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Future renewable energy targets in the EU: Impacts on the German transport

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A R T I C L E I N F O

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A B S T R A C T

The transport sector is at the center of discussions on accelerating the energy transition due to its still increasing contribution to greenhouse gas emissions worldwide; therefore, the EU has set binding targets for the use of renewable energy in transport through the Renewable Energy Directive. To analyze the economic impact of these targets, we developed an optimization model that considers bio- and electricity-based fuel options, various transport sectors, and future policy requirements. Our study of the German transport sector found that imported alternative fuels play a key role in reducing fossil fuel usage. We also identify two technological and managerial obstacles: policymakers need to prioritize the rapid electrification of vehicles in the near future; and in the distant future, more attention is needed in research for new technologies in commercial transport. Although our findings are tailored to Germany, the employed approach can be transferred to other models and countries.

1. Introduction

Transport is considered a hard-to-abate sector contributing more than 37% of CO_2 emissions from end-use sectors in 2021 globally, with a clear trend of absolute emissions growth so far (IEA, 2021b). The perspective is not much different in Europe, as the transport sector was responsible for around 24% of the total greenhouse gas (GHG) emissions in the European Union in 2021, while absolute emissions have changed little for years (EEA, 2021). Due to its economic significance and the heterogeneity of stakeholders, it is not an easy task to defossilize transportation as it requires a profound transformation of various sectors and activities involved (e.g., energy, agriculture, chemical and automotive industries). Therefore, governments are carefully designing and implementing their plans in a stepwise manner (IEA, 2021a). The generation and use of green synthetic drop-in fuels promises to largely maintain today's value chains, but at the price of high energy losses compared to the direct use of electricity.

In Europe, policy measures to reduce GHG emissions in the transport sector are in place for almost 15 years. The Renewable Energy Directive (2009/28/EC, or so-called RED I), which was mandated initially by the European Parliament and Council in 2009, promoted the consumption of renewable energy in the European Union (2009). The original RED has been requested to procure 20% of the consumed energy within the European Union from renewable sources till 2020. While this mandate was exceptional at the time, it was merely a milestone for more ambitious targets. In 2018, European countries revised and replaced the original plan with

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directive 2018/2001/EC, the so-called RED II (European Parliament, 2018). Under the subsequent RED II, the European countries have pledged to increase the share of renewable sources to 32% of the final energy consumption until 2030. In the transport sector, RED II stipulates renewable energy to contribute at least 14% of the energy demand in the rail and road transport sectors by 2030. In addition to the REDs, the Fuel Quality Directive (FQD) is another important policy instrument by which the EU member states can reduce the GHG emissions in the transport sector (European Parliament, 2009). A set of GHG reduction targets is specified in the FQD for fuels placed on the market; therefore, fuel suppliers are obliged to report the GHG emissions of fuels they offer on the market.

The EU directives are translated into the national legislation of EU member states. In the case of Germany, these directives are implemented through the GHG quota (Deutscher Bundestag, 2021). The implemented quota system emphasizes that the total GHG emissions of fuels supplied have to be reduced compared to a defined reference value by providing low-carbon alternatives, such as biofuels, synthetic fuels, hydrogen or certificates from electric vehicle owners. The GHG reduction quota for road transport has been continuously updated since 2015 from 3.5% to 6% in 2020, with hefty penalties in the case of failure in compliance. To be recognized as a climate friendly candidate fuel for blending, the policymakers specified standards and requirements (e.g., the minimum percentage of alternative fuels) that are becoming more strict every year. The implemented scheme has provided incentives to obligated parties (e.g., fuel producers) to lower their carbon footprint. According to the Federal Office for Agriculture and Food (BLE), 124 petajoules (PJ) of certified biofuels were produced by industries for the German market in 2019 (BLE, 2021), contributing to the road transport fuel supply with 5.51%. According to BLE's report, the production of biofuels was dominated by two types of conventional biofuels, namely FAME (fatty acid methyl esters) and bioethanol, which accounted for over 95% of the total output.

Although European governments promote the use of biofuels in transport-related sectors, they have concerns regarding conventional biofuels.[1] Since conventional biofuels consume energy crops as feedstock, they have undesirable impacts on food security and put pressure on agricultural lands and water resources (Rulli et al., 2016; Esmaeili Aliabadi et al., 2022). Therefore, policymakers have decided to prevent conventional biofuels from growing while promoting advanced biofuels (i.e., the second and third generations biofuels) (Commission et al., 2022). Based on German legislation, the total amount of conventional biofuels produced in 2030 should not surpass 4.4% of the total energy used in the rail and road sectors. For the same reason, the production of biodiesel from used cooking oil (UCO) and animal fats is confined to 1.9% of total energy consumption in the road and rail sectors.

While the RED II targets for road and rail transport are clearly defined, the directives are ambiguous for aviation and marine transport due to technological challenges. Using PROMETHEUS, Fragkos (2022) illustrates that an ambitious climate policy would reduce the trade of fossil fuels and international shipping activities, resulting in greater opportunities for mitigation efforts. This highlights the potential synergies between international transport and national climate action. The European Commission has proposed to increase the share of Sustainable Aviation Fuels (SAF) to above 63% by 2050, of which 28% should be synthetic fuels (European Parliament, 2021). Bullerdiek et al. (2021) study the RED II obligations in relation to the use of SAF in Germany. The authors point out that the underlined targets induce a high demand for SAF, which surpasses the production capacity by a factor of two. Ueckerdt et al. (2021) also raise concerns regarding the future of electricity-based synthetic fuels. The authors suggest to consider e-fuels only when direct electrification is not possible. RED II sets a sub-target for the energy-related consumption of biogas and biomethane in the transport sector, which may provide incentives for the use of sustainable gaseous fuels in maritime transport (Prussi et al., 2019; Kreyenberg et al., 2015). Focusing on road and rail transport sectors, Meisel et al. (2020) investigate cost-optimal fuel mixes until 2030, taking into account RED II and the national requirements using an optimization model. The authors point out that climate protection targets are missed if Germany relies on the minimum requirements of RED II. Jordan et al. (2023) compare short-term policy scenarios until 2030 with cost-optimal long-term energy scenarios until 2050. It is shown that the GHG quota, on the one hand, promotes the use of biofuels in the passenger road sector, while these fuels are in the long-term cost-optimally used in maritime and aviation. On the other hand, the GHG quota does not provide the necessary incentives for the ramp-up of battery electric vehicles, which would be the cost-optimal solution in the passenger road sector according to the investigated long-term scenarios. Using an explorative approach over three scenarios, Ehrenberger et al. (2021) also emphasize it is improbable that the German transport sector will achieve its emission reduction target by 2030 without additional efforts and a more dynamic transition process.

The following table, adopted from Naumann et al. (2021, Table 1), summarizes the announced policies in Germany related to alternative fuels. The values inside the gray cells are interpolated based on declared policies in neighboring years. Please note that the share (%) in the first target refers to the emissions, while others are for energy content.

Quantifying the impact of these measures on each transport mode can shed light on future trends and the internal dynamics of these sub-systems. Whether the specified targets can be achieved depends on a multitude of factors and drivers, such as the availability of land, biomass, and renewable electricity, as well as social and political drivers. Synergy among these factors can contribute to positive outcomes, while antagonistic effects can impede progress. However, formulating the interactions between these factors is not straightforward, given that these elements may exhibit non-linear relationships that can complicate the analysis. Against this background, we have developed a technology-rich bioenergy optimization model (*BENOPTex*) that endogenously accounts for the announced policies (Millinger et al., 2022b). BENOPTex determines the optimal allocation of biogenic materials across diverse energy conversion pathways and sectors to minimize GHG emissions and total system cost while satisfying the technical, sectoral, and political constraints. Similar to many large-scale energy systems optimization models, BENOPTex is also a linear model

[1] Conventional biofuels are also called the First-Generation Biofuels (FGBs).

Table 1
A summary of declared policies in Germany. The share (%) for the first target refers to the emissions, while others are for energy content.

Targets (in %)	Sectors	Type	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050
1- GHG quota (ρ_t^{GHG})	Road & rail	Min	–	–	7	8	9.25	10.5	12	14.5	17.5	21	25	-	-	-	-
2- Conventional biofuels	Road & rail	Max	–	–	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	-	-	-	-
3- UCO or animal fats	Road & rail	Max	–	–	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	-	-	-	-
4- Advanced biofuels	Road & rail	Min	–	–	0.2	0.3	0.4	0.7	1	1.35	1.7	2.15	2.6	-	-	-	-
5- Synthetic fuels (PtL)	Aviation	Min	–	–	–	–	–	0	0.14	0.28	0.42	0.56	0.7	5	8	11	28
6- SAF	Aviation	Min	–	–	–	–	–	2	2.6	3.2	3.8	4.4	5	20	32	38	63

considering the sheer number of decision variables and parameters, making it intractable if formulated in nonlinear or integer forms (Kotzur et al., 2021). Therefore, in this study, we suggest a new formulation that linearizes the non-linearity in RED II. Employing the implemented model, we aim to assess the burden on the clean energy supply chain (i.e., renewable energy and bioenergy) with the focus on Germany using three scenarios. These scenarios consider both the current RED and possible directions for the post-2030 period. The results of these scenarios can support policymakers to develop a roadmap for the future mechanisms (e.g., RED III) to ensure the sustainability and stability of the clean energy supply chain in Germany beyond 2030. Moreover, we carry out an ex-post analysis of the scenarios to evaluate the impact of business- and climate-driven strategies on the de-fossilization of maritime transport.

The manuscript is further organized as follows. Section 2 describes our methodology to formulate RED endogenously in BENOPTex. Three scenarios are specified, which are used to analyze the impact of varying factors on the future German transport sector. The results of the scenarios are compared in Section 3 to provide insights. Finally, a conclusion is drawn in Section 4.

2. Methodology

In order to comprehend the inter-sectoral dynamics, in Section 2.1, we implement RED II and the GHG quota targets in the BENOPTex model (Millinger et al., 2022b). BENOPTex is a linear optimization model, in which various innovative modeling techniques are applied to linearize the predetermined targets in national and international directives. Subsequently, in Section 2.2, several scenarios are generated to determine the impact of tighter (or moderate) post-2030 regulations on the bioenergy supply chains. Section 2.3 provides a detailed description of our modeling procedure from scenario generation to problem-solving. We also report the run-times in this section. Other assumptions and limitations of this study are explained in Section 2.4.

2.1. Embedding climate targets

The RED regulations are implemented in our optimization model as predefined rates and constraints, to reach the climate protection targets. The following constraints formulate target #2 until target #6 in Table 1.

$$\sum_{\substack{i \in I^{FGB} \\ s \in RR}} \pi_{tis} + \sum_{\substack{i \in I^{FGB}_{mix} \\ f \in F^{FGB}}} \eta_{tfi} \times \dot{m}_{tif} - \sum_{\substack{i \in I^{CH_4} \\ s \in S'}} \pi_{tis} \leq \rho_t^{FGB} \times \delta_t^{RR} \qquad \forall t \in T \tag{1}$$

$$\pi_t^{UCO} = \sum_{\substack{i \in I^{Oil} \\ s \in RR}} \pi_{tis} \qquad \forall t \in T \tag{2}$$

$$\pi_t^{UCO} \leq \rho_t^{Oil} \times \delta_t^{RR} \qquad \forall t \in T \tag{3}$$

$$\pi_t^{Adv} = \sum_{\substack{i \in I^{Adv} \\ s \in RR}} \pi_{tis} \qquad \forall t \in T \tag{4}$$

$$\pi_t^{Adv} \geq \rho_t^{Adv} \times \delta_t^{RR} \qquad \forall t \in T \tag{5}$$

$$\sum_{\substack{i \in I^{Av} \\ s \in AV}} \pi_{tis} + \mu_{t,AV} \geq \rho_t^{eAv} \times \delta_t^{AV} \qquad \forall t \in T \tag{6}$$

$$\sum_{\substack{i \in I^{Av} \\ s \in AV}} \pi_{tis} + \mu_{t,AV} \geq \rho_t^{eS} \times \delta_t^{AV} \qquad \forall t \in T \tag{7}$$

$$\sum_{s \in S} \mu_{ts} \leq \overline{\mu}_t \qquad \forall t \in T \tag{8}$$

Eq. (1) sets a maximum production level for biofuels from FGB technologies (i.e., I^{FGB}) for road and rail transport sectors (i.e., $s \in RR$). FGB technologies convert energy crops to biofuels (e.g., converting sugar beet to ethanol or methanol). The feedstock types can be split into two sets ($F = F^{FGB} \cup F'^{FGB}$), where F^{FGB} is the set of conventional feedstocks (e.g., maize silage, rape seed and sugar beet) and F'^{FGB} is the complementary set (e.g., grassland biomass or woody biomass such as poplar and miscanthus). π_{tis} is a decision variable representing the amount of energy supplied by technology i at year t for sector s. η_{tfi} is a parameter that represents the energetic conversion efficiency of technology i in the conversion of feedstock f into the main energy carrier at year

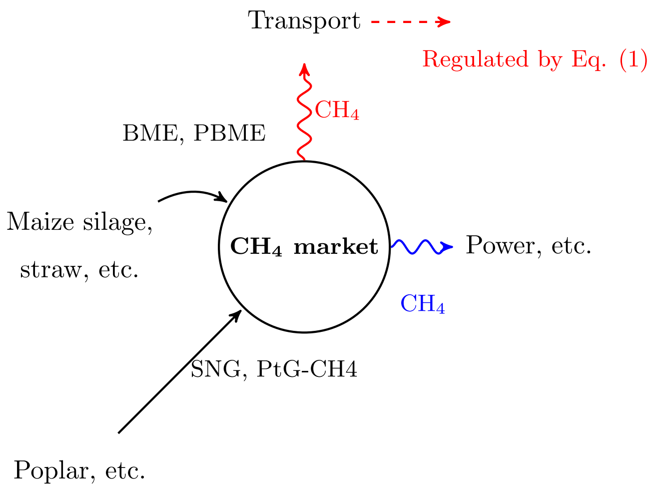


Fig. 1. Material/energy flow from/to CH_4 market. SNG: synthetic natural gas based on gasification and methanation. PtG-CH4: H_2 production using electrolysis and combine it with CO_2 to produce CH_4.

t. $\dot{m}_{tif}$ is a decision variable showing the energetic amount of consumed feedstock f by technology i at year t. The produced energy depends on technology choice. For instance, sugar beets are used as feedstock to produce ethanol when the solver employs the *Beet_EtOH* technology. In Eq. (1), ρ_t^{FGB} is the maximum rate of production from FGB technologies at year t. δ_t^{RR} stands for the total energy consumption by the rail and road transport sectors in year t. Some technologies, I_{mix}^{FGB}, such as biomethane production using anaerobic digestion (BME) and power to methane via biological methanation (PBME), can use a wide variety of inputs as feedstock f for biomethane production; therefore, one should consider the generated biomethane from these technologies as FGB if they use energy crops as feedstock ($f \in F^{FGB}$). Furthermore, biomethane that is consumed for other purposes (e.g., power production and the chemical industries), $s \in S'$, are excluded from this target. Fig. 1 delineates the flow of input materials (i.e., various feedstocks) to the technologies that produce biomethane and their output after conversion to sectors.

Eqs. (2) and (3) set an upper bound on energy production from technologies that require UCO or animal fat (i.e., I^{Oil}). The annual production from UCO is capped by ρ_t^{Oil}. Eqs. (4) and (5) define a minimum production level for technologies that are categorized as advanced biofuels ($i \in I^{Adv}$). Advanced biofuels (the so-called second and third-generation biofuels) are produced from wastes or biogenic materials that have no conflict with the food supply chain. For instance, the technology pathways that convert the lignocellulosic biomass to ethanol or methanol belong to this category. Eqs. (6) and (7) promote the use of synthetic fuels (e-fuels) and SAFs in the aviation sector ($s \in AV$), respectively. The import of e-fuels is captured via $\mu_{t,AV}$. Moreover, δ_t^{AV} denotes the energy demand of the aviation sector. Finally, Eq. (8) limits the import of e-fuels from other countries.

To ensure that readers from various disciplines can easily comprehend this manuscript, we have provided an explanation in Appendix A regarding our approach to linearize the first target (i.e., GHG quota) in the BENOPTex model. While we encourage modelers to refer to Appendix A for a detailed understanding of our methodology, readers primarily interested in policy discussions may skip it. Finally, the interested modelers are also invited to read the supplementary document of Millinger et al. (2022b) for more information regarding the unit of parameters and other constraints.

2.2. Scenarios

For this study, we define three scenarios as substitute directives post-2030: the *Base*, *Conservative*, and *Progressive* scenarios. Under the base scenario, which is adopted from the reference scenario of the BEniVer project (Esmaeili Aliabadi et al., 2023b), we assume that policymakers keep targets #2–#4 after 2030 similar to the corresponding values in RED II. Also, we do not presume a shift in diet and thus a change in food production requirements (Chan et al., 2022b). Under alternative scenarios (progressive and conservative), the parameters and assumptions are modified to demonstrate the impact of changing factors on the import and production of alternative fuels across sectors. Under the conservative scenario, we assume that people's diets will shift moderately toward vegetarianism until 2050, while the number of BEVs stays the same as in the base scenario. On the other hand, the progressive storyline assumes BEVs' ownership cost decreases, which subsequently boosts the number of BEVs in the market. Advanced biofuels are promoted, while the FGBs are counted as obsolete. Under this setting, the population shifts their diets toward vegetarian diets (Chan et al., 2022a).

The targets and parameters of each scenario are quantified and summarized in Table 2. The conservative scenario steered by a lower GHG quota level compared to the progressive and base narratives. Although there is a debate to decrease the second target for FGBs to zero due to the impact of the Russo-Ukrainian war on food security, no decision has been made at the time of conducting this study (Heinen and Vilela Oliveira, 2022). Therefore, we assume the previous values (i.e., 4.4%) for the base scenario and increase it by 1% annually for the conservative scenario. Nonetheless, considering the possibility of parliament voting in favor of zero FGBs, we decreased the second target drastically by 50% every year under the progressive scenario. The ratio of biofuels produced from used cooking oil is assumed to increase and decrease by 5% per year under conservative and progressive scenarios, respectively. Under conservative scenario, we assume that the minimum advanced biofuels are decreased slightly (1% annually) due to significantly higher production costs. Conversely, under the progressive scenario the minimum ratio for advanced biofuels increases 10% annually. The land used for planting energy crops decreases slightly under conservative scenario from 2.4 million hectares (Mha) to 2.1 Mha. We adopt 4 Mha for the progressive scenario similar to ENSPRESO database (Ruiz et al., 2019). This increase can be justified by practicing organic farming methods, which require larger amounts of land (Treu et al., 2017) and the freed-up land occurring due to shifts toward plant-based shift (Chan et al., 2022b).

In the aviation sector of the base scenario, the energy consumption is adjusted according to the business as usual (BAU) scenario considering the COVID-19 pandemic from 4D-Race (Scheelhaase et al., 2016). 4D-Race is a calculation model that generates air traffic emission inventories to determine climate effects. Under the conservative and progressive scenarios, we assume that the energy demand in the aviation sector is lower than the corresponding values in the base scenario to reflect better aircraft fuel efficiency in the future based on 4D-Race. For road transportation, we employ the Vector21 model, which is a simulation model enabling us to evaluate individual technologies in the overall context of light- and heavy-duty vehicle fleets considering techno-socio-political frameworks (Mock, 2010). The energy demand for freight transportation is retrieved from the reference and direct electrification (DEL) scenarios of Vector21. However, for passenger transport, the number of vehicles is adopted from the reference and DEL scenarios, and the calculated energy demand by fuel types is given as an upper bound to the BENOPTex model. Doing so will allow our model to incorporate its knowledge regarding the availability of alternative fuels and their costs into the decision of car owners. Finally, the Renewable Energy Mix (REMix) model (Gils et al., 2017) calculates the availability of excess renewable electricity and a dedicated amount for electrolysis in each hour.[2] REMix also computes the average electricity prices on the day-ahead market using the merit order of thermal power plants' dispatch (Cebulla and Fichter, 2017), which means the strategic bidding behavior of power generation companies is ignored (Aliabadi and Chan, 2022). REMix is a linear optimization model that optimizes capacity development as well as the dispatch, storage, and transmission of electricity on an hourly basis. Since the German electricity system is part of the European grid, neighboring countries are also modeled in REMix. The optimization is carried out myopically for the four years 2020, 2030, 2040 and 2050. The techno-economic model parameters are largely based on Gils et al. (2021). Demand scenarios and fuel conversion assumptions stem from the BEniVer project.[3]

2.3. Model description

BENOPTex generates the specified scenarios in MATLAB and solves them using an optimization model, which is implemented in GAMS. We run the model considering bi-hourly time resolution for Germany as one node. Similar to Aliabadi et al. (2022), BENOPTex is solved with parallelization on a workstation with 224 Intel Xeon Platinum–8280 processors and 768 GB RAM. The GAMS software has been set up to allocate six threads to the CPLEX solver, with one thread each for the primal and dual simplex algorithms and the remaining four threads for the interior point method. The run time spans a wide range from 1325 s (when maximizing the GHG abatement, z^{GHG}) to 34,768 s (when minimizing the total system cost, z^{c}), depending on the scenarios configurations.

2.4. Other assumptions and limitations

In this study, we assume vehicles can consume pure bioethanol and biodiesel instead of fossil gasoline and diesel. Although current German vehicles are only capable of tolerating a blend ratio of up to 10% ethanol, the technical issues associated with using higher ratios have been addressed for some time (Pacini and Silveira, 2011; Konjević et al., 2023). Also, the potential benefits and associated rewards make this analysis a worthwhile effort (Unglert et al., 2020). We thereby implicitly assume that significant shares of gasoline vehicles that are being purchased in the coming years are flex fuel vehicles capable of coping with higher shares of oxygen in bio-based fuel products.

There are new proposals, such as '*FuelEU* Maritime Initiatives', to eliminate shipping CO_2 emissions (European Commission, 2021; Christodoulou and Cullinane, 2022). This proposal aims to lower the GHG intensity of energy consumed by ships during their operation in comparison to a reference value in 2020. Korberg et al. (2021) show that biofuels (especially methanol) can be cost-competitive alternatives to replace fossil fuels in the maritime sector. While this study does not consider shipping emissions as part of the GHG quota requirements, a post-processing analysis will be carried out for each scenario.

3. Results and discussions

In the following, the model results for the case of Germany are first presented in the same differentiated manner for each scenario and then used for a scenario comparison.

[2] we adopt the reference scenario where BENOPTex and REMix reached consistent results through soft-coupling (Aliabadi et al., 2021; Esmaeili Aliabadi et al., 2023b).

[3] https://www.ufz.de/index.php?en=46330

Table 2
Varying parameters of the scenarios considered for Germany.

Targets	Base scenario	Conservative scenario	Progressive scenario
1 - GHG Quota (%)			
2035	33	31.4	41.8
2040	45	42.0	56.0
2045	60	56.2	74.9
2050	80	75.0	98.2
2 - FGBs (%)			
2035	4.4	4.62	0.14
2040	4.4	4.86	0.00
2045	4.4	5.11	0.00
2050	4.4	5.37	0.00
3 - UCO (%)			
2035	1.9	2.81	1.70
2040	1.9	3.58	1.32
2045	1.9	4.57	1.02
2050	1.9	5.84	0.79
4 - Advanced biofuels (%)			
2035	2.6	2.47	4.19
2040	2.6	2.35	6.74
2045	2.6	2.24	10.86
2050	2.6	2.13	17.49
Land for energy crops (Mha)			
2020	2.4	2.4	2.4
2050	2.2	2.1	4.0
Aviation 4D-Race (PJ)	BAU w. COVID	Conservative w. COVID	Progressive w. COVID
2035	514	510	508
2040	555	546	538
2045	603	596	565
2050	666	655	597
Freight - Vector21 (PJ)	REF scenario	REF scenario	DEL scenario
2035	568	568	586
2040	531	531	510
2045	454	454	414
2050	405	405	374
LDVs - Vector21 (number of passenger cars)			
	REF scenario	REF scenario	DEL scenario
Excess renewable electricity according to REMix			
Diet composition	No shift	Moderate veg.	More veg. diet
2020	100% BAU	100% BAU	100% BAU
2050	100% BAU	10% veg and 90% BAU	30% veg and 70% BAU

3.1. Base scenario

Fig. 2 depicts the GHG quota trends ($\hat{\rho}_t^{GHG}$) of the base scenario. The black trend shows the GHG quota when the optimization model minimizes the total system cost (z^c), considering the minimum acceptable values (ρ_t^{GHG}, delineated with a red dashed-line) as constraints. The inset plot at the right-bottom corner also depicts the distance between ρ_t^{GHG} and $\hat{\rho}_t^{GHG}$ when minimizing cost. One can notice that the black trend approaches the minimum requirements by REDs (the red dashed-line) at the beginning (i.e.,2023–2024) and at the end of the time horizon (i.e.,2047–2050). The gap between the two trends widens until 2032 before narrowing toward 2047. This behavior is due to heavy investment in the electrification of passenger vehicles, which accounts for the largest share in end-use energy demand in the transport sector. However, the model opts to invest in other energy carriers at the end of the time horizon as electricity final energy demands increase in other sectors. The inset plot indicates imminent and distant barriers that must be overcome using short- and long-term plans. The imminent barrier, which appears before 2025, necessitates ramping-up electrification of passenger vehicles. However, the distant barrier should be addressed through research and development in commercial transportation (e.g., freight, aviation, and maritime). It should be noted that any GHG quota requirements below the corresponding values in the cost-optimal solution ($\rho_t^{GHG} \leq \hat{\rho}_t^{GHG}$) have no impact on the optimality and the feasibility of the cost-optimal solution. For instance, increasing RED requirements from 25% to 40% in 2030 will not impose any burden on stakeholders as they already choose business-driven strategies beyond requirements.

Fig. 13 compares the total system cost of various scenarios. The total system cost of the optimal solution considering ρ_t^{GHG} mentioned in the base scenario when optimizing z^{GHG} is more than twofold of the optimal system cost (z^c). This comprises all costs included according to Eq. (A.11) cumulatively for the years 2020 to 2050. This cost difference is due to heavy investment in expensive technologies (e.g., production of ethanol from lignocellulosic biomass) and feedstock to exhaust potential resources.

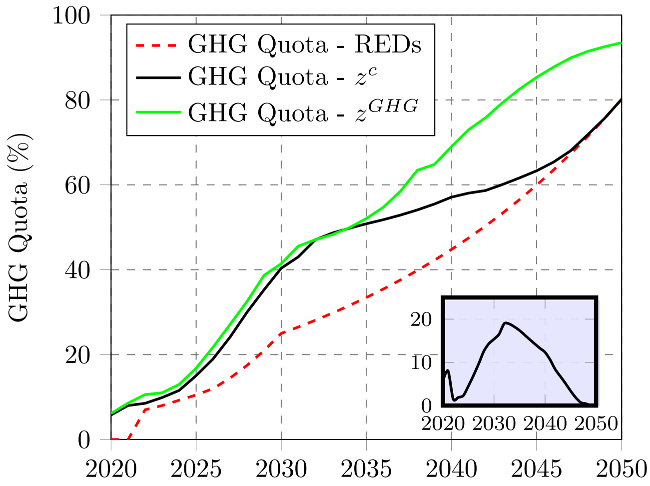


Fig. 2. $\hat{\rho}_t^{GHG}$ trend of the optimal solution (solid black line) until 2050 versus minimum requirement (dashed red line) under the base scenario. The GHG quota corresponding to the z^{GHG} is depicted in green. The small window shows the distance (in %) between red and black trends. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Counterintuitively, the $\hat{\rho}_t^{GHG}$ trend for z^c outperforms the corresponding trend when optimizing z^{GHG} in a few years, such as 2033. This phenomenon is due to the fact that the optimization model is maximizing the total GHG abatement for the whole time horizon (from 2020 until 2050). Since the state of the energy system each year can influence the state in the following years, we cannot split this model into blocks of years and solve them independently. Thus, there might exist a year in which $\hat{\rho}_t^{GHG}$ when minimizing the total system cost outperforms the same variable when maximizing the total avoided emissions. Nonetheless, the total area under green trend (i.e., 15.82) is larger than the corresponding area under black trend (i.e., 13.38). The coupling constraints of BENOPTex have been visualized in Aliabadi et al. (2022, Figure 2).

Fig. 3 depicts the optimal distribution of biofuels and e-fuels under the base scenario in Germany for the different transport modes, including road (passenger and freight transport), rail, marine, and aviation, when minimizing z^c. Based on Fig. 3, domestic production is insufficient to fulfill the predetermined GHG requirements, especially toward the end of the time horizon; therefore, Germany has to import around 150 PJ of synthetic kerosene (the light blue areas on top of the charts) from other countries.

When optimizing z^{GHG}, the model boosts substituting fossil fuels with imported synthetic fuel from other countries, as shown in Fig. 4. The imported synthetic fuel first replaces fossil gasoline and then fossil diesel. Based on Fig. 4, in the passenger transport sector, the higher efficiency of BEVs can reduce energy demand while meeting the necessary vehicle-km requirements, leading to near GHG-neutrality by 2050. However, the freight, marine, and aviation sectors need other energy carriers due to the poor energy density of batteries for these applications. In these hard-to-abate sub-sectors, liquefied methane (LCH4) and biofuels, especially from the biomass-to-liquid (BtL) process, play a central role. To further reduce emissions in the aviation sector, the development of infrastructure to produce SAF (i.e., bio-kerosene) through the BtL process is necessary.

Fig. 5(a) and Fig. 5(b) show the average production cost of biodiesel and bioethanol through years based on offered volume and price for each technology. The increasing share of advanced biofuels alleviates the conflict between food and bioenergy supply chains; however, it comes with a cost. When optimizing z^c, the average biodiesel and bioethanol costs rise from €0.97/liter in 2020 to €2.1/liter in 2050, and from €0.68/liter in 2020 to €1.7/liter in 2050, respectively. However, when optimizing z^{GHG}, the final production cost for one liter of biodiesel and bioethanol can rise even higher to €3.1 and €2 in 2050, respectively. The increase can be attributed to the fact that the optimization model under z^{GHG} prioritizes utilizing available biomass, regardless of its cost. As a result, BENOPTex chooses to consume both cheap and premium feedstock (i.e., $\dot{m}_{tifc}$, $\forall c$).

3.2. Conservative scenario

Fig. 6 exhibits the quota trends under the conservative scenario. The collected insights from Fig. 2 are valid for this figure. One major difference is the gap at 2050 between RED requirements and $\hat{\rho}_t^{GHG}$ when optimizing z^c. This relaxed constraint on the model will reduce the optimal objective function compared to the base scenario. The inset plot indicates that the distance between $\hat{\rho}_t^{GHG}$ and ρ_t^{GHG} never reaches zero, when optimizing z^c. Lowering GHG quota requirements below $\hat{\rho}_t^{GHG}$ weakens the enforceability of the regulations.

Fig. 7(a) and Fig. 7(b) show the required set of technologies to fulfill the energy demand of the transport sector under conservative scenarios when optimizing z^c and z^{GHG}, respectively. Upon comparison of the base scenario with the corresponding plots, it can be observed that the technology set remains unchanged between the two storylines, despite differences in energy demands in various transportation sectors.

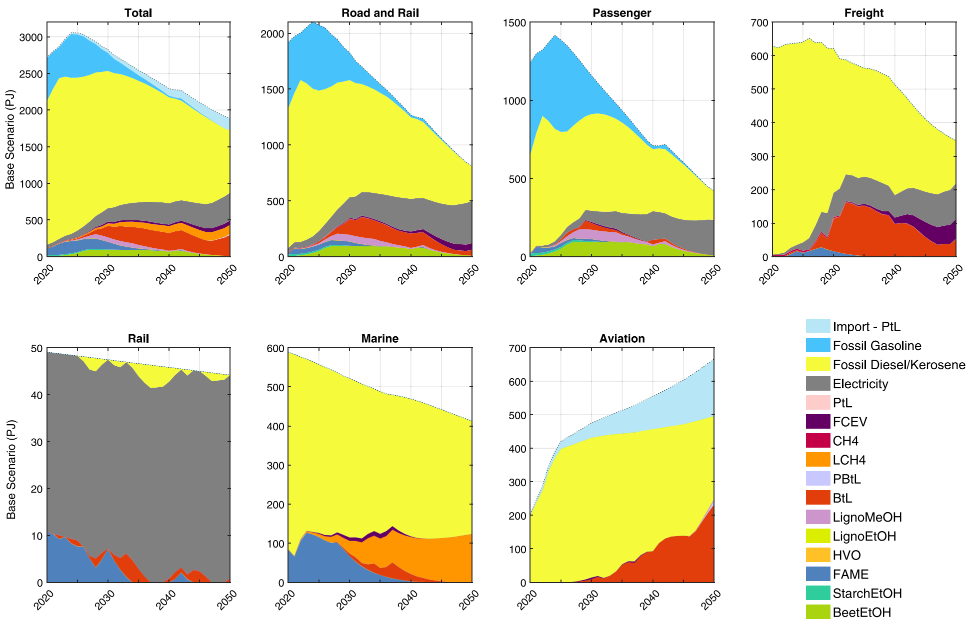


Fig. 3. The distribution of alternative fuels in various transport sectors in petajoules (PJ) under the base scenario when optimizing z^c. The dash lines illustrate the energy demand by each sub-sector considering energy efficiency improvement. PtL: Power-to-Liquid, FCEV: fuel cell electric vehicle, LCH4: liquefied methane (incl. biomethane), BtL: Biomass to liquids via Fischer–Tropsch, PBtL: Power-to-Hydrogen + BtL, LignoMeOH: Lignocellulose-based methanol, LignoEtOH: Lignocellulose-based ethanol, HVO: Hydrotreated vegetable oil, FAME: Fatty-acid methyl ester, StarchEtOH: Starch-based ethanol, and BeetEtOH: Sugar beet-based ethanol. The yellow area represents fossil kerosene in aviation and fossil diesel in others. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

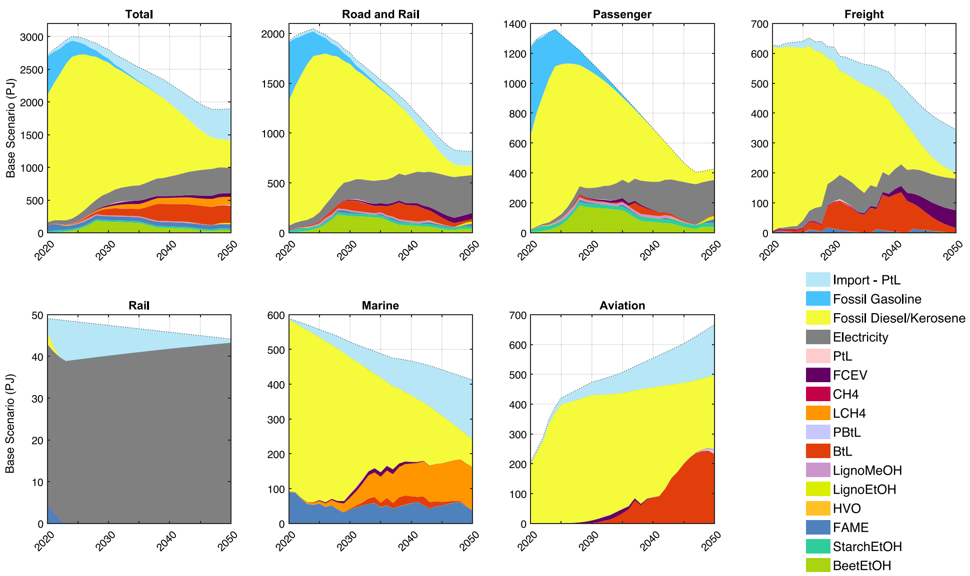
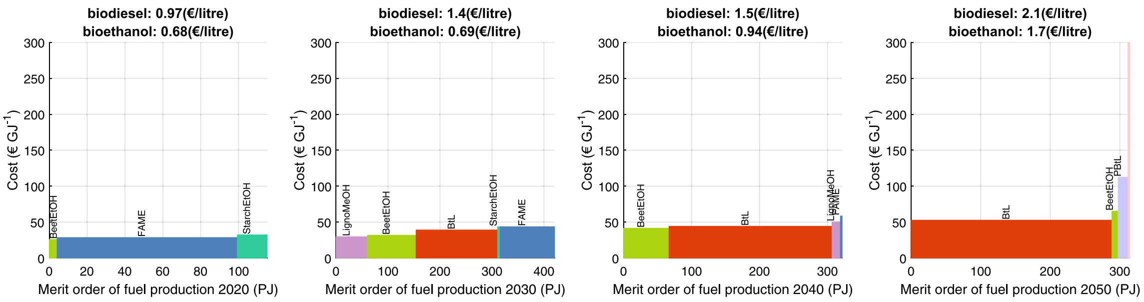


Fig. 4. The distribution of alternative fuels in various transport sectors (in PJ) under the base scenario when optimizing z^{GHG}. The dash lines illustrate the energy demand by each sub-sector considering energy efficiency improvement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As shown in Figs. 8(a) and 8(b), under the conservative scenario, the average production cost of domestic biodiesel and bioethanol is lower compared to the base scenario when optimizing z^c. This is due to the less stringent GHG requirements under the conservative setting, which allows the optimization model to choose cheaper feedstock and technologies (e.g., FGBs) over the more expensive ones (e.g., advanced biofuels). When optimizing the GHG function, the average costs will be still lower in most cases under the conservative scenario compared to the base scenario due to lower energy demand in the aviation sector.

(a) The average production cost of bioethanol and biodiesel from various technologies when optimizing cost function.



(b) The average production cost of bioethanol and biodiesel from various technology through years (2020-2050) when optimizing GHG function.

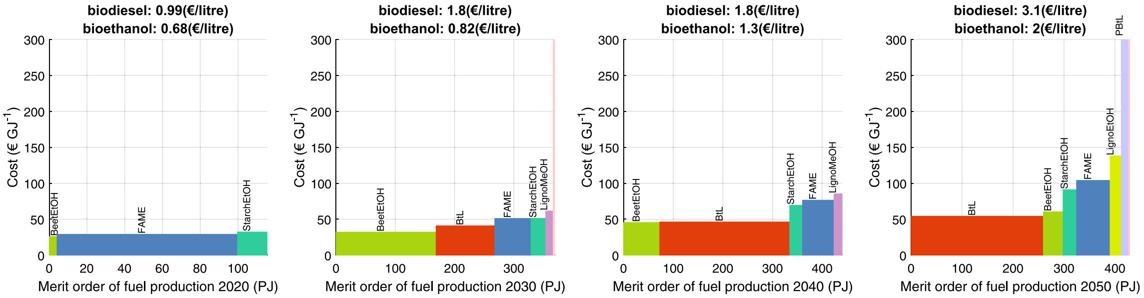


Fig. 5. The selected set of technologies by the model in 2020, 2030, 2040, and 2050 that produce domestic alternative fuels under the base scenario. The cumulative quantity is displayed on the horizontal axis of each plot, while the vertical axis showcases the cost per gigajoule of energy in a merit-order arrangement.

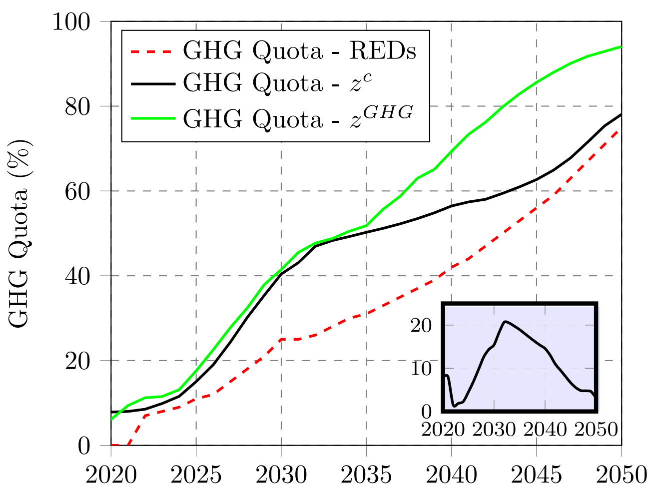
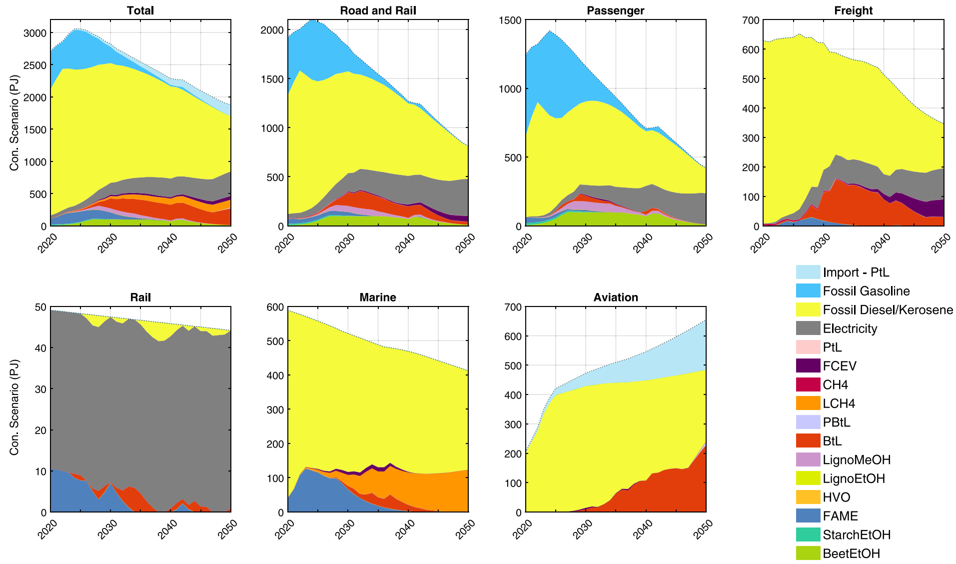


Fig. 6. $\hat{\rho}_t^{GHG}$ trend of the optimal solution (solid line) until 2050 versus minimum requirement (dash line) under the conservative scenario. The GHG quota corresponding to the z^{GHG} is depicted in green. The inset plot shows the distance between black and red trends (in %). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Progressive scenario

The progressive scenario demonstrates that the complete de-fossilization of the transport sector is a technological and economic challenge. When optimizing z^{GHG}, $\hat{\rho}_t^{GHG}$ can reach 98.2% by 2050 (see Fig. 9). To reach carbon neutrality, either the remaining

(a) The distribution of alternative fuels when optimizing z^c.



(b) The distribution of alternative fuels when optimizing z^{GHG}.

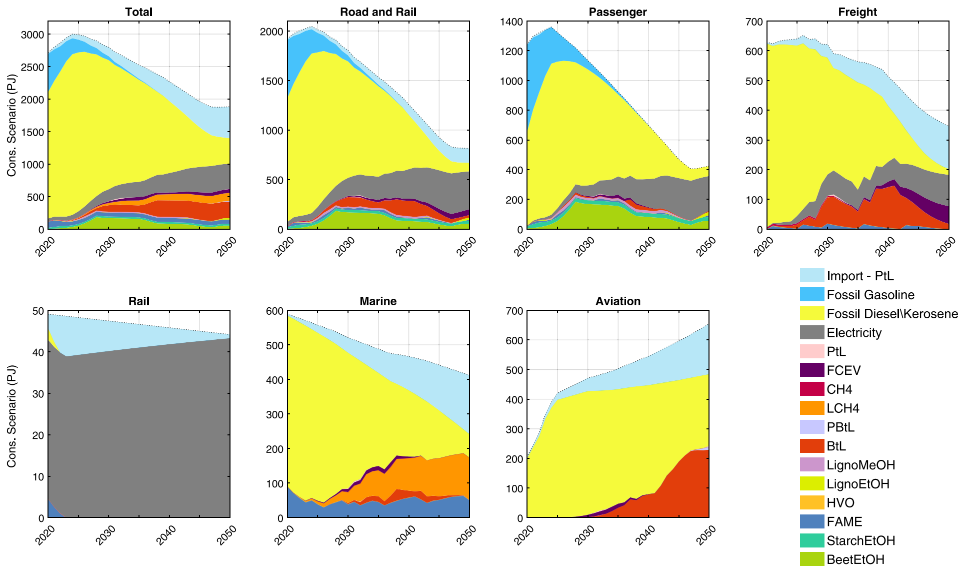
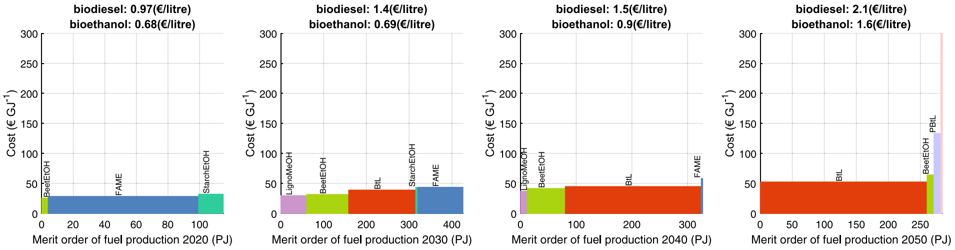


Fig. 7. The distribution of alternative fuels in various transport sectors in petajoules (PJ) under the conservative scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

emissions should be absorbed by negative emission technologies or additional synthetic fuels should be imported from other countries. The inset plot in Fig. 9 proclaims that the growth rate of $\hat{\rho}_t^{GHG}$ when maximizing z^{GHG} raises until 2026 and drops afterward (i.e., $\frac{\partial \hat{\rho}_t^{GHG}}{\partial t}$).

The unsteady curves in Fig. 10(a) are due to fluctuations in the number of passenger vehicles, as calculated by Vector21. Under the base scenario, Vector21 estimates that the number of passenger vehicles will steadily decrease from 47.5 million in 2020 to 43.4 million in 2050; however, under the progressive scenario, Vector21 predicts a quadratic trend, with the number of vehicles dropping to 44 million by 2031, before increasing back to 47.5 million in 2050, mostly due to the growth in the number of BEVs. Unlike the base and conservative scenarios, fossil gasoline consumption is expected to cease by 2045. This is due to stringent GHG quota requirements in later years (see Fig. 9). Fig. 10(b) shows freight transport as a critical sector, that requires additional synthetic fuels to becoming fully GHG neutral. We also see that bioethanol production for passenger transport using lignocellulosic biomass

(a) The average production cost of bioethanol and biodiesel from various technologies when optimizing cost function.



(b) The average production cost of bioethanol and biodiesel from various technologies when optimizing GHG function.

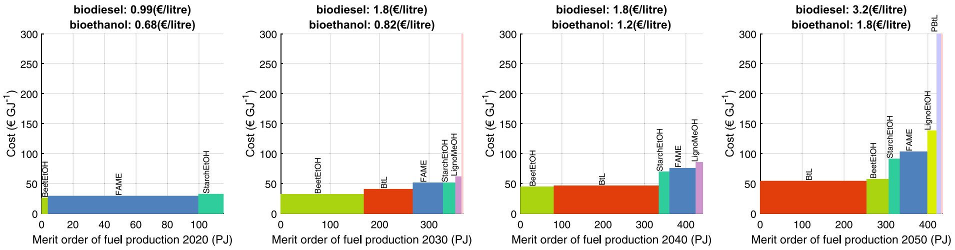


Fig. 8. The selected set of technologies by the model in 2020, 2030, 2040, and 2050 that produce domestic alternative fuels under the conservative scenario. The cumulative quantity is displayed on the horizontal axis of each plot, while the vertical axis showcases the cost per gigajoule of energy in a merit-order arrangement.

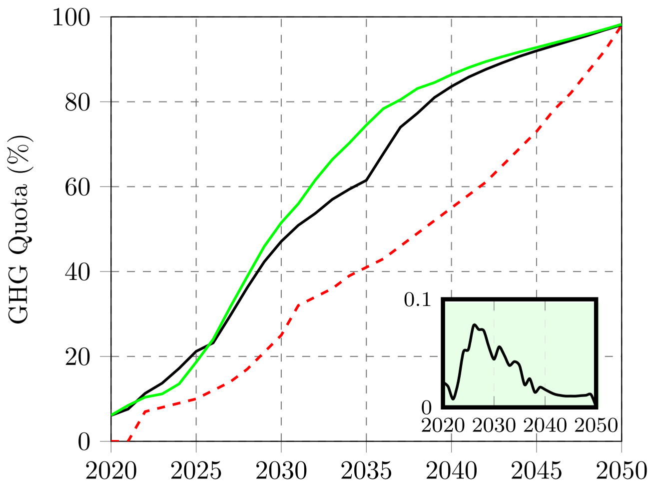
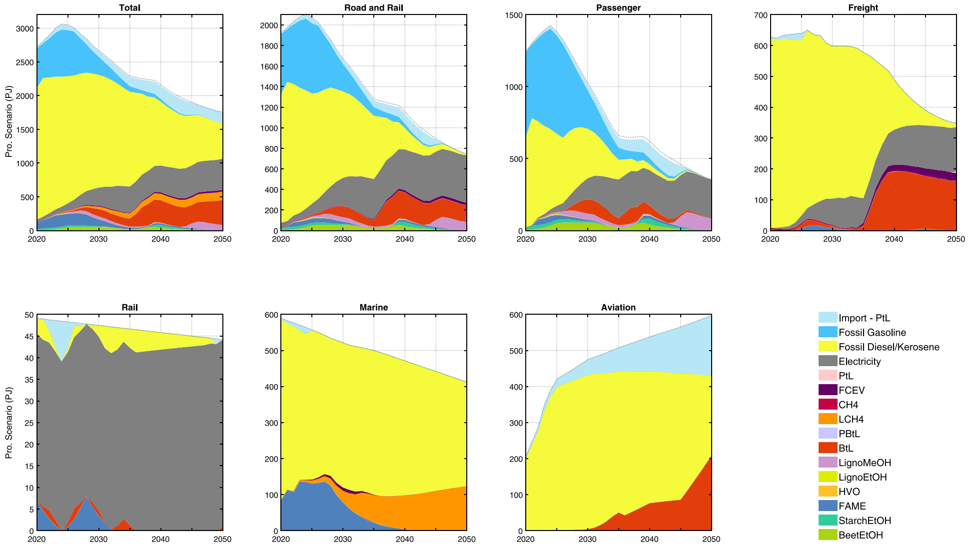


Fig. 9. $\hat{\rho}_t^{GHG}$ trend of the optimal solution (solid line) until 2050 versus minimum requirement (dash line) under the progressive scenario. The GHG quota corresponding to the z^{GHG} is depicted in green. The inset plot shows the gradient of $\hat{\rho}_t^{GHG}$ when optimizing z^{GHG}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(LingoEtOH) is ramping up at the end of the time horizon. Biodiesel production using the Fischer–Tropsch process (in BtL) is also more underlined in marine and freight transport. Moreover, H_2 consumption is higher in fuel-cell heavy-duty vehicles, as specified by Vector21.

Although the demand for alternative fuels is higher under the progressive scenario compared to the base scenario, the production cost is lower at the end of the time horizon. In 2050, the production cost of biodiesel and bioethanol are €1.9 and €1.1 per liter, respectively, as shown in Fig. 11(a). The main reason for the lower average production cost is the replacement of expensive technologies (e.g., PBtL) with BtL, considering FGBs as obsolete. When optimizing z^{GHG}, the average production cost will be slightly higher.

(a) The distribution of alternative fuels when optimizing z^c.



(b) The distribution of alternative fuels when optimizing z^{GHG}.

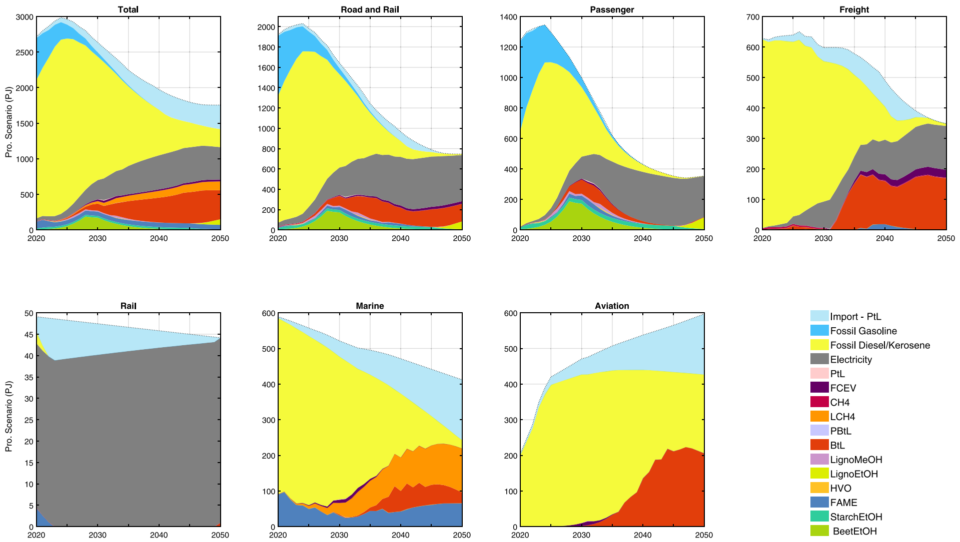


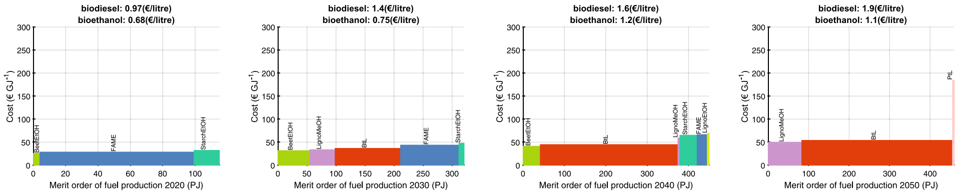
Fig. 10. The distribution of alternative fuels in various transport sectors in petajoules (PJ) under the progressive scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Maritime emissions

The FuelEU Maritime initiative wants to support the uptake of renewable and low-carbon maritime fuels, as well as fossil LNG, by introducing limits on carbon intensity of the energy used on board ships. It also offers to treat conventional biofuels similar to those of fossil fuels. Using PRIMES-Maritime, the European Commission exhibits the significance of LNG from biological sources and biofuels in decarbonizing maritime (Commission et al., 2021, Table 2). Fig. 12 depicts the GHG reduction compared to the value of 2020 in six settings (three scenarios and two objective functions).

According to our calculations, the cost-optimal scenarios (optimizing z^c) allow the de-fossilization of maritime according to the FuelEU guidelines until 2040; however, they fall short to reach 2050 values. Boosting the GHG reductions beyond 2040 values demands more investment in bioLNG and imported synthetic fuels, which should be supported by policymakers. This outcome has also been emphasized by Christodoulou and Cullinane (2022).

(a) The average production cost of bioethanol and biodiesel from various technologies when optimizing cost function.



(b) The average production cost of bioethanol and biodiesel from various technologies when optimizing GHG function.

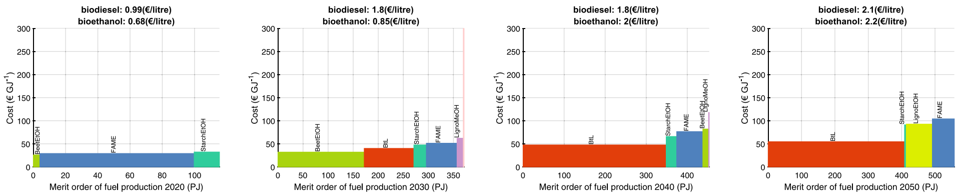


Fig. 11. The selected set of technologies by the model in 2020, 2030, 2040, and 2050 that produce domestic alternative fuels under the progressive scenario. The cumulative quantity is displayed on the horizontal axis of each plot, while the vertical axis showcases the cost per gigajoule of energy in a merit-order arrangement.

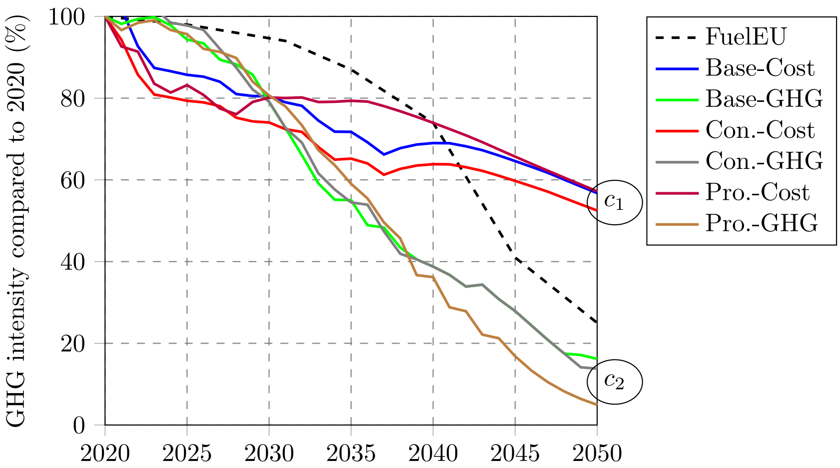


Fig. 12. The GHG reduction compared to 2020 in maritime. c_1 shows the group of cost-driven scenarios, while c_2 illustrates the collection of climate policy-driven scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.5. Managerial insight

The following managerial insights can be derived based on the model results:

- The German transport sector cannot be completely de-fossilized without imported alternative fuel.
- There exist two technological and managerial obstacles that should be addressed. First, policymakers need to step up their efforts to ensure that the widespread electrification of passenger vehicles succeeds as early as possible. The second challenge appears when policymakers impose more stringent GHG quota requirements. This will still require a major effort in many areas to research and develop new environmentally friendly technologies for commercial transport. This outcome is in accordance with Millinger et al. (2022a), which demonstrates that it is cost-effective to reduce emissions by around 2040 with partial electrification of transport, heat, and industry.
- The current requirement for the GHG quota (for road and railway transport) in 2030 can be stricter ($\leq 40\%$) without having a noticeable impact on the cost of the optimal strategy.

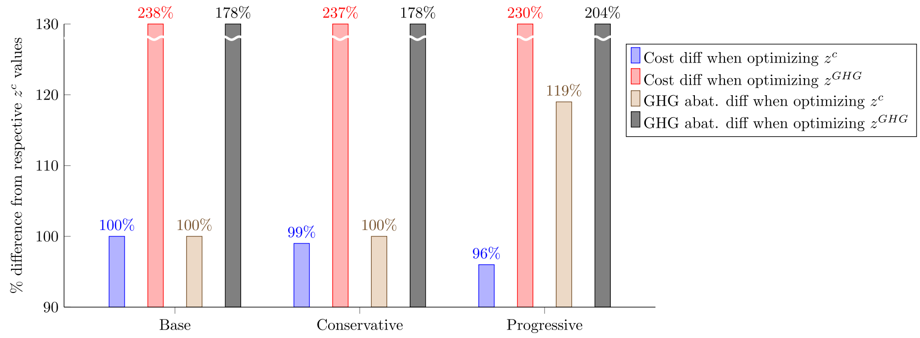


Fig. 13. The cost and GHG abatement differences among scenarios compared to respective values when optimizing the total system cost (z^c) under the base scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Biodiesel production using BtL and biomethane liquefaction are two promising pathways that can have substantial impacts on future cargo transportation. By employing these technologies, the transportation industry can rapidly reduce its dependency on fossil fuels.
- To achieve the required high GHG energy intensity reductions in maritime transport post-2040, policymakers should promote alternative fuels more vigorously.
- Fig. 13 depicts the variation in costs and the GHG abatement levels (in %) compared to the base scenario when optimizing the total system cost. The cost and GHG variation between scenarios is negligible, while the intent of policymakers to implement ambitious policies and mobilize the full potentials, can have a dramatic impact on total system cost and the GHG abatement level. As shown here, the additional cost impacts the amount of the GHG reduction positively. When optimizing the GHG abatement, the model does not consider the cost of the solution, which is why a large gap appears between optimal solutions. Policymakers can adopt a Pareto optimal solution, thereby achieving a lower cost with an acceptable GHG abatement level.

4. Conclusion

In this manuscript, we endogenously formulate the requirements of the European renewable energy directives for Germany in a bioenergy-oriented optimization model, the so-called BENOPTex. The non-linear constraint that takes into account the GHG-quota mechanism is linearized and embedded to study the interplay between various transport modes considering up- and down-stream of bioenergy and renewable energy supply chain. The results highlight the salient role of imported synthetic fuels in the future German transport sector. To reach a fossil-free transport sector, our model identified two critical time intervals that require additional efforts in both the political arena and technology development. By contrasting various scenarios, key technologies with profound impact on heavy-duty transport are identified. While road and railway transport may achieve higher GHG reductions between 2030 and 2045 compared to the presumed requirements dictated by the GHG quota due to the direct electrification of vehicles, policymakers should promote alternative fuels more strongly in maritime transport post-2040 to achieve the required GHG energy intensity reductions. The assumption of different objective functions (costs versus emissions) and scenarios (baseline, conservative, progressive) in the modeling have a partly significant impact on the merit order of the alternative transport technologies and their temporal implementation paths. In terms of the total costs of the transformation, however, the resulting differences between the three scenarios are rather small, whereas the choice of the optimization objective function has a very large influence. The optimization of GHG reduction causes consistently higher system costs by a factor of 2 to 2.5, whereby GHG emissions are lower by a factor of 1.7 to 2 over the entire period until 2050 than in the cost-optimized case.

This study can be extended in numerous directions. Our model assumes that future vehicles can accept any blend ratio of biofuels with fossil fuels. However, the current fleet of automobiles can accept a fuel mixture of 10% bioethanol and 90% gasoline. Therefore, one can model the future design of vehicles to reflect the mechanical/physical properties of future engines. Investigating the impact of ammonia produced from biomass for the maritime sector seems an interesting topic. A more differentiated look into the trade-offs between domestic e-fuel, domestic biofuel production and e-fuel imports also seems promising. Refining the BENOPTex model spatially (Esmaeili Aliabadi et al., 2023a) and temporally (Sadr et al., 2023) can assist us in distinguishing progressive regions from those that lag behind. Finally, enriching the technology portfolio can also be pursued by including negative emissions technologies (Wollnik et al., 2023).

CRediT authorship contribution statement

Danial Esmaeili Aliabadi: Conceptualization, Methodology, Visualization, Formal analysis, Investigation, Data curation, Coding, Writing – original draft, Writing – review & editing. **Katrina Chan:** Formal analysis, Writing – original draft. **Niklas Wulff:** Formal analysis, Writing – original draft. **Kathleen Meisel:** Conceptualization, Formal analysis, Writing – original draft. **Matthias Jordan:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Ines Österle:** Formal analysis, Investigation. **Thomas Pregger:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Daniela Thrän:** Writing – original draft.

Declaration of competing interest

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

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Appendix A. Formulating the GHG quota

To model the GHG quota scheme in target #1, one should calculate the (real) emissions (γ_t^N) in the transport sector over a reference value (γ_t^D) at year t. Eq. (A.1) describes the GHG quota in simple terms: ρ_t^{GHG} represents the minimum permissible value for the GHG quota target at year t, determined by political instruments (see target #1 in Table 1), while the left-hand side (i.e., $\hat{\rho}_t^{GHG}$) represents the decision variable corresponding to the achieved value in the solution at year t.

$$\overbrace{100\% - \frac{\gamma_t^N}{\gamma_t^D}}^{\hat{\rho}_t^{GHG}} \geq \rho_t^{GHG} \qquad \forall t \in T \tag{A.1}$$

Eq. (A.1) is a non-linear constraint and cannot be added to the model in its current form; however, it is known that $\gamma_t^D \geq \gamma_t^N$ and $\gamma_t^D > 0$ by definition. Thus, Eq. (A.1) can be linearized, as shown in Eq. (A.2).

$$\gamma_t^D - \gamma_t^N \geq \rho_t^{GHG} \times \gamma_t^D \qquad \forall t \in T \tag{A.2}$$

According to the credit framework in RED II, additional factors are associated with each fuel type (Pavlenko et al., 2019; Naumann et al., 2021), of which the powertrain efficiency and multi-counting factors are notable. The powertrain efficiency factor takes into account the fuel performance respecting the employed end-use technology. For instance, the powertrain efficiency factors of hydrogen in fuel cell electric vehicles (FCEVs) and electricity in battery electric vehicles (BEVs) are equal to 0.4. On the other hand, the multi-counting factor is a political instrument that reflects the significance of alternative fuels in achieving climate targets (e.g., electricity used in BEVs has a triple counting factor). Bannert et al. (2023) analyze the impact of different multi-counting factor values for the years 2023 and 2030 on the generated revenues and the market ramp-up of renewable energy in the transport sector.

Eqs. (A.3) and (A.4) formulate the real and reference GHG emissions, respectively. The Upstream Emission Reduction (UER) measures the reduced emissions from crude oil production. We assume a modest value of 0.36% for UER in our model. The emission factor of petroleum products, ε_t^{FF} (ktCO$_2$eq/PJ), is multiplied by the annual demand for petroleum products, δ_t^{FF} (PJ). In Eq. (A.5), δ_t^{FF} is calculated by subtracting the produced energy from the total energy demand in the rail and road sectors. While the counting factor for FGB and UCO technologies is one, the advanced biofuels differentiate the base and extra production: The advanced biofuels produced over the base level of 2.6% are double-counted. Eq. (A.6) specifies the minimum (i.e., base level), which can be easily linearized. Eqs. (A.6) and (A.7) assist us to monitor the amount of advanced biofuels above 2.6%. The penultimate term in Eq. (A.3) estimates the GHG emissions from BEVs and FCEVs, considering the powertrain efficiency and multi-counting factors. The last term calculates the GHG emissions from imported and domestically produced e-fuels. In Eq. (A.4), instead of calculating emission factors using Life Cycle Analysis (LCA), a reference GHG emission factor is adopted from Federal Ministry of Justice (2017) ($\mathbb{E}(\varepsilon_{ts}^{sub})$ =94.1 ktCO$_2$eq/PJ).

$$\begin{aligned}
\gamma_t^N = & -UER + \overbrace{\varepsilon_t^{FF} \times \delta_t^{FF}}^{\text{liquid fossil fuels emissions}} + \overbrace{\sum_{i \in I^{FGB}, s \in RR} (\varepsilon_t^i \times \pi_{tis})}^{\text{Emissions from FGBs}} \\
& + \overbrace{(\underline{\varepsilon}_t^{\text{Adv}} \times \underline{\pi}_t^{Adv}) + 2\varepsilon_t^{\text{Adv}} \left(\pi_t^{Adv} - \underline{\pi}_t^{Adv}\right)}^{\text{Emissions from advanced biofuels}} + \overbrace{\sum_{i \in I^{Oil}, s \in RR} (\varepsilon_t^i \times \pi_{tis})}^{\text{Emissions from UCOs}} \\
& + \overbrace{\sum_{s \in RR} 0.4 \left(3 \times \varepsilon_t^{\text{BEV}} \times \pi_{t,\text{BEV},s} + 2 \times \varepsilon_t^{\text{FCEV}} \times \pi_{t,\text{FCEV},s}\right)}^{\text{Emissions from (FC)EVs}} \\
& + \underbrace{2 \times \varepsilon_t^{\text{PtL}} \times \left(\pi_{t,\text{PtL},s} + \mu_{ts}\right)}_{\text{Emissions from imported and produced electricity-based fuels}} \qquad \forall t \in T
\end{aligned} \tag{A.3}$$

$$\gamma_t^D = \mathbb{E}(\varepsilon_{ts}^{sub}) \times (\delta_t^{FF} + \sum_{\substack{i \in I^{FGB} \\ s \in RR}} (\pi_{tis})$$

$$+ \underline{\pi}_t^{Adv} + 2\left(\pi_t^{Adv} - \underline{\pi}_t^{Adv}\right) + \pi_t^{UCO} + \sum_{s\in RR}\left(3\pi_{t,\mathrm{BEV},s} + 2(\pi_{t,\mathrm{PtL},s} + \mu_{ts} + \pi_{t,\mathrm{FCEV},s})\right)) \quad \forall t \in T \tag{A.4}$$

$$\delta_t^{FF} = \delta_t^{RR} - \sum_{i\in I, s\in RR}\left(\pi_{tis}\right) + \mu_{ts} \quad \forall t \in T \tag{A.5}$$

$$\underline{\pi}_t^{Adv} = \min\{2.6\% \times \delta_t^{RR}, \pi_t^{Adv}\} \quad \forall t \in T \tag{A.6}$$

$$\pi_t^{Adv} = \sum_{\substack{i\in I^{Adv}\\ s\in RR}} \pi_{tis} \quad \forall t \in T \tag{A.7}$$

To linearize Eq. (A.6), we replace it with constraints (A.8) and (A.9) and incentivize $\underline{\pi}_t^{Adv}$ in objective functions (i.e., Eqs. (A.10) and (A.11)), which either maximize the GHG abatement level or minimize the total system cost.

$$\underline{\pi}_t^{Adv} \leq 2.6\% \times \delta_t^{RR} \quad \forall t \in T \tag{A.8}$$

$$\underline{\pi}_t^{Adv} \leq \pi_t^{Adv} \quad \forall t \in T \tag{A.9}$$

$$\begin{aligned}\max z^{GHG} = & \overbrace{\sum_{t,i,s}\left(\mathbb{E}(\varepsilon_{ts}^{sub}) \times w_{is} - \varepsilon_t^i\right)\pi_{tis}}^{z_1\text{: Avoided emissions}} - \overbrace{\sum_{t,i,f}\left(\varepsilon_t^f + \varepsilon_t^{tra}\right)\dot{m}_{tif}}^{z_2\text{: Energy crops emissions}} \\ & - \overbrace{\sum_{t,i,r}(\varepsilon_t^{tra} \times \dot{m}_{tir})}^{z_3\text{: Residues emissions}} - \overbrace{\sum_{t,i}(\varepsilon_t^{el} \times \dot{m}_{ti,\mathrm{EL}})}^{z_4\text{: Emissions from electricity}} \\ & - \underbrace{\sum_{t,i,s}(\varepsilon^{CO_2} \times \dot{m}_i^{CO_2} \times \pi_{tis})}_{z_5\text{: Additional emissions from utilized } CO_2} + \underbrace{\lambda\sum_t\left(\underline{\pi}_t^{Adv}\right)}_{z_6\text{: linearizing Eq. (A.6)}}\end{aligned} \tag{A.10}$$

$$\begin{aligned}\min z^c = & \overbrace{\sum_{t,i,s}(m_{ti}^{opex} + \dot{m}_i^{el} \times p_{ti}^{el} + \dot{m}_i^{th} \times p_t^{th} + \dot{m}_i^{CO_2} \times p_t^{CO_2}) \times \pi_{tis}}^{z_7\text{: Production costs}} \\ & + \underbrace{\sum_{t,i}(I_{ti}^{+} \times k_{ti}^{endo})}_{z_8\text{: Investment costs}} + \underbrace{\sum_{t,i,f,g}(p_{tfg} \times \dot{m}_{tifg})}_{z_9\text{: Domestic feedstock costs}} \\ & + \overbrace{\sum_{t,i,f}(p_{tf}^{imp} \times m_{tif}^{imp}) + \sum_{ts}(p_{ts}^{imp} \times \mu_{t,s})}^{z_{10}\text{: Imported feedstock/synthetic fuel costs}} - \underbrace{\mu\sum_t\left(\underline{\pi}_t^{Adv}\right)}_{z_{11}\text{: linearizing Eq. (A.6)}}\end{aligned} \tag{A.11}$$

In this study, we employ two objective functions. The first objective function that maximizes the GHG abatement level (z^{GHG}) consists of two positive terms (i.e., z_1 and z_6), and four negative terms (i.e., z_{2-5}). In z_1, the term within parenthesis specifies the amount of avoided emissions by producing one PJ from technology i at year t for sector s (ktCO$_2$eq/PJ). w_{is} (in %) takes into account the tank-to-wheel relative fuel economy compared to the sub-sector specific reference option. For instance, passenger vehicles that run on electricity or hydrogen can drive multiple times farther than an Otto engine vehicle. Also, ε_t^i is the production emissions of the alternative fuel (biofuels and synthetic fuels) produced by technology i at year t. In z_2, two emission factors are associated with energy crops: emissions from cultivation-related (ε_t^f) and transportation-related (ε_t^{tra}) activities. These emission factors are multiplied by $\dot{m}_{tif}$, which stands for the energy crop f (in PJ) consumed by technology i at year t. For residues (r), z_3 merely considers emissions from transport-related activities. In z_4, we take into account the carbon intensity (ktCO$_2$eq/PJ) of the utilized electricity from the grid (ε_t^{el}). z_5 evaluates the additional CO_2 emissions from fossil fuels that are captured and used for the production of alternative fuels. Since our model uses carbon from renewable sources, z_5 is zero. Finally, z_6 incentivizes the model to increase $\underline{\pi}_t^{Adv}$ to its maximum permissible value, which activates either Eq. (A.8) or Eq. (A.9).

The second objective function (z^c) minimizes the total system cost. As it is evident, z^c consists of five terms including the production (z_7), investment (z_8), consumed feedstock/fuel (including domestic z_9 and imported z_{10}), and a penalty (z_{11}) costs. In z_7, m_{ti}^{opex} (in Mil € per PJ) represents the operational expenditure of technology i at year t (excluding feedstock and energy costs). The second term calculates the electricity cost used by technology i to produce one PJ of energy. The third term incorporates the heating cost used by technology i at year t, and the last term is for the cost of CO_2 per PJ of energy produced by technology i at year t. z_8 specifies the investment cost for establishing new facilities. In z_8, I_{ti}^{+} is a parameter determining the levelized investment cost of new facilities using technology i at year t in Mil € per GW, and k_{ti}^{endo} is a decision variable determining the net installed capacity in GW. p_{tfg} and p_{tf}^{imp} are the unit cost of domestic and imported feedstock f at year t and quality group g, respectively. These unit costs are multiplied by the exploited quantity (in PJ) of domestic and imported feedstock. To be in line with REPowerEU (European

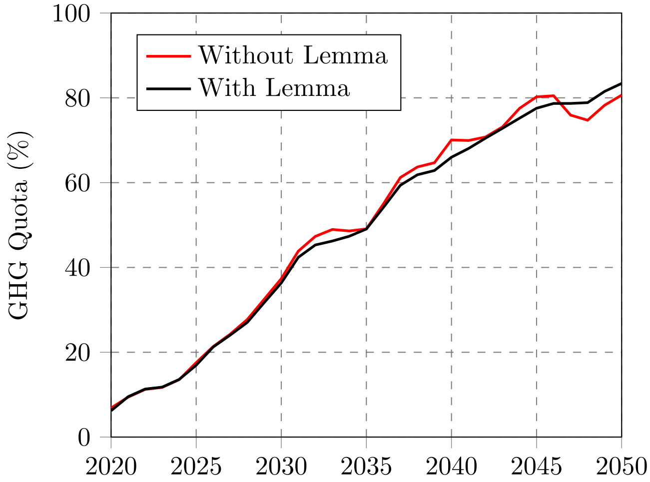

Fig. A.14. The impact of adding constraints for non-decreasing GHG quota trend.

Commission, 2022), we assume that imported synthetic fuel is more expensive than domestically produced fuel, considering external costs such as reliability and sustainability. Similar to z_6, z_{11} incentivizes the model to increase $\underline{\pi}_t^{Adv}$ to its maximum permissible value, which activates either Eq. (A.8) or Eq. (A.9). Determining appropriate values for λ and μ is straightforward in our case, as they are related to the avoided emissions from advanced biofuels and their associated costs.

We expect to witness more rigorous climate-protection policies in the future. To model this strategic behavior, we assume that the GHG quota is a non-decreasing function using Eq. (A.12).

$$\hat{\rho}_t^{GHG} \geq \hat{\rho}_{t-1}^{GHG} \qquad \forall t \in T \tag{A.12}$$

Lemma A.1. *Eq. (A.12) holds if $\gamma_{t-1}^D + \gamma_t^N \leq \gamma_t^D + \gamma_{t-1}^N$, $\forall t \in T$ and $\gamma_{t-1}^D + \gamma_{t-1}^N \geq \gamma_t^D + \gamma_t^N$ when $\gamma_{t-1}^D \geq \gamma_t^N$ and $\gamma_t^D \geq \gamma_{t-1}^N$.*

Proof. We can rewrite Eq. (A.12) as

$$\begin{aligned} &\frac{\gamma_t^N}{\gamma_t^D} \leq \frac{\gamma_{t-1}^N}{\gamma_{t-1}^D} && \forall t \in T \\ \Rightarrow\ &\gamma_{t-1}^D \times \gamma_t^N \leq \gamma_t^D \times \gamma_{t-1}^N && \forall t \in T \end{aligned} \tag{A.13}$$

We can recall from basic algebra that $xy = \frac{1}{4}\left((x+y)^2 - (x-y)^2\right)$ (Constante-Flores et al., 2022). Therefore, the bilinear terms in Eq. (A.13) can be rewritten as

$$\overbrace{\left(\gamma_{t-1}^D + \gamma_t^N\right)^2}^{L_1} - \overbrace{\left(\gamma_{t-1}^D - \gamma_t^N\right)^2}^{L_2} \leq \underbrace{\left(\gamma_t^D + \gamma_{t-1}^N\right)^2}_{R_1} - \underbrace{\left(\gamma_t^D - \gamma_{t-1}^N\right)^2}_{R_2} \ \forall t \in T. \tag{A.14}$$

The inequality of Eq. (A.14) can hold, if the positive part of the left-hand side is smaller than the positive side of the right-hand side ($L_1 \leq R_1$), and the negative side of the left-hand side is larger than the negative side of the right-hand side ($L_2 \geq R_2$):

$$\left(\gamma_{t-1}^D + \gamma_t^N\right)^2 \leq \left(\gamma_t^D + \gamma_{t-1}^N\right)^2 \qquad \forall t \in T \tag{A.15}$$

$$\left(\gamma_{t-1}^D - \gamma_t^N\right)^2 \geq \left(\gamma_t^D - \gamma_{t-1}^N\right)^2 \qquad \forall t \in T \tag{A.16}$$

Knowing that all components of Eq. (A.15) are non-negative, one can take the square root of both sides of Eq. (A.15). Thus, the following linear constraint can be obtained:

$$\begin{aligned} &\sqrt{\left(\gamma_{t-1}^D + \gamma_t^N\right)^2} \leq \sqrt{\left(\gamma_t^D + \gamma_{t-1}^N\right)^2} && \forall t \in T \\ \Rightarrow\ &\gamma_{t-1}^D + \gamma_t^N \leq \gamma_t^D + \gamma_{t-1}^N && \forall t \in T \end{aligned} \tag{A.17}$$

By definition, the values within parentheses in Eq. (A.16) are positive at later years since $\frac{\gamma_t^N}{\gamma_t^D} \leq 1$ for all $t \in T$ is a decreasing trend (i.e., $\gamma_t^N \downarrow$ and $\gamma_t^D \uparrow$); therefore, we can take the square root of both sides. We will have $\gamma_{t-1}^D + \gamma_{t-1}^N \geq \gamma_t^D + \gamma_t^N$ when $\gamma_{t-1}^D - \gamma_t^N \geq 0$ and $\gamma_t^D - \gamma_{t-1}^N \geq 0$. □

In practice, $\gamma_{t-1}^{D} + \gamma_{t}^{N} \leq \gamma_{t}^{D} + \gamma_{t-1}^{N}, \forall t \in T$ would be enough to form a non-decreasing GHG quota trend at early years; however, for later years when $\gamma_{t-1}^{D} \geq \gamma_{t}^{N}$ and $\gamma_{t}^{D} \geq \gamma_{t-1}^{N}$, we should consider $\gamma_{t-1}^{D} + \gamma_{t-1}^{N} \geq \gamma_{t}^{D} + \gamma_{t}^{N}$. Fig. A.14 shows the GHG quota trends for a case study with and without constraints in this lemma. One can see that without these constraints, the red trend can decline compared to the prior year.

In this manuscript, both objective functions are employed. We utilize z^{GHG} to illustrate the highest level of GHG reduction possible considering underlying assumptions. This value provides an upper bound for the avoided emissions from the transport sector, which can be contrasted with other scenarios with minimum cost (z^{c}) considering various ρ_{t}^{GHG}.

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