Germany as a case study, a mixed method approach was implemented to conduct a systematic policy analysis for the sustainable transition of the transport sector. Germany serves as an excellent example given both its long history in the energy transition as well as its strong role within the EU. The main objective of this research is to synthesize the complex policy landscape that directs and shapes the transport sector's transition to a sustainable sector. The main contributions of this study can be summarized as (I) comprehensive identification of policies across different policy fields affecting the sustainable transition in the transport sector, (II) development of a coding scheme to systematically account for key perspectives (challenges and opportunities in the sector) within policy analysis for climate neutrality in transport sector, (III) application of a mixed method approach to conduct a comprehensive policy analysis in order to understand the coherence among targeted policies, transport modes, and fuel alternatives, (IV) discussion of policy implications for addressing the identified gaps and conflicts. Accordingly, this study addresses the following research questions:

- Which policy fields shape Germany's future transport sector? What are the sub-policies and specific types of regulatory measures in each policy field?
- What are the main quantitative and qualitative policy targets related to structures and market developments in the transport sector, vehicle technologies, fuel alternatives, and emission standards?
- How coherent are policies across different policy fields?
- Which fuel alternatives are targeted within each policy?
- Which policies support which fuel alternatives? How coherent are policies in regulating a specific fuel alternative?
- What policy implications can be derived for the design of future roadmaps for the sustainable transition of Germany's transport sector?

To answer these questions, in Section 2, the framework for the policy review is devised. Section 3 discusses selected policies, their target transport modes, fuels, and emission reduction targets. Results of the policy review are presented in Section 4. Managerial and political implications as well as policy recommendations and limitations are discussed in Section 5. Finally, conclusions remarks are drawn in Section 6.

2. Conceptual and methodological framework

To provide a comprehensive overview of relevant transport policies, a systematic review is conducted through a semi-quantitative content analysis using content-based codes on policy documents to identify the relevant targets and potential coherence among policies. This section presents a new conceptual and methodological framework for reviewing policies related to transport and other policy fields with indirect effects on transport. Section 2.1 provides a general overview of the recent studies on policy analysis for the energy transition in transport. In Section 2.2, the data collection process is presented. Finally, Section 2.3 provides a review framework for the content-based analysis of the collected transport policies.

2.1. Policy reviews on the energy transition

Given the prominent role of the transport sector in GHG emissions and its profound impact on future trajectories, several studies have been undertaken. These studies are mostly focused on conducting policy analyses with the intent to promote the energy transition within the transport sector.

Rogge and Reichardt [43] developed an analytical framework for analyzing the policy mix governing the energy transition in Germany. Their primary findings underscore the critical importance of a well-designed policy mix in driving technological advancements and facilitating coherent policymaking within the complex regulatory framework. Fichert [44] used a text analysis to explore challenges and opportunities in German transport policies. Findings highlight various shifts in the German policy system towards monetary incentives for a modal shift in transport as well as a high focus on road and rail modes. Naegler et al. [45] analyzed twenty-six different scenarios for decarbonizing the energy sector in Germany. The results show several pathways for decarbonizing German transport through energy scenarios; however, no consensus scenario exists. Moreover, BEVs are identified as the promising option for decarbonizing the sector along with PtX fuels in potential future endeavors. Peiseler and Serrenho [46] analyzed four key EU and German policies aiming to decarbonize the road transport through EVs. The results reveal low effectiveness of current policies for using the full potential of EVs as well as improper subsidy and taxation systems. Thus, recommendations for a taxation system and adoption policy are provided to enhance the role of EVs in decreasing emissions in road transport. Löffler et al. [47] applied a global energy system model for the German energy transition, where computational results determined that electrification is currently the best alternative for the transport sector. Using the same approach, Hanisch [48] investigated relevant policy areas for the energy transition in the German transport sector. The results indicate that the energy system plays a significant role in the decarbonization of the transport sector considering energy consumption, emissions, and carbon pricing. Thus, a quick transition to a zero-emission transport sector with high focus on electrification is the main recommendation.

Beyond Germany, other countries also have shown serious efforts to move towards a low-carbon or zero-emission transport sector. For Southeast Asia, Bakkar et al. [49] studied transport policies of the ASEAN countries for the low-carbon transition. Although major changes are considered in various policies, serious decisions should be made in favor of renewable fuels to meet the climate change goals. For the USA, Stokes et al. [50] examined seven policies for the energy transition considering solar, wind, biofuels and EVs, where results show how policies fail regarding immature technologies and high costs. Malvestio et al. [51] used a systematic content analysis to investigate social and environmental challenges in transport policy making in Brazil based on twenty-one policies. For Vietnam, Shem et al. [52] applied a multi-criteria policy analysis to investigate the effectiveness of the Vietnamese policy framework for a low-carbon energy system. Results show that higher support is required for renewable energy policies in order to fulfill the goals. Kotilainen et al. [53] utilized an analytical approach to investigate the political mechanisms and policy mixes for the diffusion of EVs in the Nordic countries. Results indicate that a cross-sectoral policy mix is essential to enhance collaborative behavior for the electrification of the sector through different policy fields and institutions. Winkler et al. [54] presented a mathematical model to assess the effectiveness of policy options for the sustainable transition in the London urban mobility system. Findings reveal that a reduction in car use is equally crucial to emission reduction changes. Moreover, consensus sub-national and sector-based carbon budgets can play a significant role in improving current insufficient policies.

Considering the complexity of the transport sector, policy analysis on different transport modes can be quite different given the specific technical and regulatory characteristics. In this regard, Berker and

Böcher [55] applied a political process-inherent dynamics approach to facilitate instrument choice in aviation policies in Germany and the Netherlands. Their findings highlight importance of tax systems in both countries and the EU under the EU Emission Trading System (ETS) and the Energy Taxation Directive (ETD). In the same context, Proost [39] analyzed climate policies governing aviation related to carbon taxes, EU ETS, sustainable aviation fuel (SAF) blending mandates, and fuel efficiency standards. Considering the climate neutrality target for 2050, the study reveals a weakness of the Paris Agreement and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) due to their reliance on the will of the political majority. In addition, it is found that subsidies for R&D on fuel efficiency and new fuel alternatives would be beneficial for aiding the EU ETS in reducing intra-EU emissions. For maritime, Vierth et al. [40] investigated cost implications of the Fit for 55 package on the shipping sector of Sweden by introducing a new tax on marine fuel as well as including ships with specific weights in the EU ETS. Their results indicate that smaller ships would lead to lower emissions within the ETS, while introducing a tax system on marine fuel promotes using larger ships despite high fuel costs. Various studies have addressed regulatory aspects in road transport [41,56]. In one of the most recent studies, Haywood and Jakob [41] studied the role of the revised EU ETS within the Fit for 55 package for decarbonizing the European road transport. A carbon pricing scheme based on the EU ETS was adopted such that the study detects major issues with its current format including but not limited to, e.g., political backlash, unsuitability for low-income households, high economic burden on rich countries, reliance on correct implementation of the Effort Sharing Regulation (ESR), the ETD, the Directive on the Deployment of Alternative Fuels Infrastructure (AFIR), and directives on CO_2 emissions standards. To address these issues, reducing price volatility, increasing the size of the Social Climate Fund (SCF), and clarifying the exact penalties for violating countries are recommended as promising options to facilitate the decarbonization of road transport.

Although several studies have conducted policy analysis focusing on the transport sector, no study exists which comprehensively investigates policies across multiple sectors, different transport modes and fuel types with direct and indirect effects on the transport sector. Most of the recent studies focus on transport policies to analyze the regulatory dynamics governing the transport sector under specific circumstances or are limited to selected fuel alternatives and transport modes. However, indirect and cross-sectoral effects of different policy fields such as energy, agriculture, bioeconomy, fiscal, and circular economy also significantly shape the transport sector's transition to a sustainable one. Thus, understanding potential implications of the complex regulatory framework is of high significance for identifying inefficiencies and conflicts between policies and for deriving recommendations for future policy design. The current study, thus, for the first time, conducts a comprehensive cross-sectoral policy analysis using the sustainable transition in German transport as a case study to provide a more robust understanding of the coherence between policies regarding fuel economies for the 2030 and 2045 targets.

2.2. Data collection

For a systematic content-driven methodology, the selection of policy documents is an important step with high influence on the research outcomes. Considering the complexity of the transport sector and its multiple interdependencies with other sectors, the determination of selection criteria for the inclusion of relevant policies is highly critical.

In this regard, an early-stage goal was to identify policy fields with highest relevance to the sustainable transition in the transport sector. To do so, the official website of German ministries as well as the Council of the EU were considered as major sources to understand the current status quo of transport-related policies and potential policy fields relevant to decarbonizing the transport sector. For this purpose, the focus was on the EU Green Deal and the Fit for 55 package, the two main legal frameworks addressing climate change in the EU mandating new policies, revisions to previous policies, regulations, and initiatives. Based on the concerns discussed in the EU Green Deal and the Fit for 55 package, it was discerned that policies within the energy, fiscal, agriculture, bioeconomy, and the circular economy fields show strong relevance to the sustainable transition in the German transport sector. Therefore, the selection framework accounts not only for transport policies but also includes policies in the identified relevant policy fields, namely energy and fuel, climate change and environment, agriculture and land-use, sustainability, bioeconomy, circular economy, as well as infrastructure and physical systems.

A search framework was developed and used to identify and to select policies. To accomplish this objective, policies within each of the identified policy domains were systematically collected and subjected to a comprehensive content analysis. This rigorous examination made sure that each policy possessed the potential for direct or indirect influence on the evolution and advancement of the transport sector. Similar to the initial search of the policy fields, the official websites of the German ministries and the EU Council served as the primary platform for the selection of the policy documents. For German policies, all relevant documents were collected using online databases of ministries. For the EU's policies, the official website of the European Commission was used to collect the relevant documents. Within the search framework, all transport related policies in Germany and the EU are considered. In case of policies exerting an indirect impact on the transport sector, a systematic search procedure was employed. This procedure entails a comprehensive investigation of policies within a given sector, with a discerning focus on identifying policies that exhibit logical relevance and connectivity to the subject matter at hand. Such selected policies are then included in the analysis. In addition to the EU's English-language documents, German-language documents were also taken into account for comprehensive coverage. According to the procedure, a total of 44 policies with 121 documents were selected (Table 1).

2.3. Review framework

To conduct a systematic examination of policies within a multi-perspective system across numerous sectors, it is significant to employ a specifically developed content analysis framework. This framework serves as a crucial tool for scrutinizing policies, with the primary objective of discerning potential interrelated patterns aimed at facilitating the transition towards sustainability within the transport sector. To do so, the well-established data analysis approach of developing and assigning codes to text is adopted [57], which provides the opportunity to identify and compare key features and findings of scientific research with a combination of qualitative and quantitative techniques. For this purpose, the research questions defined in Section 1 are converted into the coding procedure.

The objectives for reviewing the collected policies are generally divided into four types concerning the conceptual impact of policies, their jurisdiction scale, transport modes, fuels, and their compliance with other policies. To operationalize these questions for the content analysis, appropriate codes were defined. Individual codes within various categories were developed to specify differences more precisely. This way, the sustainable transition in the German transport sector can be studied in different directions. Regarding transport modes, policies can employ different regulatory measures based on, e.g., historical emergence, economic requirement, the physical characteristics as well as technological capabilities. Thus, one category refers to transport modes including road, rail, aviation and maritime. Moreover, fuel alternatives and energy carriers play a significant role in the transition process. Therefore, one category was considered for fuel alternatives and energy carriers, where current fuel alternatives as well as future potential fuel alternatives are identified according to the EU energy market. As mentioned earlier, an important objective of the current study is

Table 1
Identified policies and corresponding number of documents.

Policy	# documents	Policy	# documents	Policy	# documents
BEHG	1	AFIR	6	LULUCF	1
BImSchG	1	EEG	1	MFS	1
Biokraft NachV	1	ESR	2	National Electromobility Plan	2
BioKraftQuG	4	EnergieStG	1	National Hydrogen Strategy	1
BioSt-NachV	2	Energy Efficiency Directive	3	NPM	1
Carbon Border Adjustment	3	EnWG	1	Paris Agreement	3
Circular Economy Action Plan	5	ETD	3	Renewable Energy Directive (RED) III	1
Clean Vehicle Directive	9	EU Bioeconomy	2	ReFuelEU Aviation	6
Climate Action Plan 2050	4	EU CAP	4	SDGs	1
Climate and Energy 2020–2030	1	TEN-T	1	SCF	2
CO_2 Emission for Cars and Vans	8	EU Low-Emission Mobility	3	EU Taxonomy for Sustainable Activities	4
CO_2 Emission for Heavy Vehicles	3	REPowerEU	2	Zero Pollution Action Plan	5
FTIP	1	FuelEU Maritime	3	EU ETS	4
Fuel Quality Directive	7	German Bioeconomy Strategy 2030	2	Innovation Fund (IF)	3
Sustainable and Smart Mobility Strategy (SSMS)	1	Net-Zero Industry Act (NZIA)	1		

Table 2
Coding scheme for analyzing policies based on targets, transport modes, fuel alternatives, and coherence with other policies.

Keywords		Transport modes	Fuel alternatives		Policies
Sustainability	Circular economy	Road	Kerosene: jet fuel	Natural gas: CNG, LNG	[Title]
Climate change	Energy	Rail	Fossil fuels: petroleum, gasoline, diesel	Biofuels: bioethanol, biomethane, biodiesel, biogenic, algae	
Fuel: fossil fuels, biofuels, alternative fuels, PtX	Transport	Aviation	Methanol	Methane	
Climate neutrality	Renewable energy	Maritime	Electricity (EVs): Battery	Renewable fuels: e-fuels, ammonia, ethanol, PtX (PtG and PtL), synthetic fuels, alternative fuels, sustainable aviation fuels (SAF)	
			LPG	Hydrogen: green hydrogen	

to review the current EU and German policies regarding both their direct and indirect effects on the transport sector as well as coherence among them. Hence, another category was defined based on the refers to the identified policies across all policy fields. Another category was defined to understand governing domain of cross-sectoral policies on significant challenges and concepts through several keywords related to the sustainable transition. Table 2 presents the developed coding scheme for the policy review. A summary of the methodology used in this study is presented in Fig. 3.

3. Policies: Roles and targets

Before applying the coding scheme for a comprehensive analysis, a further description of policies within different policy domains is advisable to understand the policy paradigm regulating the transport sector. Table 3 presents the selected policies and a summary of their jurisdiction scale, transport modes, target fuels, and their transport-related policy targets. For the considered policies, sixteen of the 44 policies enacted in Germany (DE), twenty-six policies passed by the EU and two global (GL) policies are considered. This section serves to present an overview of policies based on the main policy fields: transport, energy, fiscal, agriculture and bioeconomy, and circular economy.

3.1. Transport policies

In the 2010s, Germany passed several important transport policies aiming to address different challenges to meet the requirements of the 2030 emission reduction target. The German Federal Government's National Electromobility Development Plan, passed in 2009, is one of the initial and major policies targeting the potential role of EVs in implementing the sustainable transition within the transport sector through decreasing the dependence on oil, mitigating GHG emissions, and facilitating EV integration in the transport system. The National Electromobility plan aimed to expedite R&D in BEVs as well as measures to promote market introduction and diffusion to reach the goal of one million EVs by 2020 [58]. One year later, in 2010, the National Platform for Electric Mobility (NPE) was passed as a crucial stakeholder-based consultation process to support the National Electromobility Development Plan through technical developments, improving charging infrastructures, coordination of power grid integration, compliance to regulations and standards, enhancing recycling and by creating 30,000 additional jobs. In 2013, the Federal Government's Mobility and Fuel Strategy (MFS) was introduced. Unlike the National Electromobility plan and the NPE, which exclusively focused on EVs for road, rail and maritime, the MFS was introduced to highlight the importance of other fuel alternatives to replace combustion engine-based vehicles. Significant goals of the MFS strategy were diversification of the energy and fuel sources and increasing energy efficiency, a minimum of 10% reduction in final consumption by 2020 and a minimum of 40% reduction by 2050 (compared to 2005), mitigation of GHG emissions by at least 80% in 2050 (compared to 1990), and most importantly, increasing the share of renewable fuels to 18% of gross final energy consumption by 2020 and 60% by 2050 [59]. In 2016, Germany released a new and central transport policy known as the 2030 Federal Transport Infrastructure Plan (FTIP 2030). It covered about 1000 projects. Almost half of the funds were allocated to roads, 41.6% to railways, and 9.1% to waterways [60]. The FTIP 2030 generally aimed to enhance the safety through maintenance and modernization of infrastructures, facilitating mobility and ensuring the competitiveness of enterprises through increasing the reliability of operations, reducing

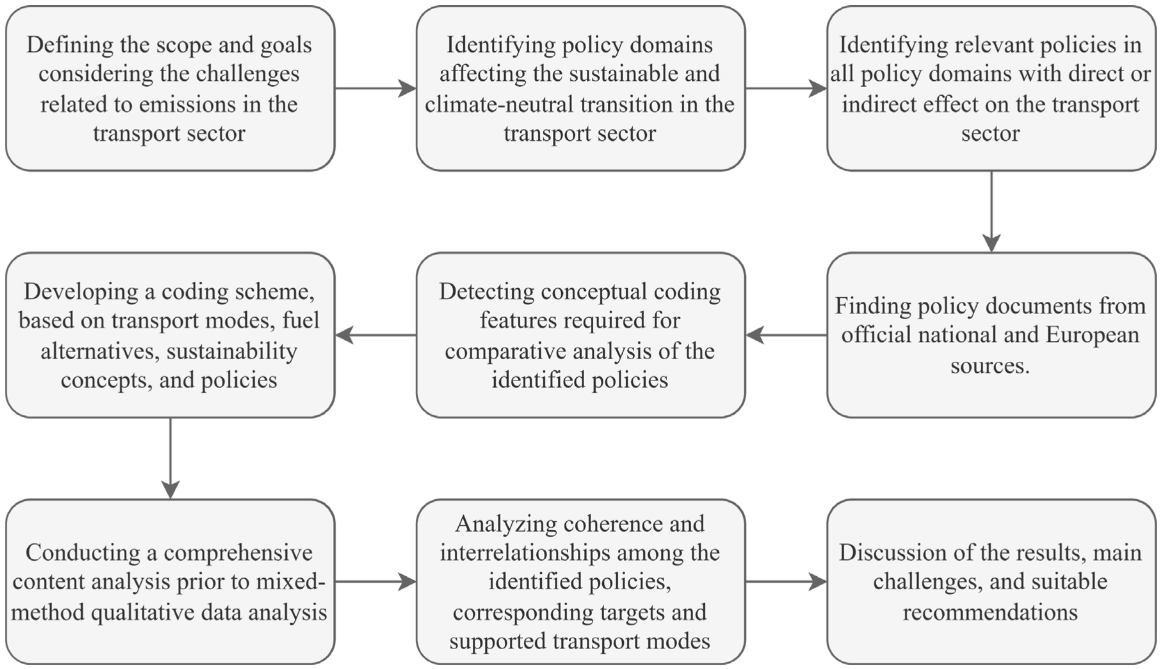


Fig. 3. A flowchart of the study.

GHG emissions and pollutants by low-carbon transport modes and fuels (mainly EVs and hydrogen), mitigating ecological footprints by restricting additional land take, and improving the quality of life through the prevention of noise pollution [60]. To extend the NPE's role in covering different pathways other than EVs, the German government updated the NPE and changed it to the National Platform for Future Mobility (NPM) to promote renewable fuels and digitalization.

Among the earliest undertakings of the EU on transport stands the DIRECTIVE 2009/33/EC on promotion of clean and energy efficient road transport vehicles. This directive, a pivotal milestone, was designed based on the primary objective of promoting environmentally friendly and energy-efficient road transport vehicles. It underscored the diverse range of alternative fuels, including electricity, hydrogen, natural gas, biomethane, biofuels, and PtX fuels for road transport [61]. Its primary goal was to set clear standards by stating the various rates at which the previously approved fuels were to be adopted and used. Simultaneously, the directive aimed to stimulate an environment of creativity and technical progress, with particular attention to technologies directed towards lowering emissions. Strong support of the growth of a healthy market ecosystem for clean and energy-efficient cars was also essential, as it created an atmosphere that was favorable for the widespread adoption of the advocated fuels and technologies. As DIRECTIVE 2009/33/EC was only concerned with road transport, the EU generalized its previous policies in 2016 and introduced a new policy called "A European Strategy for Low-Emission Mobility" addressing all four main transport modes. This strategy covered various fuels including electricity, hydrogen, natural gas (CNG, LNG), LPG, PtX fuels, biofuels, methane, methanol and ethanol as well as fossil fuels. The primary objectives of "A European Strategy for Low-Emission Mobility" can be summarized in three key aspects: efficient pricing, promoting multi-modal transport, and advancing zero-emission vehicles [62]. In the late 2010s, the EU launched new regulations for setting specific targets for road transport considering the role of fuels and reducing emissions through REGULATION (EU) 2019/631 on setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles, and REGULATION (EU) 2019/1242 on setting CO_2 emission performance standards for new heavy-duty vehicles [63,64].

3.2. Energy policies

Germany has played a pioneering role in addressing the adverse consequences of environmental exploitation, air pollution, and political instability in the context of climate change through its Energiewende. By the early 1990s, the awareness of global warming and its effects arose great motivation towards the decarbonization, which led to initial steps towards renewable energies [10]. In 2000, the coalition agreement of the Social Democratic party and the Green party marked a turning point in energy policy with a first approach of nuclear power phase-out and the establishment of the Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG). The peak of green and sustainable movements in Germany were in the 2010s when the Climate Action Plan was introduced to decrease GHG emissions until 2030 and move towards climate neutrality by 2050 (later changed to 2045 in 2021).

EU energy policies can be categorized into fuel policies, emission and pollution policies, and renewable energy policies. The DIRECTIVE 2018/2001 on the promotion of the use of energy from renewable sources also known as RED II, may be considered the key EU-level policy for supporting renewable energies [65]. The main goal of the RED is to promote the use of energy from renewable sources by at least 32% of the EU's gross final consumption and 14% in the transport by 2030. In this regard, the RED II aimed to highlight the roles of renewable fuels, renewable electricity, hydrogen, carbon-based fuels and specifically biofuels (with at least 3.5% share in final consumption of energy in transport) in achieving the binding targets for 2030 within all transport modes [65]. Recently, a revision of the RED II was introduced (RED III), which increased its previous targets by setting a minimum of 42.5% binding renewable energy target for 2030.

A notable policy in the field of fuel regulations is the EU Fuel Quality Directive (FQD), which was implemented for petrol, diesel, and biofuels in the road transport sector. Its primary objective was to achieve a minimum 6% reduction in emissions by 2020. This reduction was to be realized through the adoption of various cleaner energy sources, including biofuels, electricity, less carbon-intensive fossil fuels, and RFNBOs [66]. Recognizing the limited coverage of the FQD in addressing maritime and aviation, the EU introduced two important initiatives as part of the Fit for 55 package: FuelEU Maritime and ReFuelEU Aviation. The ReFuelEU focuses on promoting PtX fuels and advanced biofuels as well as hydrogen as potential fuel alternatives for climate-neutral aviation. Important goals of the ReFuelEU Aviation can be summarized as CO_2 reduction in line with the 2030 and 2050 targets and high-scale production of the renewable fuels [67]. Alternatively, the FuelEU Maritime addresses market barriers for development of the hydrogen, renewable and carbon-based fuels to increase share of the non-fossil sustainable fuels to 86% and 88% by 2050 for GHG reduction in maritime [68].

Germany has included biofuels in the mitigation of GHG emissions in the transport sector for a long time. It has passed the Biofuel Quota Act (BioKraftQuG) in 2006, which ensures a minimum target share of biofuels (biodiesel and bioethanol) as well as providing tax relief for products containing biofuels. The Ordinance on the Generation of Electricity from Biomass, known as the Biomass Ordinance (BiomasseV), is one of the important policies defining the biomass and sustainable requirements for the power generation. However, the BiomasseV does not explicitly discuss the utilization of electricity in transport [69]. The Biomass Electricity Sustainability Ordinance (BioSt-NachV) and the Biofuel Sustainability Ordinance (Biokraft NachV) are two further key policies to ensure environmental sustainability of biofuels and electricity generation from biomass under the EEG [15].

3.3. Agriculture, bioeconomy, and circular policies

Although agriculture, ecology and environment, as well as bioeconomy policies may seem of less relevance to the sustainable transition in the transport sector, they play a crucial role for specific fuels including biofuels and PtX fuels. The EU Green Deal, passed in 2020, can be considered as one of the most important policy packages in this regard. The Green Deal is a set of initiatives targeting climate neutrality in the EU by 2050, in accordance with goals in various policy areas such as clean energy, sustainable mobility, industry, farming, building and renovation, biodiversity, finance, and most importantly GHG reduction by 50%–55%. The EU Green Deal can be considered as one of the most recent policy packages promoting renewable fuels, specifically EVs, biofuels, and PtX fuels [70–72].

On the global scale, the Land Use, Land-Use Change and Forestry (LULUCF) is a well-known policy, defined by the United Nations Climate Change Secretariat to decrease GHG emissions related to direct human-induced land-use change and forestry activities. Although the LULUCF does not directly affect the transport sector, its goals for restricting land-use changes have significant effects on biofuels production. At the EU-level, the EU Common Agricultural Policy (CAP) counts as a key policy for the sustainable transition in the agricultural sector. Similar to the LULUCF, the CAP also affects the transport sector indirectly by its requirements on supporting the production and use of bioenergy in rural areas, establishing perennial energy grasses, and reducing the possibility of producing energy crops for biofuels production on agricultural land [73,74].

Given the role of biomass as the feedstock for biofuels production and electricity generation, bioeconomy has emerged as a crucial concept to support the use of biomass in the production of goods and services as well as energy. The EU Bioeconomy Strategy is the main strategy addressing bioeconomy practices. Although the EU Bioeconomy directly deals with biomass-based products, it also aims to support the replacement of fossil fuels by renewable fuels and support infrastructures for bioenergy. Biofuels and electricity generation from biomass are main transport-related topics addressed in the EU Bioeconomy Strategy. Germany, as a pioneer in the bioeconomy, passed the National Bioeconomy Strategy 2030 in 2020. In accordance with the EU Bioeconomy Plan, the German Bioeconomy Strategy also supports biofuels, specifically biodiesel, bioethanol and algae production in Germany. Moreover, the German Bioeconomy Strategy also promotes biomass as feedstock in the production of PtX fuels [75]. For a cleaner and more competitive green EU, the EU also adopted a Circular Economy Action Plan (CEAP) in 2020 as a part of the Green Deal for climate neutrality in 2050. Highlighting the importance of recycling, the CEAP deals with the recycling and reusing of EVs' batteries as well as valuable materials from batteries [76].

3.4. Fiscal policies

Financial systems are an integrated part of the German and the EU legislation for GHG reduction. Emission pricing, specifically carbon pricing is one of the critical mechanisms for controlling emissions. To control and limit the utilization of fossil fuels, the EU has passed key policies, the EU ETS, the Carbon Border Adjustment (CBA) Mechanism and the ESR. The ESR aims to decrease GHG emissions by 30% by 2030, improve energy efficiency in heavy duty vehicles and support renewable policies in the context of the RED. Unlike the CBA which only indirectly affects the transport sector, the ESR directly influences the transport sector covering both fossil fuels and renewable fuels [77]. The EU ETS plays a more general role and regulates the emission budget in all sectors including transport, considered most recently in the last revision made in 2021.

Moreover, the ETD has established a framework for the taxation of electricity, electric products, aviation fuels, as well as heating fuels. The ETD is an important part of the Green Deal with the aim of protecting the environment and the climate and contributing to the current targets for 2030 and future climate neutrality target in 2050. The ETD empowers member states to design their own tax systems, and it proposes several exemptions for renewable energy sources and electricity for public transport. Along with the ETD and within the Fit for 55 package, the EU extends its taxation to the building and road transport sectors through the SCF. The SCF acts as a facilitator for future investments to increase the uptake of zero- and low-emission mobility. In more general words, the fund is considered to tackle social and distributional challenges from the sustainability transition, necessary to combat climate change by reducing social consequences of road transport [78]. For better and more reliable investment decisions, the EU proposed a classification system known as the EU taxonomy for sustainable activities (Regulation 2020/852) under the EU Green Deal that aims to clarify under which circumstances investments are environmentally sustainable based on climate change mitigation, climate change adaptation, the circular economy, pollution, effect on water, and biodiversity aspects [79].

Table 3 presents an overview of the identified policies, their policy level (DE, EU, or GL), regulating transport modes, addressing fuel alternatives, and main targets relevant to transport.

4. Policy review: Results and implications

Increasing concerns about the insufficient reduction of GHG emissions and potential pathways towards climate neutrality in the transport sector are reflected in the growing number of policies across multiple sectors. By approaching 2030, understanding the impact of current policies on meeting the defined targets is of high significance for shaping the future of the German transport sector. Although Table 3 presents a summary of the identified policies, an in-depth analysis is required to explore the coherence among policies and their support for sustainable transport.

Current policies in both Germany and the EU are strategically formulated to withstand existing challenges in the transport sector. These policies can be dissected and analyzed from several distinct perspectives, encompassing critical sectors such as energy, transport, renewable energy, climate change, sustainability, fuel alternatives, climate neutrality, and the principles of the circular economy. Understanding the coherence between policies in addressing different concerns regarding the sustainable transition can help to detect whether a policy actually addresses an up-to-date challenge in transport sector. The occurrence frequency of defined keywords are determined accordingly. Occurrence frequencies of the relevant terms are as follows: "Energy" (10 593), "Transport" (9943), "Renewable energy" (1198), "Climate change" (1645), "Sustainability" (5357), "Fuel" (9751), "Climate neutrality" (728), and "Circularity" (900) are, respectively. Results indicate

Table 3
A summary of the selected policies.

Policy	Scale	Mode	Focus	Main topic-related goals
FTIP 2030	DE	Road, rail, maritime	Electricity, EVs (PEV, BEV) hydrogen	(1) Facilitating mobility in passenger transport, (2) enhancing transport safety, (3) reducing GHG emissions, (4) limiting the impact on nature and the landscape, (5) improving the quality of life including the noise.
Trans-European transport Network (TEN-T)	EU	Road, rail, maritime, aviation	Electricity hydrogen, natural gas renewable fuels	(1) Building and upgrading transport infrastructure to ensure efficient and multi-modal travel across the EU. (2) promoting integration of renewable fuel alternatives through developing required infrastructures for refueling and recharging. (3) improving the transport network in terms of resilience to withstand climate change and other natural hazards.
A European Strategy for Low-Emission Mobility (EU Low-Emission Mobility)	EU	Road, maritime, rail, aviation	Electricity, hydrogen, natural gas (CNG, LNG), liquefied Petroleum gas (LPG), synthetic fuels, biofuels, methane, methanol and ethanol, Diesel, Gasoline	(1) Supporting digital mobility, (2) fair and efficient pricing in road transport, (3) promoting multi-modality transport, (4) effective framework for low-emission alternative energy for transport, (5) standardization and inter-operability for electro-mobility, (6) moving towards zero-emission vehicles, (7) implementing the single market and the digital single market strategy including free flow of data and standardization policy.
Promotion of clean and energy efficient road transport vehicles (Clean Vehicle Directive)	EU	Road	Electricity, hydrogen, natural gas, biomethane, biofuels, synthetic or paraffinic fuels	(1) For light-duty vehicles, member states must reach a share ranging from 16% to 35%, which is the same for the 2025 and for the 2030, (2) for buses, individual member state targets range from 29% to 50% (2025) and from 43% to 75% (2030), and for trucks from 6% to 10% (2025) and from 7% to 15% (2030), (3) innovation in new technologies to lower vehicle CO_2 emissions, (4) promoting the market for clean and energy-efficient road transport vehicles.
Directive on setting emission performance standards for new light commercial vehicles (CO_2 emissions for cars and vans)	EU	Road	Alternative fuels, LPG, CNG, ethanol, fossil fuels	(1) Cars: 95 g CO_2/km: 15% reduction from 2025 on and 37.5% reduction from 2030 on, (2) Vans: 147 g CO_2/km: 15% reduction from 2025 on and 31% reduction from 2030 on.
Directive on determination of the CO_2 emissions and fuel consumption of heavy-duty vehicles (CO_2 emission for heavy vehicles)	EU	Road	Alternative fuels, LNG, electricity	(1) CO_2 emission reduction for the reporting periods of the year 2025 onward by 15%, (2) CO_2 emission reduction for the reporting periods of the 2030 onward by 30%.
German Federal Government's National Electromobility Development Plan	DE	Road, rail, maritime	Electricity	(1) Meeting national and EU climate protection targets, (2) improving supply security in the long term using renewable sources, (3) improving power grid efficiency through utilization of information technologies, (4) making Germany as a lead market for electromobility, (5) supporting German industries through production of cell and battery systems.
MFS	DE	Road, maritime, rail, aviation	Petrol, Ethanol, LPG, Diesel, Kerosene, Methane, Hydrogen, Electricity	(1) Diversification of energy sources in transport, (2) increasing in energy efficiency through innovative technologies, (3) decreasing final energy consumption by 10% by 2020 and by 40% by 2050 (baseline = 2005), (4) reducing GHG emissions to be reduced by 40% by 2010 and at least 80% by 2050 (baseline = 1990), (5) increasing share of renewable energies for 18% of gross final energy consumption by 2020 and 60% by 2050.
NPE & NPM	DE	Road, maritime, rail, aviation	Electricity, alternative fuels	(1) Becoming international lead supplier and lead market for electric mobility by 2020, (2) reaching one million EVs on German roads by 2020, (3) ensuring and increasing employment within the electric mobility.

(*continued on next page*)

that "Energy" and "Fuel" are the two most frequently addressed keywords across all policies. The SDGs, the Climate Action Plan 2050, the AFIR, and the EU Low-Emission Mobility are central policies with highest frequency of occurrence of the defined keywords. In this regard, "Fuel" and "Transport" with $n_{occurrence} = 2020$ and $n_{occurrence} = 1112$ are the two most frequently discussed directions in the AFIR. "Sustainability" holds higher share compared to other keywords in the SDGs with $n_{occurrence} = 2157$.

To understand the interconnections of keywords, Fig. 4 depicts the coherence network based on the frequencies of occurrence in a policy. In the graph, edges among the keywords and their thickness represent relations between keywords (whether two keywords are discussed in a policy), and the degree of how frequent two keywords are discussed together in a single policy, and font size shows the number of frequency. The distance between the keywords signifies their frequency of co-occurrence in the same documents. When two keywords are in close proximity, it suggests that they are commonly mentioned together in the majority of policies. Conversely, a larger distance indicates that these two keywords are less frequently mentioned together and occur in a relatively lower number of policies. These findings provide useful implications on how key challenges regarding the sustainable transition are discussed in policies and enables to identify whether a key challenge is addressed in less cohesion to others.

According to Fig. 4, keywords are classified into three major clusters based on their relevance to each other. "PtX", "Biofuels" and "Alternative Fuels" are classified as one and "Energiewende" as another cluster

Table 3 (*continued*).

BioKraftQuG	DE	–	Biofuels	(1) Setting a minimum target level for biofuels by 2020, (2) granting tax relief for energy products containing biofuels.
BioSt-NachV	DE	–	Biofuels	(1) To ensure that liquid biomass used for electricity production and paid for under the EEG will comply with binding ecological and social sustainability standards.
Sustainable-biofuels ordinance (Biokraft NachV)	DE	–	Biofuels	(1) To ensure the environmental sustainability of biofuels (cultivation, reducing GHG emissions).
EU Bioeconomy	EU	–	Biofuels, bio-based electricity	(1) Reducing dependence on non-renewable resources including replacing fossil fuels, (2) mitigating and adapting to climate change, (3) supporting new infrastructures and instruments for bio-energy.
German Bioeconomy Strategy 2030	DE	Road, maritime, rail, aviation	Biofuels (biodiesel, Algae, bioethanol), synthetic fuels	(1) Using climate-neutral production to achieve the 1.5 °C goal, (2) reducing the pressure on land for product production including renewable energy, (3) enabling an internationally competitive and sustainable use of biomass for energy self-sufficiency.
LULUCF	GL		–	(1) Ensuring an EU net removal target of −310 Mt CO_2 by 2030 with national LULUCF targets for each member state.
EU CAP	EU	–	Biofuels	(1) Supporting the production and use of bioenergy in rural areas through building biogas plants, planting trees for short-rotation, establishing perennial energy grasses, etc., (2) minimizing the risk of biofuels production on agricultural land (indirect land use change).
CEAP	EU	Road	Electricity (BEVs), biofuels, fossil fuels	(1) Supporting rules on recycled content and measures to improve the collection and recycling rates of all batteries, ensuring the recovery of valuable materials and providing guidance to consumers, (2) addressing non-rechargeable batteries with a view to progressively phasing out their use where alternatives exists, (3) improving sustainability and transparency requirements for batteries considering the carbon footprint of battery manufacturing, ethical sourcing of raw materials, security of supply, facilitating reuse and re-purposing and recycling.
German Sustainability Plan — SDGs	DE	Road, maritime, rail, aviation	Green hydrogen, renewable fuels: biofuels and electricity-based fuels, electricity, fossil fuels	(1) SGD 3.2.a: reducing emissions of air pollutants, (2) SDG 7.2.a: increasing share of renewable energies in gross final energy consumption, (3) SDG 7.2.b: increasing share of electricity from renewable energy sources in gross electricity consumption, (4) SDG 11.1.a: expansion of settlement and transport area, (5) SDG 11.2.a: decreasing final energy consumption in goods transport, (6) SDG 11.2.b: reducing final energy consumption in passenger transport, (7) SDG 11.2.c: Accessibility of medium- sized and large cities by public transport, (8) SDG 12.3.b: reducing CO_2 emissions of commercially available vehicles in the public sector, (9) SDG 13.1.a: decreasing GHG emissions, (10) SDG 13.1.b: supporting international climate finance for the reduction of GHG and adaptation to climate change.
SCF	EU	Road	Fossil fuels, alternative fuels	(1) Supporting finance measures and investments to increase the uptake of zero- and low-emission mobility and transport.
Innovation Fund (IF)	EU	Road, maritime, rail, aviation	Green hydrogen, renewable fuels, renewable electricity, biofuels	(1) Accelerating the deployment of breakthrough technologies that can significantly reduce GHG emissions. (2) supporting the transition to renewable energies and advanced storage technologies. (3) boosting the competitiveness of the EU market in low-carbon technologies. (4) financing risky demonstration projects through different funding options.
ETD	EU	Road, maritime, rail, aviation	Fossil fuels, biofuels, RFNBOs, electricity, hydrogen, synthetic fuels	(1) Providing an adapted framework contributing to the EU 2030 targets and climate neutrality by 2050 in the context of the EU Green Deal. This would involve aligning taxation of energy products and electricity with EU energy, environment and climate policies thus contributing to the EU efforts to reduce emissions, (2) providing a framework that preserves and improves the EU internal market by updating the scope and the structure of rates as well as by rationalizing the use of tax exemptions and reductions, (3) preserving the capacity to generate revenues for the budgets of the member states.

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placed far from each other. The third cluster includes the remaining keywords. In this context, the notable thickness and proximity of edges between all keywords, particularly "Fuel", "Transport", and "Energy", highlight a strong interconnectedness among themselves, indicating high co-occurrence in relevant policies. This suggests a robust linkage between policies addressing the multi-aspect challenges in the transport sector, specifically related to the drawbacks associated with fossil fuels. "Renewable Energy" as an important pathway for decarbonizing the transport sector also shows high coherence with "Fuel", "Transport", and "Energy", which is reflected in real-life developments of EVs and renewable fuels. While it is evident that all examined keywords exhibit strong interconnections, the coherence between "Climate Neutrality" and the keywords in the light blue cluster appears to be more pronounced rather than with circularity. This observation underscores the influence of relevant policies on the advancement of climate neutrality, particularly within the context of the light blue cluster. The relationship between circularity and climate neutrality appears to be peripheral, as indicated by the substantial distance and thin edge between these two

Table 3 (*continued*).

Fuel Emissions Trading Act (BEHG)	DE	–	Fossil Fuels	(1) Pricing of emissions in the transport and heating sector that are not covered by the ETS in order to achieve national climate targets.
EU Taxonomy for Sustainable Activities (EU Taxonomy)	EU	Road, maritime, rail, aviation	Renewable fuels, electricity	(1) Establishing an internal market that works for the sustainable development of Europe in all sectors including transport, (2) supporting climate-neutral mobility to achieve climate neutrality, (3) producing clean and efficient fuels from renewable or carbon-neutral sources, (4) establishing criteria for environmentally sustainable economic activities in all sectors including transport to reduce its 26% contribution to GHG emissions, (5) increasing the use of environmentally safe carbon capture and utilization and carbon capture and storage technologies that deliver a net reduction in GHG emissions.
EU ETS	EU	Aviation, maritime and road (potential)	Fossil fuels, RFNBOs, electricity, hydrogen, natural gas (LNG)	(1) GHG emission reduction based on a cap system to meet relevant EU climate change targets, (2) development of economic incentives for different industries to transit to low-emission energy carriers, (3) supporting low-carbon technologies through carbon pricing, (4) harmonization and linkage to foster efforts of all EU member states to tackle GHG emissions.
CBA	EU	–	Fossil Fuels	(1) Addressing the risk of carbon leakage to fight climate change by reducing GHG emissions, (2) contributing to the provision of a stable and secure policy framework for investments in low or zero carbon technologies, (3) ensuring that domestic production and imports are subject to similar level of carbon pricing, (4) encouraging producers in third countries who export to the EU to adopt low carbon technologies.
AFIR	EU	Road, maritime, aviation	Alternative fuels, electricity, biomethane, hydrogen, LNG, CNG, LPG, ammonia	(1) Installing electric recharging infrastructure for light-duty and heavy-duty EVs, (2) installing hydrogen refueling infrastructure of road vehicles, (3) opening LNG infrastructure for road transport vehicles, (4) supporting shore-side electricity supply in maritime and inland waterway ports, (5) increasing supply of LNG in maritime ports, (6) promoting supply of electricity to stationary aircraft.
Federal Immission Control Act (BImSchG)	DE	Road, maritime, rail, aviation	Fossil Fuels	(1) Mitigating harmful effects of fossil fuels by constructions and installations, sustainable of fuels and vehicles.
Energy Duty Act (EnergieStG)	DE	–	Fossil fuels, biofuels	(1) Ensuring the taxation of the fuels, (2) tax exemption of sustainable fuels.
Climate Action Plan 2050	DE	Road, maritime, rail, aviation	Hydrogen, RFNBOs e.g. PtX (out of hydrogen using renewable electricity), biogenic fuels, 2nd generation biofuels	(1) Increasing the proportion of electricity generated from renewable sources to at least 80%, (2) reducing primary energy consumption by 50%, (3) reducing final energy consumption in transport by 40%, (4) funding electric mobility, (5) extending cycling and walking, (5) expanding rail transport, (6) implementation of digitization in transport, (7) expanding use of electricity-based fuels in aviation and maritime.
Paris Agreement	GL	–	Fossil Fuels	(1) The Paris Agreement, in seeking to strengthen the global response to climate change, reaffirms the goal of limiting global temperature increase to well under 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees.
REPowerEU	EU	Road, maritime, rail, aviation	Green hydrogen, Electricity, RFNBOs, biomethane	(1) Increasing EU's 2030 target to 45% renewables in the EU mix, up from the current target of 40% (an additional 169 GW to the Fit for 55 target of 1067 GW), (2) accelerating the roll-out of PV energy, with a dedicated EU Solar Energy Strategy, aiming to deploy over 320 GW of new solar PV by 2025, and almost 600 GW by 2030, (3) speeding up renewables' permit to minimize the time for the roll-out of renewable projects and grid infrastructure improvements, through the revising of the RED, (4) increasing the EU's 2030 binding energy savings target to 13% (up from 9% in the EED), (5) aligning sub-targets for RFNBOs in the EU and finalize hydrogen market package.
EEG	DE	–	Electricity	(1) Increasing the share of electricity generated from renewable energy sources to at least 80% of gross electricity consumption by 2050, (2) increasing the share of renewable energy sources in terms of total gross final energy consumption to at least 18% by 2020.

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keywords. This distance suggests that they are mentioned together in a relatively limited number of policies. This observation can be explained by the fact that, at the moment, the EU's main and only policy for recycling and remanufacturing EV batteries is the CEAP. Given the nature of this policy, it does not focus as explicitly as other policies on the goal of carbon neutrality due to lack of connection to other sectors. Three well-known renewable fuels are located very close to each other in the green cluster showing high coherence and co-occurrence in relevant policies. Moreover, these keywords are at a medium distance to "Renewable energy" and long distance to "Transport" and "Sustainability", showing that discussions on the utilization of renewable fuels for transport occur in policies specifically on renewable energy. The noticeable distance between the green cluster and central keywords in the light blue cluster stems from the lack of policies addressing these fuels.

For a deeper analysis of synergies between policies, analyzing coherence of policies is of high importance. One effective means of measuring policy coherence is by examining the presence and frequency of policy references within their respective documents. Accordingly, the policies

Table 3 (*continued*).

Zero Pollution Action Plan (ZPAP)	EU	Road, maritime, rail, aviation	Synthetic fuels & biofuels	(1) Reducing health impacts (premature deaths) of air pollution by more than 55%, (2) decreasing the share of people chronically disturbed by transport noise by 30%, (3) protecting the EU ecosystems where air pollution threatens biodiversity by 25%.
FQD	EU	Road, maritime	Petrol, diesel and biofuels	(1) GHG reduction by 6% by end of 2020 through the use of biofuels, electricity, less carbon intense fossil fuels, and renewable fuels of non-biological origin (e.g., e-fuels) or a reduction of upstream emissions (such as flaring and venting) at the extraction stage of fossil feedstocks, (2) GHG reduction by an indicative additional target of 2% by end of 2020 through the supply of energy for transport or the use of any technology (including carbon capture and storage) capable of reducing life cycle GHG emissions per unit of energy from fuel or energy supplied.
ESR	EU	Road	Fossil fuels, biofuels, electricity, hydrogen, LNG, CNG	(1) Reducing 30% of GHG emissions in non-ETS sectors by 2030, (2) improving average annual energy efficiency for new fossil and hybrid heavy duty vehicles by 1.5% between 2010–2030 and 0.7% between 2030–2050, (3) supporting renewables policies to achieve 27% target, reflected by RES values applied in electricity, heating and cooling and transport sectors.
FuelEU Maritime	EU	Maritime	Biofuels, RFNBOs, carbon based fuels	(1) Ensuring that renewable and low-carbon fuels represent between 6% and 9% of the international maritime transport fuel mix in 2030 and between 86% and 88% by 2050 to contribute to the EU economy-wide GHG emissions reduction targets.
Energy Efficiency Directive (EED)	EU	Road, maritime, rail, aviation	Alternative fuels, electricity (out of biomass), fossil fuels	(1) Promoting more efficient vehicles, a modal shift to cycling, walking and collective transport, and urban planning that reduces demand for transport. In addition, schemes which accelerate the uptake of new, more efficient vehicles or policies fostering a shift to better performing fuels that reduce energy use per kilometer, (2) improving energy efficiency throughout the full energy chain, including energy generation, transmission, distribution and end-use, will benefit the environment, improve air quality and public health, reduce GHG emissions, improve energy security by reducing dependence on energy imports from outside the EU.
A Policy Framework for Climate and Energy in the Period from 2020 to 2030 (Climate and Energy 2020–2030)	EU	Road, maritime, rail, aviation	Alternative fuels, biofuels (first, second, third generations)	(1) Reducing GHG emissions to 24% and 32% lower than in 1990 by 2020 and 2030, respectively (reducing GHG emissions from the transport sector by 60% by 2050 compared to 1990 and by around 20% by 2030 compared to emissions in 2008.), (2) rising the share of renewable energy to 21% in 2020 and 24% in 2030.
RED III	EU	Road, maritime, rail, aviation	Biofuels, RFNBOs, renewable electricity, carbon based fuels, hydrogen	(1) Ensuring that the share of renewable energy within the final consumption of energy in the transport sector is at least 14% by 2030, (2) supporting advanced biofuels and biogas produced from the feedstock as a share of final consumption of energy in the transport sector shall be at least 0.2% in 2022, at least 1% in 2025 and at least 3.5% in 2030, (3) ensuring a minimum of 42.5% share of renewable energies in 2030.
Energy Industry Act (EnWG)	DE	–	Electricity, biogas, hydrogen, renewable energies	(1) Ensuring free pricing, (2) ensuring a sustainable, efficient, flexible and grid compatible production of electricity, (3) guaranteeing competition on the electricity and gas market. (4) regulation of hydrogen grids, (5) increasingly base energy and gas supply on renewable energies.
Net-Zero Industry Act (NZIA)	EU	–	Natural gas, biofuels, hydrogen electricity	(1) Supporting the development of zero-emission vehicles, including EVs and hydrogen-based vehicles. (2) boosting production of other clean technologies to facilitate the green transition. (3) supporting producing sustainable batteries for EVs. (4) boosting the establishment of hydrogen production and storage facilities.

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are classified into four different clusters (Fig. 5) based on the frequency of occurrence in policy documents. The font size signifies the cumulative frequency of references, where a larger font size corresponds to a greater number of mentions. Closeness of two policies indicates high frequency of occurrence in same policies. Ultimately, the thickness of the links reflects the degree of coherence, with thicker links indicating strong coherence and thinner links signifying a weaker level of coherence.

According to Fig. 5, EU-level policies within the EU Green Deal and the Fit for 55 package such as EU ETS, ESR, ETD, and RED along with the EEG and the Paris Agreement are categorized into the same category (dark blue cluster), hereafter named the Energy & Emission category. While, transport-related policies in the EU along with the FQD, TEN-T, AFIR and SSMS are clustered in another category (green cluster), hereafter, called the Transport category. The CEAP, CAP, LULUCF, bioeconomy, and SDGs are placed in the same cluster (yellow cluster), hereafter, referred as the Sustainable Resource category. The remaining policies including most of the German policies as well as global policies are categorized in a separate cluster (light blue cluster), the Eco-energy and Transport category.

A look at the Energy & Emission category reveals the key roles of the Paris Agreement, RED III and ETS. The EU Green Deal's emission reduction target is reflected in the ETS, which is highly aligned with the Paris Agreement for 2030. Upon closer examination of the ESR and its alignment with other pivotal policies, it becomes evident that substantial endeavors have been undertaken to reduce emissions from fossil fuel-dependent road transport. The Fig. 5 highlights the importance of the EU ETS with the largest font size denoting the highest frequency across all policies. The ETS regulates the emission pricing and therefore play a significant role in empowering most of the policies dealing with

Table 3 (*continued*).

ReFuelEU Aviation	EU	Aviation	Second and third generation biofuels, RFNBOs: e-kerosene, hydrogen, batteries	(1) Reducing aviation emissions in line with the 2030 and 2050 climate objectives of the EU by transitioning away from fossil jet fuel and tap into the high decarbonization potential of SAFs through establishing a competitive SAF market, while at the same time ensuring a level playing field on the aviation market, (2) achieving large-scale production of sustainable aviation fuels in the EU with high decarbonization potential, and ensuring adequate levels of supply to the aviation sector at competitive costs, (3) maintaining a level playing field in the aviation market and achieving a gradual and continuous uptake of SAF with high decarbonization potential by the aviation sector at lower prices than estimated today and based on the uniform.
SSMS	EU	Road, maritime, rail, aviation	Kerosene, jet fuel, SAF, EVs, fossil fuels, methane, natural gas: LPG, LNG, CNG, biofuels, renewable fuels, ammonia, PtX, hydrogen	(1) Aiming for a minimum of 90% reduction in transport's emissions by 2050. (2) increasing the adoption of EVs and ensuring development of infrastructures. (3) promoting use of biofuels, PtX fuels, and other synthetic fuels to replace fossil fuels. (4) supporting digitization and automated transport vehicles.
National Hydrogen Strategy	DE	Road, maritime, rail, aviation	Hydrogen	(1) Allowing use of green hydrogen for the production of fuels to be counted towards GHG reduction with a target for electrolysis capacity of minimum 10 GW by 2030, (2) designing the legislation transposing the RED into national law in such a way that green hydrogen can be used for the production of fuel as soon as possible, (3) production of electricity-based jet fuel using green hydrogen, (4) market activation to boost investments in hydrogen-powered vehicles (light and heavy-duty vehicles, buses, trains, inland and coastal navigation, car fleets), (5) construction of a needs-based refueling infrastructure for vehicles including heavy-duty road haulage vehicles, vehicles public transport and in local passenger rail services, (6) establishment of a competitive supply industry for fuel-cell systems including an industrial basis for large-scale fuel-cell stack production for vehicle applications, exploration of the possibility of creating a center for hydrogen technology and innovation to facilitate the emergence of vehicle platforms for fuel-cells and support for the establishment of a fuel-cell systems supplier for logistics/intra-logistics.

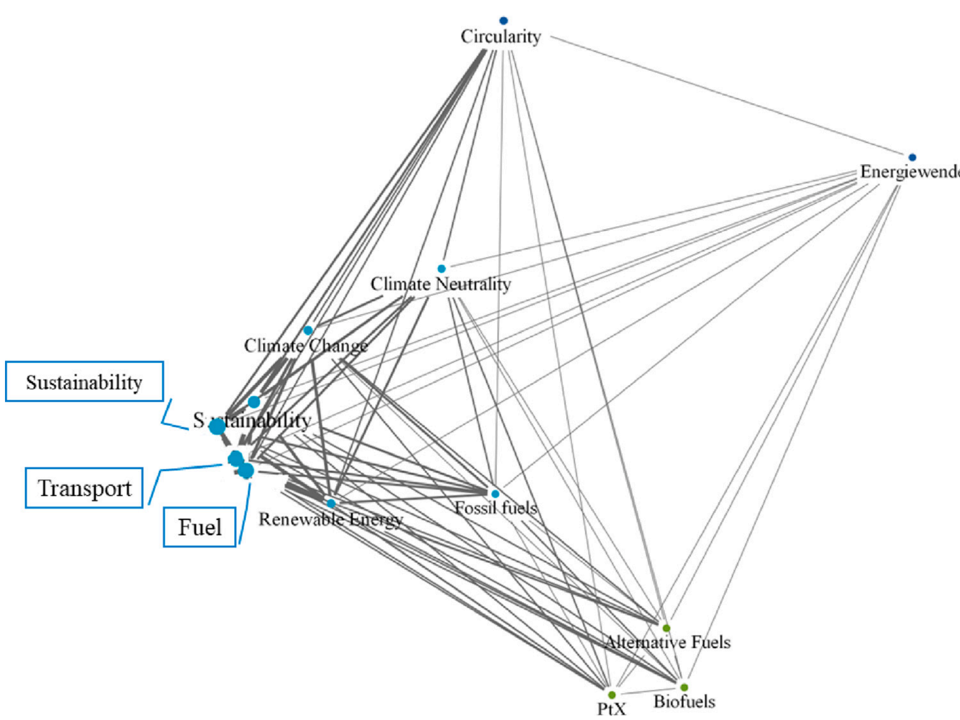

Fig. 4. Keywords' interrelationships based on frequency of occurrence within a policy.

emission reduction targets. Despite its far distance from the major policies, the RED III shows high potential as a game-changer policy in combating emissions through the utilization of renewable fuels. A noteworthy synergy emerges between the RED III and the AFIR from the Transport category, with the AFIR playing a complementary role to the RED III by furnishing the necessary infrastructures for EVs and alternative fuel vehicles. While both policies exert a robust influence on the transport sector, the RED III places its focal emphasis on an several renewable fuels, encompassing biofuels, carbon-based fuels, renewable electricity, and PtX fuels.

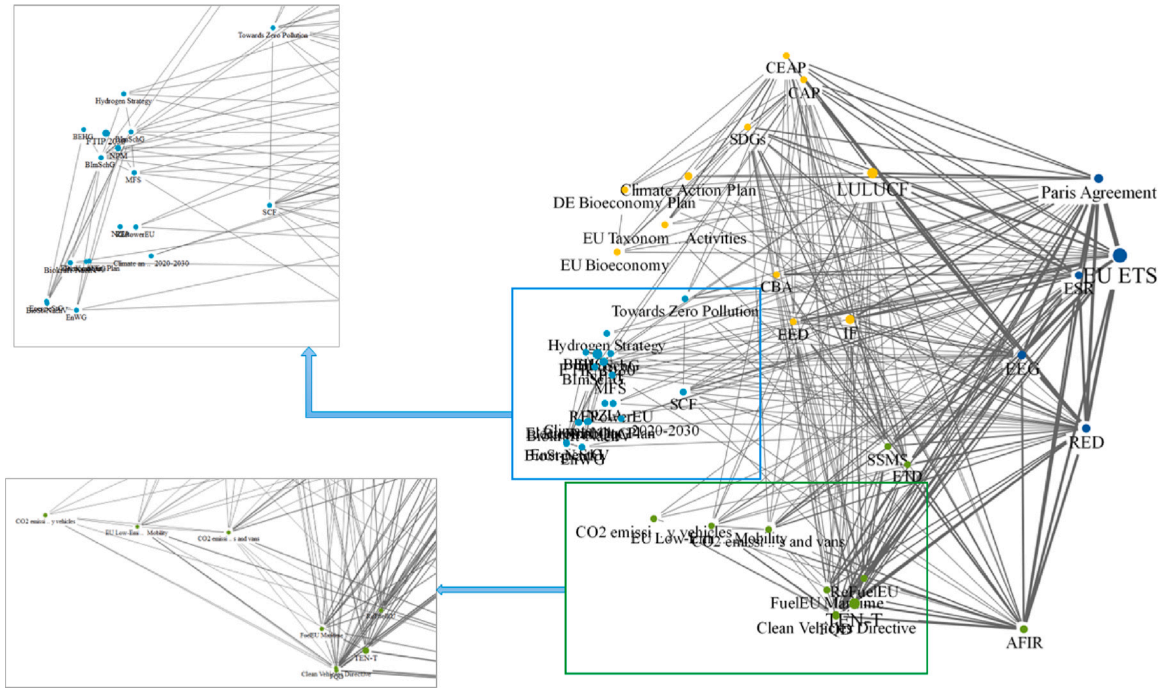

Fig. 5. Policies' coherence based on the frequency of occurrence within a same policy.

In the German context, a strong coherence between the EEG with the RED III as well as the AFIR can be observed. The RED III and the EEG share similar targets in terms of increasing electricity generation from renewable sources where the EEG aims to guarantee a minimum of 80% in total consumption by 2050. This is also visible by the closeness of both policies in the graph that denotes the high frequency of occurrence of both in similar policies. In this way, both the EEG and the RED III play a significant role in ensuring supply of renewable electricity for direct usage in EVs, and hydrogen and PtX production. To support the RED III, the Fit for 55 proposed the FuelEU Maritime and the ReFuelEU Aviation to support reducing GHG emissions in maritime and aviation. Both policies mainly focus on the promotion of renewable fuels, including advanced biofuels, hydrogen, and PtX fuels. In this regard, the coherence between the RED III and policies in the Transport category is higher than other policies, showing its key role in regulating the transport sector. This is visible in its coherence with FuelEU maritime, ReFuelEU aviation, the Clean Vehicle Directive, SSMS and the FQD. The crucial coherence of the RED III with the FQD can be explained based on the FQD's efforts fostering the development of biofuels and RFNBOs. Within the Transport category, main transport policies as well as the FQD are showing strong coherence with each other. The highest coherence can be seen between the REFuelEU aviation and the FuelEU maritime as well as the EU Low-emission Mobility, and CO_2 emission directives for light and heavy vehicles. The closeness of the FQD and the Clean Vehicle Directive reflects the latter's strong focus on using efficient energy carriers for road transport, where the FQD plays a significant role by providing the regulation to improve fuel efficiency. Moreover, two key infrastructural policies in the EU, the AFIR and the TEN-T, show high coherence with each other. They are placed in the same category with a notable short distance between each other.

The Sustainable Resource category encompasses several policies across different fields. Of notably high importance (shown by larger font), the LULUCF plays a central role in addressing resource-based challenges. Similarly do the SDGs, the CAP and CEAP as well as the German and EU Bioeconomy strategies. In the center, the CBA and IF appear in very close distance to the Energy & Emission and Transport categories, which highlights their importance in promoting sustainable fuel alternatives for transport sector. Another important observation highlights how well the German Bioeconomy strategy is aligned with the EU Bioeconomy Plan regarding reducing the dependence on non-renewable fuels by supporting biofuels as well as synthetic fuels.

The remaining policies are densely categorized in the Eco-energy and Transport category. As shown in Fig. 5, most of the German policies are in very close distance to each other reflecting the high coherence, specifically among the MFS, German Electromobility Plan, the NPM, and the FTIP 2030. The so called Agenda for the sustainable transition in the German transport sector is supported by policies that were mainly introduced in the early 2010s, of which the NPM and the German Electromobility Plan focused on EVs, the MFS highlighted the significance of renewable fuels, and the FTIP 2030 provided an overall framework for infrastructure requirements. To promote renewable fuels, Germany has also implemented a set of policies including the Hydrogen Strategy, BioKraftQuG, BioSt-NachV, Biokraft NachV, and BImSchG, which also exhibit close and strong coherence among each other and further transport policies (Fig. 5).

A crucial aspect to determine the efficacy and suitability of policies is their targeted approach in mitigating emissions across various modes of transport. Currently, the road and aviation sectors play significant roles in increasing emissions due to the market dominance of combustion engine-based road vehicles and fossil jet fuels. Examining the corresponding policies, the frequency of occurrence of the transport modes in the identified policies are $n_{occurrence} = 3407$ for road, $n_{occurrence} = 1790$ for aviation, $n_{occurrence} = 2507$ for maritime, and $n_{occurrence} = 1279$ for rail, confirming the significance of the road, maritime, and aviation sectors in the current regulatory framework. Fig. 6 presents an overall distribution of all modes based on their

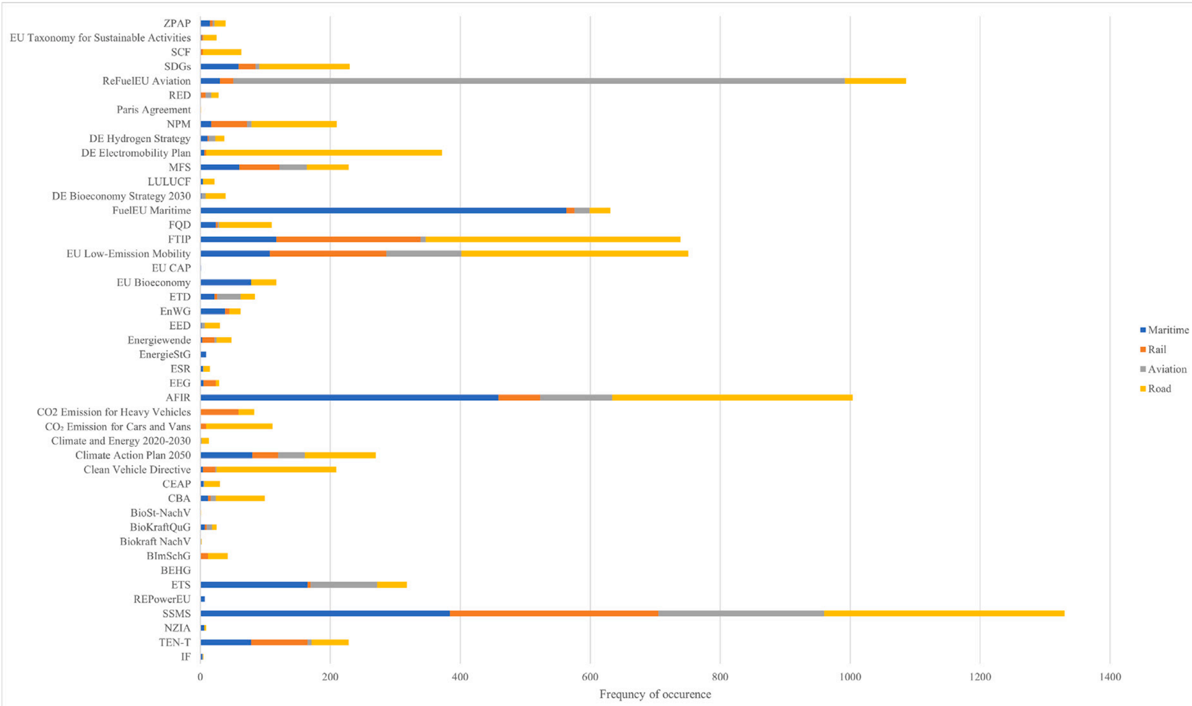

Fig. 6. Frequency of occurrence of transport modes in the policies.

frequency of occurrence in all identified policies. As shown in Fig. 6, the road sector, as the major contributor of emissions, is in the main focus of most policies. For Germany, it becomes apparent that the majority of policies, including the NPM, the MFS, the FTIP 2030, and the Climate Action Plan pursue a comprehensive approach addressing emissions in various modes of transport. Within the EU, policies such as the SSMS, ReFuelEU, FuelEU, AFIR, and ETS are predominantly referenced in relation to various modes of transport. Here, the SSMS, introduced as part of the Green Deal, plays a central role in addressing sustainability challenges across all transport modes.

Lastly, the analysis to comprehend the role and influence of fuel alternatives within the transport sector is expanded further. Similar to the previous sections, observations are built on the frequency of occurrence (Fig. 7) as well as a network analysis of coherence among fuels in policies (Fig. 8). In this regard, the analysis is based on the coding scheme defined in Section 2.3. Electricity is observed to be the most discussed fuel alternative with a total of $n_{occurrence} = 4329$ across the policies addressing EVs and renewable fuels such as PtX fuels. Within its relevant terms, renewable electricity and batteries are also discussed $n_{occurrence} = 192$ and $n_{occurrence} = 632$ times respectively. The term “EV” is also used a total of 1069 times, mainly in the AFIR, DE Electromobility Plan, and EU Low-Emission Mobility. Biofuels are the second frequently discussed fuel type in all identified policies by $n_{occurrence} = 1815$, where terms such as bioethanol, biomethane, algae, biodiesel, and biogenic fuel are used by $n_{occurrence} = 73$, $n_{occurrence} = 61$, $n_{occurrence} = 101$, $n_{occurrence} = 187$, and $n_{occurrence} = 19$, respectively. Hydrogen is the third most frequently discussed fuel alternative across policies with $n_{occurrence} = 1854$, while green hydrogen is only referred to by $n_{occurrence} = 48$. Next, the frequency of occurrence of natural gas generally as well as methane, LNG, and CNG are $n_{occurrence} = 808$, $n_{occurrence} = 762$, $n_{occurrence} = 1113$, and $n_{occurrence} = 364$. Fossil fuels and the derivatives such as diesel, gasoline, and petroleum were mentioned by a total of 840 times. PtX (including PtL and PtG) fuels and its interchangeably used terms such as e-fuels, and RFNBOs are mentioned 341 times.

According to the results shown in Fig. 7, the AFIR has the highest total frequency of occurrence of fuels, $n_{occurrence} = 3092$. By taking a deeper look at the AFIR, natural gas with a total of $n_{occurrence} = 1225$, hydrogen with a total frequency of occurrence of $n_{occurrence} = 616$, and electricity including renewable electricity and batteries with a total of $n_{occurrence} = 651$ are found as three highly discussed fuel alternatives. EVs, PtX fuels, methane, LPG, and biofuels are other fuel alternatives discussed frequently by the AFIR. The Climate Action Plan is the second policy which addresses different fuels frequently and a total of $n_{occurrence} = 1325$ times. Electricity including renewable electricity and batteries is the most highly discussed fuel among all fuel alternatives in Germany, followed by methane, fossil fuels, hydrogen, and natural gas. The RED III and the EEG are the main policies addressing various types of fuels. While the EEG pays an exclusive attention to renewable electricity, the RED III addresses fossil fuels, PtX fuels, electricity, biofuels, and hydrogen. To understand the coherence among fuels, a network is constructed based on the frequency of occurrence of fuel alternatives within same policy documents. According to Fig. 8, fuel alternatives are categorized into four clusters, where the light blue cluster shows the most frequently discussed fuels. The coherence of fuel alternatives is similarly governed by network attributes, including font size, proximity, and link thickness. Electricity and fossil fuels are two repeatedly discussed fuel alternatives followed by biofuels, hydrogen, natural gas, and renewable fuels. A robust and interconnected coherence is evident among electricity, fossil fuels, hydrogen, and biofuels, with all four elements mutually reinforcing one another. Considering current challenges in the sector regarding the high emissions, all policies are designed to directly and indirectly decrease the dependency on fossil fuels. The EU and Germany both have noticeably invested in electrification. For this reason, electricity is observed frequently in most of the policies, followed by hydrogen considering its major advantages and usability as fuel cells and as a resource for PtX fuels. A high occurrence of biofuels is observed in several policies, specifically in German policies. Accounting for the various challenges of first generation biofuels given their food crop based production process,

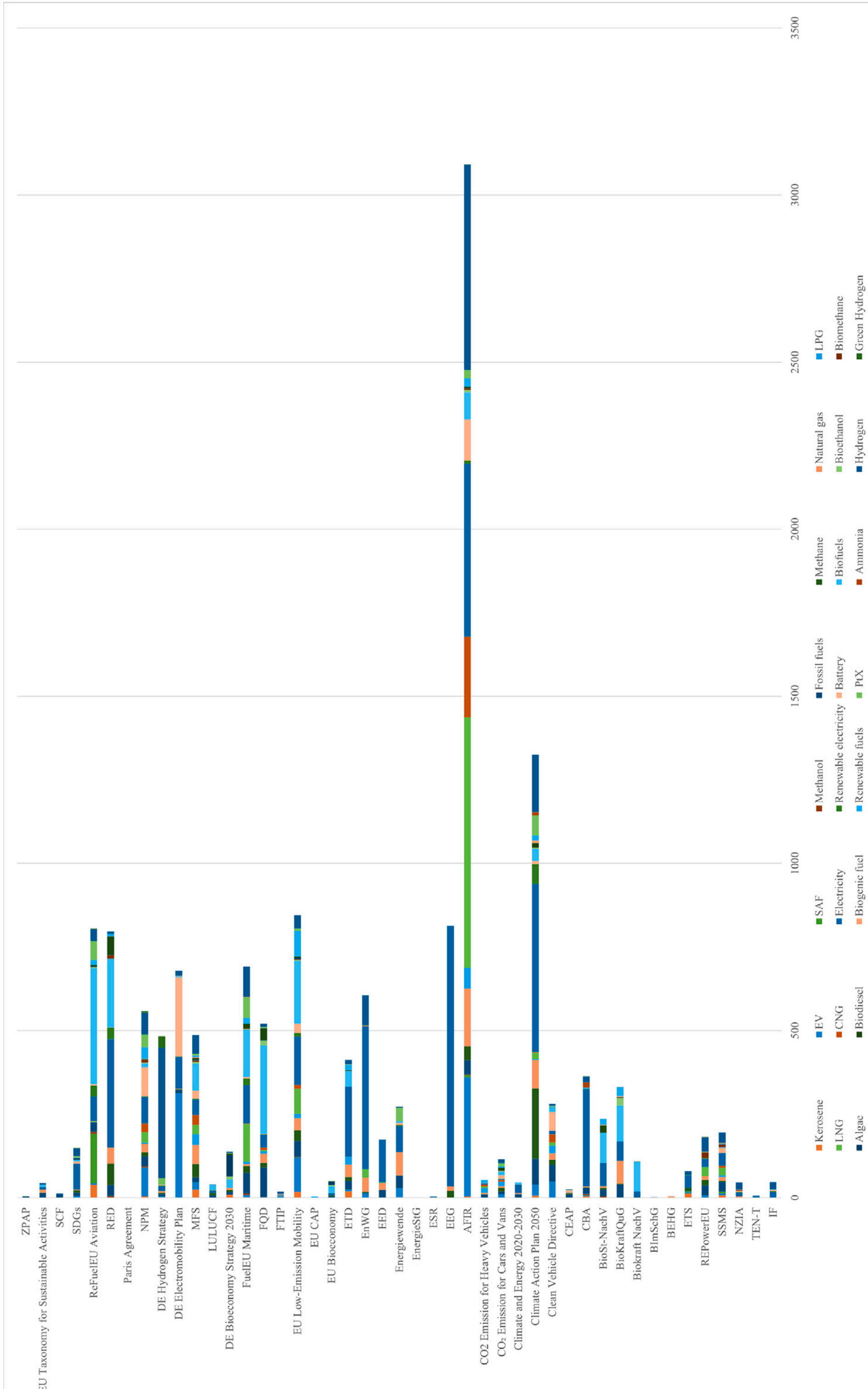

Fig. 7. Frequency of occurrence of fuels in the policies.

revised policies and other new policies have put significant focus on advanced biofuels recently. In this regard, far but tight and direct connections are observed between biofuels and other bio-based fuels in the green cluster (Fig. 8). Finally, renewable fuels show potential to play a role in the defossilization of the transport sector. Despite being far from electricity, PtX fuels show closeness to renewable electricity and hydrogen considering the crucial role of renewable electricity in the production of PtX fuels and green hydrogen.

5. Discussion: Policy implications and lessons learned

5.1. Cutting GHG emissions

The main results of this study show that for climate-neutrality in the transport sector, Germany pursues a comprehensive policy mix design. Specific policies play key roles in the German and EU legal frameworks.

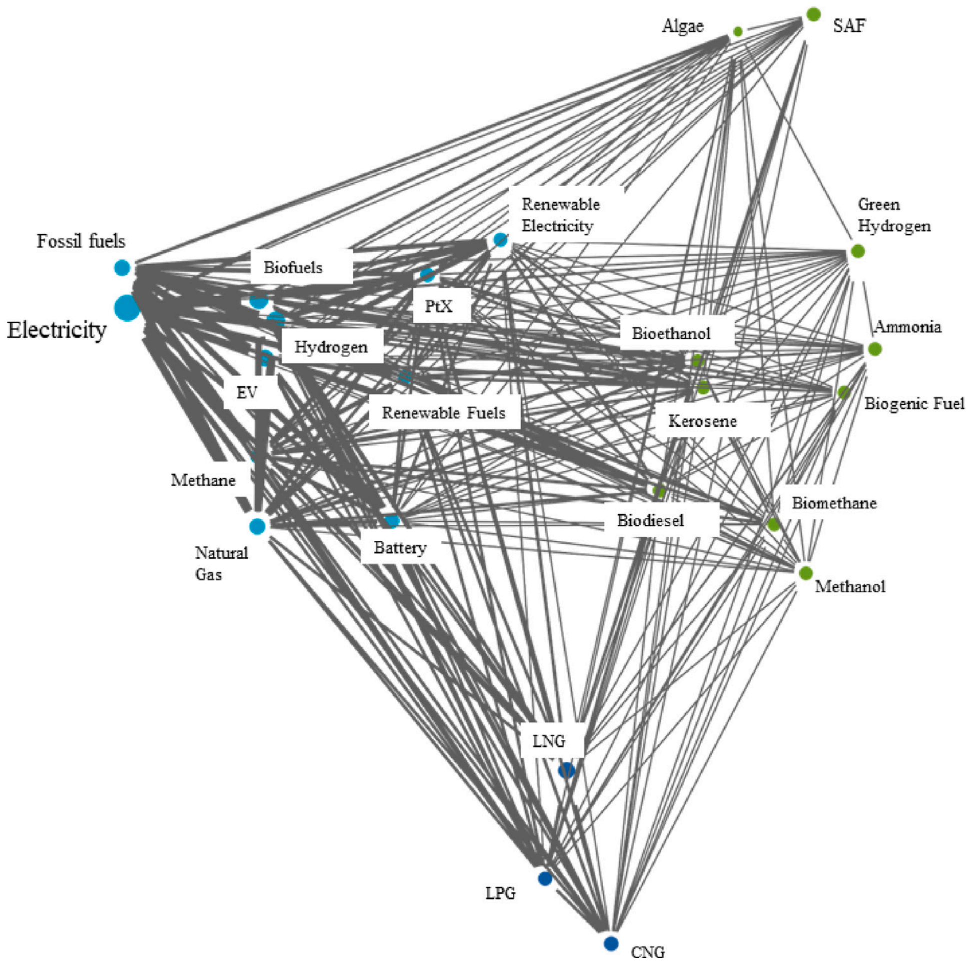

Fig. 8. Fuels' coherence based on the frequency of occurrence within a policy.

The EEG in Germany strongly supports renewable electricity generation. It has had an effect on increasing the share of renewables in electricity generation. Currently, Germany aims for an 80% share of renewables in electricity generation by 2030. The target is of high significance for the German transport sector considering its high priority for the large-scale diffusion of EVs as well as the production of green hydrogen and PtX fuels. In the EU, specific standards for various types of vehicles in road transport are provided in terms of CO_2 emissions, setting a limit of 95 g/km and 147 g/km for cars and vans for 2021–2024, which implies 15% and 55% reductions for cars, and 15% and 55% for vans by 2029 and 2034. From 2035 on, the EU demands zero-emission cars and vans. For this purpose, Germany is required to reduce its emissions from 154 g/km per person in passenger cars to 95 g/km before 2034. For aviation and maritime, the urgency is more clear considering the necessity of shifting from fossil fuels to renewable fuels with high energy density. Although the EU proposed two new initiatives to support the decarbonization in both transport modes, a minimum of 63% decrease in the aviation emissions by 2050 is in conflict with the EU's target for climate neutrality, thus urging the EU council to reform this initiative accordingly. Similarly, the FuelEU faces a similar challenge; therefore, amendments are required to align both initiatives with the EU Green Deal target of climate neutrality.

Considering the EU's success in reaching the 2020 target of a 20% share of renewables in total energy consumption, the RED II's target was modified from 32% to 42.5% in the RED III. This change is expected to lead to a 13% reduction in GHG, a 5.2% increase in renewable fuels, and a 4.4% increment in the share of biofuels. Based on the 42.5% share of renewables, a high proportion of fossil fuels is still expected in final energy consumption. Thus, a revision of the EED was also provided in the Fit for 55 to focus more on improving energy saving with a target of 36% in final consumption compared to 2007 (1.5% annually).

Regarding fiscal and finance aspects, along with the EU ETS, the EU also introduced the CBA for non-EU countries to reduce emissions in support of international climate agreements. The CBA acts similar to the ETS on specific products such as electricity that can be used directly in EVs or production of PtX fuels. In the same context, the EU revised the ETD to align the taxation system with its current policies. The ETD serves as an important pivot by putting restrictions on the utilization of fossil fuels in all sectors including transport. In this regard, the revised ETD covers aviation and maritime fuels as well by putting higher taxes on fossil fuels and near-to-zero taxes for sustainable fuels. Given these changes, the number of economically vulnerable stakeholders will inevitably increase, affecting a large part the involved ones. To address this expected challenge, the EU launched the SCF, a fund of €59 million budget for vulnerable groups' uptake of zero and low-emission transport.

Indeed, the efforts to reduce GHG emissions in the transport sector necessitate more stringent policies, even with the updated Climate Action Plan released in 2021. While the EU's policies in the Fit for 55 package aim for a 55% reduction target by 2030, Germany has set a more ambitious target of 65% by the same year. Germany's plan to achieve climate neutrality five years sooner than the EU highlights the need for more immediate and robust policies. Currently, many of Germany's policies that affect the transport sector have a stronger focus on the year 2050 rather than the 2045 target. To bridge this gap, there is a clear requirement for the development of long-term policies tailored to meet the 2045 climate neutrality goal, ensuring a smoother and more effective transition to a sustainable and low-emission transport sector. Moreover, a sooner climate neutrality target in the transport sector would require Germany to enhance the coherence among different the cross-sectoral policies including the energy, fiscal, environmental, agricultural, bioeconomy, and circular economy. This will be key to success of the regulatory framework governing the transition of the transport and other sectors.

5.2. Electrification vs. Renewable fuels

Electrification and renewable fuels are two potential pathways for decarbonizing the German transport sector. Renewable fuels, including biofuels, PtX fuels and hydrogen as well as EVs are the main pathways to achieve the EU's climate neutrality target.

With the highest share in total GHG emissions, the road passenger transport is of main national concern. After failing the target of one million EVs by 2020, Germany set the target of seven to ten million EVs for 2030, which seems to be very ambitious considering the current capacities. One of the main challenges hindering the electrification in Germany is the relatively high purchase price of EVs as well as battery costs and recharging cost along with insufficient availability of recharging stations. The FTIP and the NPM represent two pivotal policies aimed at facilitating substantial investments in charging infrastructure to accommodate the expected demand for seven-ten million EVs. Nevertheless, given the evolving targets within the German legal framework, both policies require revision and adjustment to align with these new objectives and ensure they remain effective in supporting the nation's growing EV infrastructure needs. Given such targets, the coherence between the EEG policies in the Energy & Emission category as well as the Transport categories with its European relevant policies should be further enhanced.

It is important to acknowledge that some transport modes are not well-suited for electrification. Under such circumstances, the adoption of hydrogen as a low-emission or even zero-emission fuel emerges as a viable alternative, particularly for maritime and aviation. Such diversification in fuel alternatives can contribute to reducing emissions in transport modes where electricity might not be the most practical choice. One of the very first examples in this regard is the most recently manufactured hydrogen-fueled push boat Elektra funded by the Federal Ministry of Transport and Digital Infrastructure. The need to defossilize the maritime sector requires deliberate financial decisions on multiple projects accordingly. In aviation, Germany is one of the leading countries in R&D of SAFs. Germany has been actively involved in multiple projects aimed at meeting the demand for sustainable jet fuel, aligning with EU policies regarding emission reduction targets in aviation (the RED III and the ReFuelEU). Required measures need to be taken to avoid missing the 2030 target in the aviation sector considering the dominance of fossil jet fuel in the energy market and low incentives to use SAFs. To reach this target, Germany relies on the National Hydrogen Strategy aligned with the EU Hydrogen Strategy; however, the improved coherence among policies supporting hydrogen help to promote the market ramp-up in the years to come.

Hydrogen can also be used for production of PtX fuels. PtX fuels are usually considered as potential alternatives for fossil fuels-based combustion engines. Currently, Germany has implemented the GHG reduction quota regulation in BImSchG, PtL roadmap to support SAFs, and different industrial PtX roadmaps, including the Kopernikus projects. As part of the National Hydrogen Strategy, the goal is to supply 200 kt of Kerosene for German aviation by 2030. To achieve this goal, Germany has proposed several pathways including purchasing more efficient aircrafts, optimizing fuel production processes, developing newer technologies with a better sustainability performance, and stricter carbon pricing policies through the ETS, CORSIA as well as the to-be-updated national policies such as the BEHG. On the EU level, the ReFuelEU Aviation is the most directly supporting framework for utilization of advanced biofuels and PtX fuels in aviation. However, currently targets of the ReFuelEU Aviation are insufficiently synchronized with the Climate Action Plan and the Green Deal considering a maximum blend rate of 70% by 2050.

Similarly, maritime can also benefit from the opportunity of using PtX fuels. Supported by the FuelEU Maritime, several companies dealing with imports and exports within the international markets have shown high interest to invest in PtX fuels. The PtX roadmap for the maritime energy transition is one of the well-known initiatives by the German VDMA company to promote these fuels for container ships by 2045 for intra-European maritime. As mentioned earlier, green hydrogen is one of the important options for maritime, while this initiative also suggests ammonia, methanol, synthetic natural gas (SNG), and synthetic diesel. In this regard, several collaborations with international partners in South American, North Africa, Middle East, and Australia are agreed on to meet the future demand [80]. PtX policies are highly affected by the insufficiency in policies to regulate their production and utilization within the transport sector. The RED II and III are the only policies considering PtX fuels, as RFNBOs, by setting specific targets. However, as discussed before, Germany currently strongly relies on industrial roadmaps to promote PtX production and utilization. To reduce emissions in those parts of transport where further policy support will be required to meet the future emission reduction targets.

Finally, to regulate biofuels, Germany has implemented the BioKraftQuG, the BioSt-NachV, and the Biokraft NachV as well as the EnergieStG that deal with environmental standards of biofuels production, electricity generation from biomass, and taxation. Unlike for electricity and hydrogen, Germany does not pursue a specific policy framework for the promotion of biofuels exclusively in the transport sector. The German Bioeconomy Strategy 2030 is the main policy within which biofuels are addressed. Land-use change and food crop utilization are two major challenges of first generation biofuels which are targeted by agriculture policies such as the EU CAP. Thus, second and third generation biofuels are only potential clean alternatives. The main concerns regarding advanced biofuels are high production cost and large-scale production. Given the production of only sixteen million tons in 2019, the EU would likely need new or adapted roadmaps to meet the estimated demand. In the recent update of the Climate Action Plan, more attention has been given to second generation biofuels to extend current capabilities to produce larger amounts. However, more targeted policy incentives would be required, e.g., in the form of a roadmap or policy to promote advanced biofuels in Germany's future transport, specifically in aviation.

In summary, the implemented policies seek to move the German transport sector towards climate mobility through the adoption of EVs, PtX fuels, and advanced biofuels. Germany is strategically implementing a blend of policies designed to progressively phase out fossil fuels and decarbonize the sector. Presently, the policy landscape in Germany and the EU places a strong emphasis on electrification, particularly for road passenger transport. Meanwhile, PtX fuels and advanced biofuels are expected to play unceasingly key roles, mainly in the aviation and maritime sectors, as essential components of the broader effort to reduce emissions and transition towards sustainable transport.

5.3. Policy implications

Based on the discussions in the previous parts, this section presents recommendations for a mixed policy framework considering cross-sectoral policies to address the sustainability challenges ahead. One of the most crucial recommendations centers on the strong need to establish a robust, science-based foundation for identifying the most sustainable and suitable fuel alternatives and technologies. While the EU policy framework deliberates on various fuel alternatives, there remains a need for more concrete and decisive actions to determine which fuels will be most effective in realizing the climate-neutral transport objectives. This evidence-based approach serves as the basis for a clearer roadmap for policy implementation and support of more effective decision-making in the pursuit of sustainable and environmentally responsible transport solutions.

Currently, the EU policies such as the ETS and the ETD regulate carbon pricing and taxation in the EU. To address the expected economic consequences of phasing-out fossil fuels, the EU has implemented the SCF. The SCF acts as a supportive policy framework to compensate monetary aspects. Monetary policies serve as an important means to increase the adoption rate of new technologies and fuels by allocating adequate funds. An important step to take in this regard require improving the coherence among policies in the Energy & Emission category.

The analysis has shown that policies in the Sustainable Resource category are mostly isolated from other policies in the network (Fig. 5). In this context, the CEAP, as the most important circular economy policy in the EU, has the weakest coherence with policies in the Transport and Energy & Emission categories. Resource depletion is one of the environmental and economic challenges in the EU. Considering the growth of energy consumption in the German transport sector, optimizing resource utilization and end-of-life recycling processes in transport can play a key role in reducing emissions. The coherence between the Sustainable Resource category and the Transport category is thus of central importance considering the strong resource intensity of EVs. Enabling sustainable manufacturing practices and efficient end-of-life processes for EV batteries holds considerable importance in achieving carbon removal throughout the entire value chain.

Given the regulatory targets to increase the adoption of EVs and the expected price parity before 2030, one important challenge will be to design effective subsidy programs. Inadequate subsidies can potentially hinder progress in meeting the emission reduction targets. Proactive and appropriately scaled subsidies can play a significant role in accelerating the transition to EVs and achieving the desired environmental goals. Such efforts can be supported by improving the coherence between policies addressing renewable electricity generation including the EEG and REPowerEU as well as policies in the Transport category.

Considering the challenges related to first-generation biofuels, it is necessary for Germany to reassess its current biofuels policies. The revision of relevant policies should aim to align these policies with the characteristics and potential of advanced biofuels. Furthermore, establishing a policy framework dedicated to, specifically, the deployment of advanced biofuels within the transport sector can expedite their market development. In a multi-sectoral policy framework, the synergy between agricultural and bioeconomy policies plays an important role in the development, production, adoption, and diffusion of advanced biofuels. Moreover, considering the roles of agricultural and bioeconomy policies in biofuels production, enhancing the coherence between biofuels policies and the policies mainly in the Sustainable Resource category and the Eco-Energy and Transport category is of high significance for the adoption and diffusion of advanced biofuels.

Biofuel and fiscal policies in Germany extend tax incentives to facilitate their market penetration. Similarly, tax incentives for PtX fuels can be considered to enable them to compete with fossil fuels, particularly in aviation and maritime. These tax relief initiatives should be meticulously delineated for hydrogen and PtX within the framework of national legislation or be integrated into forthcoming revisions of the ETS and the ESR.

An important challenge regarding biofuels is related to land use and resource exploitation. The EU's efforts to shift from fossil fuels to renewable fuels such as biofuels depend heavily on the coherence of biofuel policies with the LULUCF, the EU CAP, and bioeconomy strategies. Considering the unsuitability of first-generation biofuels, the coherence between fuel production policies should be enhanced with the LULUCF and similar policies in order to minimize the ongoing conflicts over land and crops, and support environmental conservation and food security. Efficient utilization of biomass feedstock to produce advanced biofuels can be improved by enhancing the coherence among fuel production policies and policies in the Sustainable Resource category in order to reduce waste and increase resource efficiency. Moreover, the relationship between land use, resource exploitation and emissions can be fortified in the Energy & Emission category e.g., the ESR as a major policy addressing GHG emissions in agriculture sector next to transport and industry.

Hydrogen is expected to play an important role in fuel cells for EVs especially in the road freight transport as well as the production of PtX fuels. Proper strategies need to be adopted considering the probable and desired diffusion of hydrogen and PtX fuels mainly in these sectors. While the German Hydrogen Strategy, the EU Hydrogen Strategy, and industrial PtX roadmaps provide a foundational framework for hydrogen and PtX fuels, it is crucial for Germany to craft specific policies tailored to these fuels. Given a particular focus on aviation and maritime sectors, dedicated policies can address the unique challenges and opportunities in these domains and provide the necessary impetus for the development and adoption of sustainable fuels, required for decarbonizing transport.

Unlike in the case of EVs and biofuels, no national policies exist to directly target PtX fuels in Germany besides the National Hydrogen Strategy. Considering their expected potential in maritime and aviation, Germany should explore the potential of specific national policies to address PtX fuels. Currently, a PtL roadmap exists to be exclusively implemented in aviation; however, Germany should consider updating this roadmap to provide an effective and targeted regulatory framework to improve its capability in utilizing PtX fuels for both maritime and aviation. The coherence of policies in the Transport category, specifically ReFuelEU Aviation and FuelEU Maritime, with policies in other categories should be improved. High coherence between policies in all four categories is recommended considering the production requirements of PtX, including, renewable electricity, carbon, water, and biomass feedstock. In this regard, the coherence among policies aiming at environmental challenges, specifically related to water management has been neglected. Therefore, the coherence between production requirements, importantly water, should be considered in future discussions given the role of water in the production of hydrogen and PtX.

Considering the discussed strategies concentrated on the deployment of sustainable fuels, meeting the high future demand of sustainable fuels will require high contributions of renewable energies. For this purpose, Germany's ambitious target of 65% reduction by 2030 is very dependent on the successful implementation of the RED III, the GHG reduction quota in the BImSchG, and the EEG. In addition, adequate and affordable renewable electricity will also play a significant role in the development of hydrogen and PtX fuels. Thus, the coherence among these policies with policies in all categories should receive notable attention.

The effective implementation of policies considering ecological, economic, and social implications is important for optimizing the sustainable transition in the transport sector. Driven by the comprehensive changes in the EU and German national policy frameworks, new products are introduced into the market, thus changing market structures, infrastructures, existing value chains and business models as well as entire industry logic. Understanding and managing changes in market dynamics and value chains will become critical. Significant economic, ecological, and social effects must be well understood for sustainable policy design. In light of the significance of EU import regulations for renewable fuels, developing reliable and resilient global value chains will be essential to achieving future climate commitments. One of the key examples in the EU is the Renewable and Low-Carbon Fuels Value Chain Industrial Alliance. This value chain industrial alliance is focused on the production and supply of renewable and low-carbon fuels in aviation and maritime. To optimize the EU aviation and maritime sectors within the complex policy framework and value chain, the alliance is founded on the key processes of the renewable fuels supply chain through providing a collaborative environment for industry leaders, technology and finance providers, civil society organizations, and governments in both demand and supply sides.

Currently, the transport sector finds itself subject to a plethora of regulations stemming from diverse policy domains, resulting in a complicated regulatory framework. While the multi-perspective nature of these policies offers an advantage in its comprehensive coverage of potentially relevant domains, it also presents a disadvantage by potentially fostering policy redundancy or inefficiency. Consequently, establishing the optimal level of complexity within the regulatory system is crucial. It enhances the efficacy of proposed policies aimed at mitigating GHG emissions and facilitating the transition to a sustainable sector.

5.4. Limitations

While a growing catalog of research on policies focused on the sustainable transition, many open questions remain. Despite the broad spectrum of research approaches for policy analysis, the coding scheme allowed us to investigate the ongoing regulatory framework to understand the dynamics affecting the sustainable transition in the transport sector. However, as part of the research process, the following limitations were identified.

The primary focus of this study is the comprehensive selection of policies across different policy sectors. There is a chance of missing policies in different indirectly relevant policy domains that could influence the transition in the transport sector. Another policy domain of potential relevance especially for future development is related to carbon capture, storage and utilization. The first steps for carbon utilization date back to the Directive on the Geological Storage of Carbon Dioxide and the RED II. In 2022, the European Commission adopted a new proposal for carbon removal in order to support industrial carbon removal technologies, such as bioenergy with carbon capture and storage, and direct air carbon capture and storage. Most recently, in February 2024, the EU released the Industrial Carbon Management Strategy as a comprehensive approach for scale up the carbon management. The proposed strategy holds significant potential in facilitating the transition of the transport sector. It not only addresses emissions from fossil fuels but also capitalizes on stored carbon resources to produce PtX fuels. This is achieved through the support and development of direct air capture infrastructures as well as carbon supply through other carbon sources. Considering new carbon-related policies along with the CBA and the EU ETS can offer valuable insights into how these policies are coherent with other domains, thereby aiding the transition in the transport sector.

Global collaboration and strategic alliances, e.g., energy partnerships, represent additional regulatory mechanisms that can support the transition within the transport sector. In light of the ongoing global push for decarbonization, Germany has been actively engaging in various collaborative initiatives, particularly in energy projects aimed at the sustainable production and importation of renewable energies. However, the scope of this study primarily centers on examining policies, regulations, directives, strategies, roadmaps, and acts, rather than delving into inter-governmental partnerships, which lie beyond the purview of this work.

From a methodological standpoint, this study employs a mixed method qualitative approach, which involves analyzing policy documents using a framework built based on a coding scheme. This methodology extracts meaningful insights regarding policy coherence, the promotion of fuel alternatives, and the support for various transport modes in alignment with the climate neutrality target. The coherence analysis for policies and fuel alternatives are investigated in a semi-quantitative environment within a network analysis. Nonetheless, there is a possibility of overlooking potential policy coherence, which could be addressed through stakeholder engagement via policy mapping, policy integration analysis, or impact assessment.

6. Conclusion

The challenge of reducing GHG emissions in the German transport sector is undeniably significant, as the country attempts to meet its 2030 emissions target and ultimately achieve climate neutrality by 2045. Germany has to reduce emissions by 65% in less than ten years in order to fulfill the 2030 target, therefore time is of essence. To meet these targets, Germany should re-assess its policy framework and establish a coherent set of policies that provide strong incentives for achieving these milestones. In this context, it is of high importance to gain a comprehensive understanding of the current policies that affect the transition of the German transport sector to a sustainable one. Thus, in order to comprehensively review policies in a cross-sectoral system, this study uses a mixed method content analysis approach. To thoroughly examine the current policy portfolio, 44 policies from both the EU and Germany have been identified, spanning various fields, with direct or indirect influence on the transport sector. This endeavor is a vital step in guiding the country's transport sector towards a sustainable future and lower emissions.

The findings highlight Germany's predominant emphasis on the electrification of road transport. This focus aligns with the country's effort to address the significant emissions stemming from the utilization of fossil fuel-based combustion engines. Electrification serves as a pivotal strategy to transition to cleaner and more sustainable transport alternatives and reduce emissions in the passenger road transport sector. Aviation and maritime have received increasing attention by the recent EU legislation packages such as the EU Green Deal and the Fit for 55. Meaningful coherence is found among the major EU policies and their interrelationships with energy and transport policies. However, coherence across the German policies and the EU policies especially between energy and transport sectors is much weaker. Moreover, less accordance with the EU policies are observed in the current German policies regarding the recent updated targets. Given Germany's even more ambitious goals, a substantial imperative exists to comprehensively revisit and revise existing policies. This is crucial for realigning the policy framework with the revised timeline. Doing so it is vital to rest decisions on an evidence-based approach to highlight the need for policies that accelerate the sustainable transition but also prevent adverse socio-economic effects in other fields.

While this study addresses a crucial and timely topic, it is essential to acknowledge that numerous challenges persist, which can serve as guiding principles for future research endeavors. Understanding and investigating policy coherence between the transport policies and other policies from different sectors can provide in-depth insights for a cross-sectoral policy system. In this regard, including carbon policies, along with any other directly or indirectly relevant policy domains, can be beneficial for robust and comprehensive policy coherence analysis. Such a comprehensive policy framework can maximize Germany's efforts in moving towards sustainable transport. Thus, utilization of quantitative and qualitative techniques to examine the coherence among policies can provide useful insights. A policy coherence analysis holds the potential to offer valuable insights regarding the appropriate level of complexity inherent in the existing regulatory framework. In addition, emerging and advancing technologies such as autonomous vehicles, artificial intelligence, or blockchain offer potential for addressing climate change challenges in the transport sector through new advancements in smart grids, forecasting demand, resource management as well as transparent carbon trading, improved supply chain transparency, and enhanced security. For example, artificial intelligence techniques such as large language models can be used to systematically analyze policies to devise optimized coding schemes in order to analyze the coherence between policies. Thus, an specific focus can be analyzed based on coherence of the investigated policies in this study with technological policies.

Stakeholders play significant roles in shaping policies and other regulatory frameworks. Therefore, conducting a coherence analysis based on their perceptions through a comprehensive policy mapping could provide meaningful insights to identify conflicts and synergies between policies. Moreover, policy effectiveness of the German policy portfolio directly addressing the sustainable transition in the transport is of high significance which can be quantified using different techniques such as multi criteria analysis or decomposition analysis. Furthermore, a policy optimization approach with the goal of costing and GHG emission estimation of renewable fuels in transport can provide useful implications on the competitiveness of renewable fuels in different transport modes. A sound analysis of strengths, weaknesses, opportunities, and threats of least addressed renewable fuels such as advanced biofuels, PtX fuels, and green hydrogen can build the initial steps for improving their market diffusion. Understanding current incentives, taxation, and subsidies for PtX fuels and their effectiveness in market diffusion should be a topic of another study. Furthermore, the market diffusion of new technologies and fuels is a critical process affected by several factors within a complex environment. Policies have strong effects on the market diffusion; therefore, simulation models, data analysis, network models, and game theory can be applied for deeper analysis of various market diffusion mechanisms under different policies. Examining the multi-perspective factors influencing the market diffusion, analyzing market diffusion barriers, and investigating effects of policy mechanisms on the diffusion process are further important topics that should be addressed in future research.

CRediT authorship contribution statement

Ali Ebadi Torkayesh: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Validation, Writing – original draft, Writing – review & editing. **Sandra Venghaus:** Conceptualization, Investigation, validation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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