Final report of the UFZ subproject for BEniVer – Accompanying research on energy transition in transport

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UFZ HELMHOLTZ Zentrum für Umweltforschung

Contents

List of figures

List of tables

Abbreviations

BENOPT BioEnergy Optimization Model

BENOPTex the extended bioenergy optimization model

BESS battery energy storage systems

BEVs battery electric vehicles

BMWi The Federal Ministry for Economic Affairs and Energy

BMWK The Federal Ministry for Economic Affairs and Climate Action

DEL Direct ELectrification

EEM European Energy Markets

ERE excess renewable electricity

EVs electric vehicles

GHG greenhouse gas

GJ gigajoule

HDVs heavy-duty vehicles

LCA life-cycle assessment

LDVs light-duty vehicles

MAE Mean Absolute Error

PtX Power-to-X

PVs photovoltaic systems

RED II Renewable Energy Directive II

REMix Renewable Energy Mix

RES renewable energy sources

RMSE Root Mean Square Error

SAF sustainable aviation fuel

SYN SYNthetic fuel

WP work packages

1 Background and Objective

Decarbonizing the transport sector in Germany is of utmost importance due to its significant role in mitigating climate change. Transportation is a major contributor to greenhouse gas emissions, with road vehicles being the primary culprits. By transitioning to cleaner and more sustainable alternatives, Germany can significantly reduce its carbon footprint and work towards achieving its climate goals. However, it is crucial to recognize that there is no silver bullet solution to decarbonizing the transport sector. Each technology has its advantages and limitations, and a holistic approach is needed to address the complex challenges involved.

The objective of this sub-project is to explore the competition between electricity-based fuels (e-fuels) and biofuels in meeting energy and greenhouse gas (GHG) reduction targets within the German transportation sector. To accomplish this, we have extended the existing BioEnergy Optimization Model (BENOPT) to include relevant e-fuel options, thereby addressing four wh-questions of which fuel paths become relevant in which sectors, by when, and to what extent.

Running in parallel with the Renewable Energy Mix (REMix) model, we investigate the competition between different e-fuels and biofuels in German energy and power systems using the BENOPT. Although both models overlap in objectives, they approach the problem from different angles. The BENOPT model considers the techno-economic and political aspects of the bio-economy in a bottom-up manner, whereas REMix is focused on the infrastructure needed to support the expansion of intermittent renewable energy sources such as wind and solar in the power sector. This includes examining the spatiotemporal distribution of renewable energy sources, their integration with existing infrastructure, and their overall potential to meet energy and climate goals.

The BENOPT model incorporates a detailed cost and GHG analysis using a life-cycle assessment (LCA) approach. Furthermore, technological learning effects are taken into account exogenously, which reduces the investment and operation costs over time. Employing a flexible temporal resolution[1], BENOPT finds the most cost-efficient long-term strategy in order to meet the energy and GHG reduction targets under multiple scenarios. Deployment and GHG mitigation costs are determined and compared to electricity-based options. Extensive sensitivity analyses check the robustness of the results.

All in all, the following objectives have been achieved in the project:

- Extension of a bioenergy optimization model (i.e., BENOPTex) to include e-fuels.
    - The extension of the technology portfolio to include e-fuel processes.
    - Calculating the GHG reduction over time for four different scenarios, given the latest developments in policy.

[1] hourly for the power market and an annually for others.

- Analysis and comparison of GHG mitigation costs over time for four different scenarios.
- Modeling the optimal use of e-fuels and biofuels, based on energy and GHG mitigation costs.

2 Tasks

As a part of the BEniVer project, UFZ played an active role in work packages (WP) 1.1 and 1.2, aimed at providing insights to transition the German transport sector towards non-fossil fuels while taking into account the latest developments in the energy and power sectors. However, the underlying parameters of the German energy systems were significantly impacted by unforeseen global upheavals such as the COVID-19 pandemic and the Russo-Ukraine conflict, necessitating multiple revisions of the scenarios and results. For instance, to ensure the accuracy of the findings, the reference scenario was synchronized more than 17 times until reaching an acceptable consistency. Our research focuses on the role of synthetic fuels and biofuels in achieving carbon neutrality by 2050. To account for the latest political developments, we extended our optimization model to incorporate the impact of the Renewable Energy Directive II (RED II) on GHG emissions. The inclusion of RED is decided in WP1 monthly meetings and reflected in the interim report on the 2nd of February 2022. Our optimization model considers the impact of RED endogenously, providing a comprehensive understanding of its effects on achieving carbon-neutral targets [1].

In close collaboration with partners in WP 1.1, UFZ contributes to designing the information flow between models and formulating parameters for various scenarios in order to estimate the energy requirements of different transport modes. The inputs generated from WP 1.1 were integrated into the extended bioenergy optimization model (BENOPTex) [2]. In addition, we collaborated with partners in work package 1.2 to design and implement an iterative coupling approach, through which energy system and power market models are integrated. The REMix is an electricity market model that was utilized to assess the availability of renewable electricity and hydrogen for the generation of synthetic fuels in Germany until 2050 under various scenarios. A seamless information exchange was conducted by harmonizing parameters between Vector21, 4DRace, REMix, and BENOPTex models and databases, thereby allowing for a comprehensive analysis of the various scenarios. Our approach also facilitated a more accurate estimation of the impact of different energy policies and market conditions on the German transport sector's transition to non-fossil fuels by incorporating the outcome of simulation and accounting models, which consider consumers' behavior and manufacturers' perspectives.

To model energy scenarios for passenger and freight transportation in road transport and aviation, we gathered data from Vector 21 and 4D-Race, as described in WP 1.1. In cooperation with experts from DBFZ, the theoretical biomass potential and the mobilizable technical potential are calculated for future years. Figure 2 depicts the devised coupling procedure by which the insights from various sources are integrated to reflect the perspectives of heterogeneous stakeholders. The soft-coupling procedure has been explained extensively in [3].

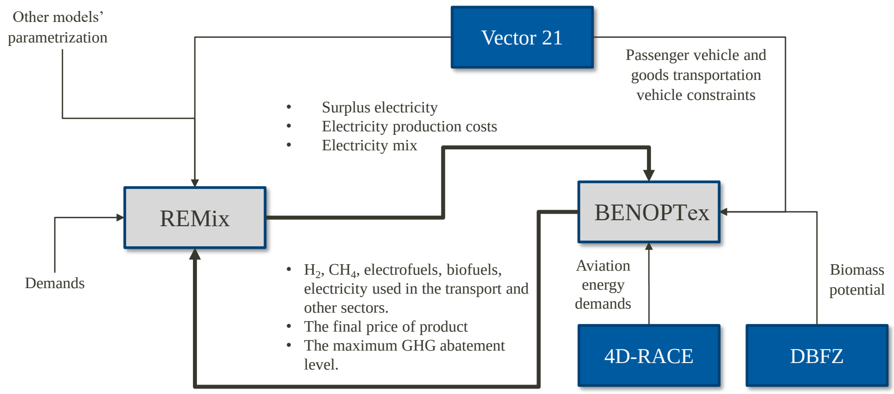

Figure 1: The implemented information flow between models and datasets.

Our linking strategy involves an iterative procedure where BENOPTex allocates available biomass residues and energy crops to various technologies, in accordance with end-use demands dictated by top-down and simulation models. This iterative approach enables us to optimize the bioenergy allocation strategy, ensuring we satisfy the demands of various end-users while considering the availability of renewable electricity using REMix. To facilitate multiple executions of the BENOPTex model within a loop with REMix for various scenarios, we have optimized the model to achieve higher performance and shorter runtimes (reported on the 28th of September 2021) [4]. Our optimization efforts have involved improving the efficiency of the model's code and exploiting new processors' architecture. This iterative process continues until the solutions of the BENOPTex model and REMix converge to equilibrium, i.e., when the change in sectoral fuel production between two consecutive iterations is no more than 10% from 2020 to 2050. This criterion serves as the necessary termination condition[2], ensuring that the model outputs are stable and reliable. The latest version of the model has been deposited in GitHub and GitLab under a creative common license.

[2]The experts are still allowed to run models to reach more stable solutions.

3 Condition under which the project was carried out

We have developed BENOPTex, an advanced optimization model that incorporates the entire bioenergy supply chain, ranging from the cultivation of energy crops to the utilization of biogenic residues by demand service technologies. The model has been tailored to Germany and employs a spatially limited, single-node framework. BENOPTex is capable of accommodating flexible temporal resolutions, with hourly resolution for electricity and annual resolution for potential biomass. The model utilizes theoretical and technical biomass potential data provided by our colleagues at DBFZ as input, but also endogenously determines the cultivation of energy crops based on techno-economic parameters and land availability. These parameters are derived from relevant literature sources. The demand side information is also acquired from DLR-TT-STB, DLR-FK, DLR-FW teams.

The BENOPTex model consists of two main components: a front-end responsible for generating scenarios, and a back-end that solves the optimization model. To implement the model, we have chosen to use MATLAB for the front-end and GAMS for the back-end, with CPLEX being utilized as the solver. MATLAB is an excellent choice for the front-end due to its powerful computational capabilities and user-friendly interface. Additionally, we have access to MATLAB through a shared license held by UFZ, allowing us to leverage its capabilities without additional cost. On the other hand, GAMS is widely recognized as the standard tool in the energy system modeling community and is ideal for the back-end optimization component of the BENOPTex model. However, GAMS is not a free programming language, and a license must be acquired. Therefore, we have obtained a GAMS license specifically for this project to ensure the model can be implemented efficiently and accurately.

The development of backend and frontend is conducted by Danial Esmaeili Aliabadi and Matthias Jordan between 2021 and 2023 and Markus Millinger and Matthias Jordan between 2019 and 2020. Karl-Friedrich Cyffka from DBFZ assist us in collection biomass potential. The coupling of REMix and BENOPT models were performed by Danial Esmaeili Aliabadi from UFZ and Niklas Wulff from DLR-TT. Colleagues at DLR-FK (Özcan Deniz, Ines Oesterle, and Samuel Hasselwander) provided us with three iterations of Vector21 outputs, with the most recent one dated 29.04.2022. Finally, the energy demand of the aviation sector in Germany is acquired from the colleague at DLR-FW (Wolfgang Grimme) on 11.10.2021.

The decisions and discussions are documented in the Confluence Wiki system during our monthly meetings, which took place on the first Thursday of each month.

4 Planning and procedure of the project

In the BEniVer project, WP 1 was coordinated by DLR-TT-STB. As a partner in this work package, the following milestones were specified:

- **M1**: The developed model is adapted to the requirements in the project and works, confirmed by a sample run with preliminary process data (12/2020)
- **M2**: At least five relevant e-fuels processes have been added to the developed model (03/2021). M2 is achieved by incorporating multiple e-fuel processes into the BENOPT model as reported in [5].
- **M3**: Integrating the GHG data for at least ten of the biofuel and e-fuel processes in the model (06/2021). You can find the detail of processes in the dedicated page for BENOPTex[3] and published studies.
- **M4**: Modeling and analysis of process competitiveness over time has been performed for at least two scenarios (11/2021).

Table 1: UFZ-related tasks in BEniVer

	2019				2020				2021				2022				2023	
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Model development								M1										
Model extension (e-fuels)									M2									
Modeling RED and GHG targets										M3					M3			
Modeling/Analysis												M4						M4

Early planning was affected by two critical years: 2020 and 2022. In response to the COVID-19 pandemic's impact on energy demand, we decided to rerun underlying models in 2021 with updated scenarios. This decision was made after multiple discussions during our monthly meetings. However, this led to delays in modeling and sensitivity analysis tasks (i.e., the M3 and M4 tasks), as reflected in the project timeline. The ongoing Russo-Ukraine war was the second important event that impacted the project, particularly REMix's expectations for natural gas availability as an energy vector to replace lignite and anthracite. The pressure on the food supply chain also affected the availability of first-generation biofuels in the BENOPTex model parameters, as the German government prioritized land utilization for food production.

5 Scientific and technical state of the art

Systematic assessment of e-fuels is a relatively new area of research [6]. While most studies have focused on the cost [7, 8], GHG emissions [9], and technical comparisons with fossil fuels [10], there has been limited research on the

[3] URL: `https://www.ufz.de/index.php?en=37180`

competition and synergy between e-fuels and biofuel options for all modes of transportation considering RED policies [11].

Unfortunately, many existing models lack the necessary technological detail for bottom-up models, which results in a limited understanding of biofuels as they are often treated with a broad brush stroke [12]. This approach fails to reveal essential information regarding the fuel type and the feedstock types consumed. By combining e-fuels and biofuels, we can address this issue and benefit from the available renewable CO_2, which can be used to produce e-fuels.

To fill this gap, in this WP, we develop an integrated system of models that consider the perspectives of heterogeneous stakeholders. The resulting framework provides a holistic view of technology pathways that finds success in different sectors due to their characteristics given the incentives and penalties specified by policymakers.

6 Cooperation with other agencies

To carry out the tasks in this sub-project, partners contacted relevant vehicle manufacturers to include their perspectives regarding the change in the design of future internal combustion engine vehicles.

7 In-depth presentation

7.1 Assumptions

In BENOPTex, ten energy crops and 13 groups of residues are modeled. The farmer's choice to cultivate various energy crops is an endogenous decision in the model based on the demand for fuel, heat, or electricity. In Germany, wheat is considered the most common crop; hence, the final price of other energy crops is calculated such that their profit margins become on par with the wheat profit margin as the benchmark [13]. The production cost of energy crops consists of direct, labor, fuel, machine (fixed and variable), and service costs, which increase at a 4% rate until 2050. The available land for planting energy crops is assumed to be 2.399 Mha in 2020, which will be reduced slightly in 2050 to 2.159 Mha in 2050 due to land competition among different sectors.

On the other hand, each residue group consists of a subset of 77 residues. The data regarding the availability of each residue type is collected from the DBFZ database [14]. The potential residues for 2020 are assumed to be as same as the mean value used for energetic purposes in 2015. We presume that 33% of mobilizable potential will be available in 2050. The residue prices are provided in ranges as depicted in Table 2. As it is evident from Table 2, the minimum scrap wood price is negative since the producers should pay the consumers in order to utilize them. The available biomass potential in each year is split into three equal size categories with different prices (from this range) to distinguish various qualities of similar commodities. Furthermore, we permit the import of energy crops, residues, and synthetic fuels with higher expenses from other countries to prioritize the consumption of domestic resources over foreign ones and to alleviate the negative impact of telecoupling energy systems.

Table 2: The availability of residues for 2020, 2030, and 2050 and the price range.

	Residues potential (PJ)			**Residue Price (€/GJ)**	
	2020	**2030**	**2050**	Minimum	Maximum
Log wood	150	150	150	11	16.8
Paludiculture	0	23	166	0	2.7
Straw	20	29.6	49	12.8	16.9
Manure/slurry	26	33.4	48	0	0
Forest residues	126	134.2	151	4.2	7.3
Industrial wood residues	21	21.7	23	3	3.4
Used cooking oil	0	1.3	4	16	16
Household bio-waste	13	13.7	15	0	0
Industrial waste	20	21.4	24	0	0
Black liquor	16	16.0	16	0	0
Scrap wood	120	120.8	122	-0.6	2.7
Sewage sludge	5	5	5	0	0

7.2 Methodology

The optimization procedure in BENOPTex consists of two stages. In the first stage, the software maximizes the level of GHG abatement while taking into account the boundary conditions established by other models and databases. The resulting solution provides a portfolio of technologies that minimize GHG emissions. In the second stage, GAMS solves the model once more using a second objective function, this time aimed at minimizing the overall system cost. While allowing for a sub-optimal solution with respect to GHG emissions by 0.5%, the second step enables the model to identify and eliminate costly technologies that have a minimal contribution to GHG abatement.

Our task in this project aims to evaluate the potential of various fuel options for different modes of transport in Germany until 2050, taking into account technical biomass potential, excess renewable electricity, and political constraints on the carbon intensity of alternative fuels. As it is known, fossil diesel, gasoline, and kerosene currently account for a significant portion of fuel consumed in the German transport sector. However, extrapolating RED II, the GHG quota mechanism will request the road and rail sectors to be 80% carbon-neutral. While gasoline passenger vehicles will continue to be available under the V21 scenario, manufacturers have little incentive to modify engine designs to accommodate higher blending ratios of ethanol and methanol (10% for ethanol and 5% for methanol), which means these vehicles will continue to rely on fossil gasoline. We observe that diesel is being replaced almost entirely in passenger vehicles, but remains heavily used in freight and maritime transport.

7.3 Convergence

To ensure that our models produce consistent and accurate results, we employ an iterative coupling approach. This approach involves using the output of one model as input for the other model, and vice versa. In our case, the output of the REMix model is used as input for the BENOPTex model, and vice versa. Specifically, the REMix outputs that are used in BENOPTex as inputs include the availability of excess electricity, the amount of electricity used for hydrolysis, the share of each technology in the power mix, and the spot price of electricity.

To compute the carbon intensity of the electricity mix, we utilize a mixture of technologies. Additionally, we use the spot electricity price from REMix as a scaling factor to predict how the mixture of technologies can impact the future electricity cost in various sectors while considering different taxes and levies. We also include hourly excess electricity in the model for different technologies to utilize. Moreover, the amount of electricity used by Power-to-X (PtX) technologies is determined by REMix, specifically the electricity used in electrolysis. To measure the accuracy of our models, we employ the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). Table 3 shows the changes between consecutive iterations in Base, SYNthetic fuel (SYN) and Direct ELectrification (DEL) scenarios. The base scenario depicts the current status quo, assuming no significant changes in policy or trends. However, the SYN scenario envisions a future where there is a greater emphasis on the consumption of synthetic fuel in road transport. In contrast, the DEL scenario imagines a scenario where road vehicles directly consume electricity. Furthermore, in the aviation sector, both hydrogen and electricity play a more prominent role compared to the base and SYN scenarios.

To enhance the consistency with Vector 21 and capture the whole energy demand in transport, we added fossil fuels to BENOPTex in the tenth iteration of the base scenario, which influenced MAE and RMSE between R10 and R9. However, these variations were subsequently reduced in the subsequent iterations.

7.4 Results

In order to achieve 63% sustainable aviation fuel (SAF) usage, as dictated by FuelEU, Germany will need to import synthetic fuel from other countries since the available electricity will be utilized directly by battery electric vehicles (BEVs), electric trains, and electric trucks for rail and road transport. According to FuelEU, 28% of the aviation sector's fuel should be synthetic, while the remaining 35% should be SAF. Biomass-to-Liquid technology is a promising option for producing SAF, with a cost of 54.47 euros per gigajoule

Table 3: The convergence of MAE and RMSE in different scenarios.

Base scenario			SYN scenario			DEL scenario		
	MAE	RMSE		MAE	RMSE		MAE	RMSE
R9 - R8	159.49	246.31	R2-R1	16.05	52.90	R2-R1	21.08	50.39
R13-R12	11.56	28.28	R4-R3	10.70	28.63	**R3-R2**	**0.31**	**1.19**
R15-R14	2.98	10.85	R6-R5	13.87	60.41			
R17-R16	3.00	8.83	R7-R6	2.82	9.55			
R18-R17	**2.07**	**6.79**	**R8-R7**	**1.01**	**3.33**			

(GJ) using poplar, making it the most economical technology for producing diesel and kerosene in 2050.

To meet the GHG quota for road and rail transport specified by RED II, our analysis suggests that we can achieve a minimum of 80% reduction in emissions by 2050, utilizing the technologies listed in Figure 2. Figure 3 illustrates the trend towards achieving this target, with the dashed gray line representing the policymakers' specified target until 2030, and the extrapolation of the trend indicating the expected attainment of 80% reduction in GHG emissions by 2050 in rail and road transportation. We calculated the GHG quota based on the formula detailed in [15]. In this formulation, we assumed that the GHG quota trend is a non-decreasing trend by adding proper constraints, which are mentioned in [1]. The trend corresponding to 99.5% of the maximum GHG abatement by minimizing cost is shown in red, black and green for Base, SYN and DEL scenarios, respectively. In all scenarios, the solid trends are approaching the dashed gray one at the beginning and at the end of time horizon, which shows 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. Also, the current requirement for the GHG quota (for road and railway transport) in 2030 can be stricter ($< 30\%$) without having a noticeable impact on the cost of the optimal strategy.

As shown in Figure 4, it is anticipated that the cost of biodiesel and bioethanol will rise in the coming years, primarily due to the displacement of conventional biofuels and the adoption of advanced biofuel technologies, which are more expensive than conventional ones. As a result, consumers should expect to see higher prices for these biofuels in the future.

As per the PtX scenario outlined in Vector21, which is also implemented in the SYN scenario, light-duty vehicles (LDVs) are expected to consume less gasoline and more electricity (see Figure 5). This shift can be attributed to the superior efficiency of BEVs over internal combustion engines. Additionally,

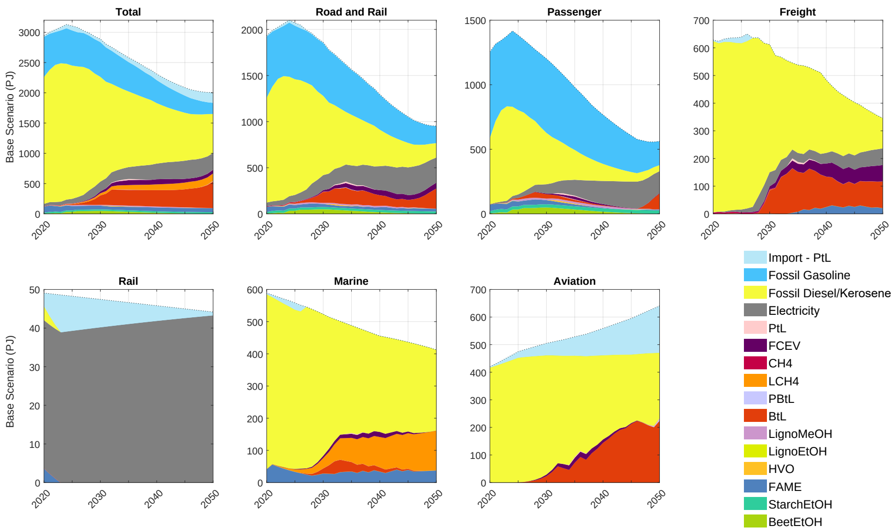

Figure 2: The distribution of alternative fuels in various transport sectors in petajoules under the base scenario when optimizing total system cost under 99.5% GHG abatement level. The dash lines illustrate the energy demand by each sub-sector considering energy efficiency improvement. PtL: Power-to-Liquid, 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.

the total amount of electricity required for LDVs will be reduced due to this increased efficiency. For heavy-duty vehicles (HDVs), the scenario envisions the use of electricity and hydrogen to replace a portion of diesel usage. However, given the remaining energy demand, biofuels will be necessary to produce biodiesel and synthetic fuels. Meanwhile, in the aviation sector, both the base and SYN scenarios adhere to the progressive scenario, which doesn't account for the impact of COVID-19.

In Figure 6 and in alignment with Vector 21, it is evident that direct electrification of road transport surpasses other scenarios, thereby facilitating the extensive substitution of gasoline and diesel fuels with electricity in passenger vehicles. However, one significant challenge associated with this scenario is the inadequate availability of renewable electricity, which hampers achieving complete replacement. In order to address this issue, policymakers should consider two potential solutions: investing in the establishment of robust transmission lines connecting with neighboring European countries to import additional

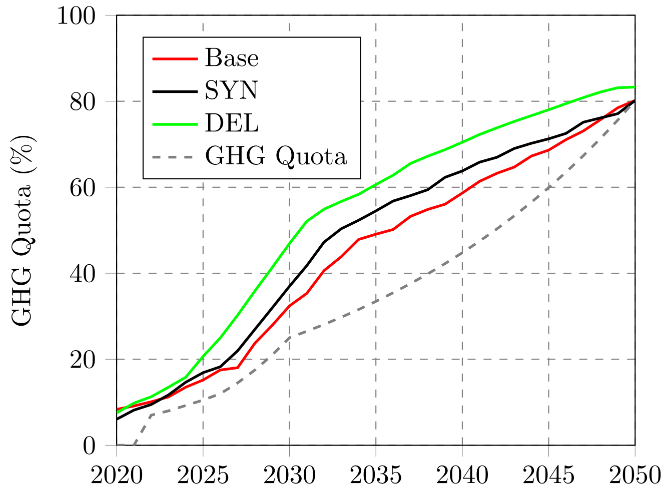

Figure 3: The GHG quota trends for the Base, SYN and DEL scenarios from 2020 until 2050.

electricity or intensifying domestic efforts to enhance renewable electricity generation within Germany.

Figure 7 illustrates the evolving consumption patterns of various domestic biomass feedstocks and electricity sources in Germany from 2020 to 2050. The trends depicted in the figure highlight significant changes in the utilization of different feedstocks for the production of biodiesel and bioethanol, as well as the impact of limited excess renewable electricity (ERE). In all scenarios, there is a discernible decline in the consumption of rapeseed and sugar beet, which are traditionally used for biodiesel and bioethanol production. This decrease can be attributed to the phased-out policies on conventional biofuels by policymakers. On the other hand, the combined consumption of maize silage and poplar exhibits an upward trajectory, indicating an increasing utilization of these feedstocks in the future. Poplar is mostly used by BtL technology to produce biodiesel and SAF for the road and aviation sectors. Maize silage, on the other hand, is used to produce biomethane and heat for industries. Also, paludiculture usage grows in all scenarios.

Furthermore, the figure showcases the influence of limited ERE through the utilization of stacked bar graphs. The dark blue bar positioned at the top of the graphs represents the ERE, signifying the surplus renewable electricity available. Beneath it, the lighter blue bar represents the electricity mix, including sources such as imported electricity and electricity generated from rooftop photovoltaic systems (PVs). As shown in the DEL scenario, the transition towards direct electrification of vehicles presents a significant challenge in terms of the increased demand for electricity and the strain it puts on transmission lines. The adoption of electric vehicles (EVs) will necessitate a greater electricity mix

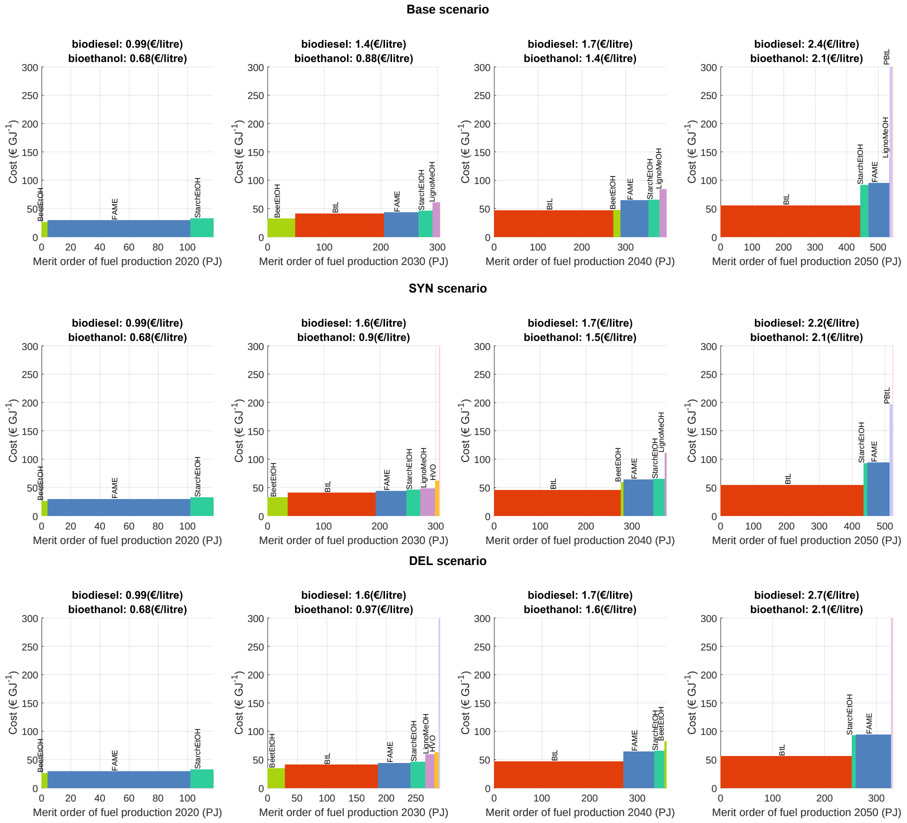

Figure 4: The production cost of each technology to produce bioethanol and biodiesel in 2020, 2030, 2040 and 2050 under various scenarios.

to meet the additional power requirements.

The costs and levels of GHG abatement for different scenarios, compared to the base scenario, are depicted in Figure 8. It is evident that the SYN scenario offers a more cost-effective solution, delivering superior GHG abatement levels. This advantage can be attributed to the utilization of a diverse range of technologies that effectively meet the end-use demands. On the other hand, while the DEL scenario exhibits higher levels of GHG abatement, the heavy emphasis on direct electrification, considering the limited availability of electricity for various applications, significantly drives up the overall system cost.

We also analyzed the impact of utility-scale battery energy storage systems (BESS) on the GHG emissions and total system cost in the base scenario [16]. Our findings indicate that considering BESS would improve the GHG abatement level; however, minimizing the total system cost when allowing sub-optimal GHG solutions eliminates BESS from the cost-optimal solutions. To

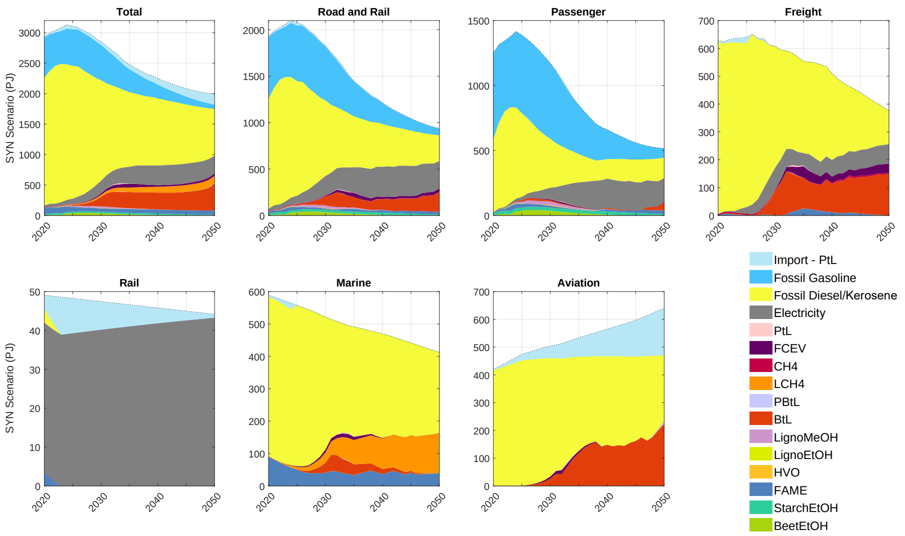

Figure 5: The distribution of alternative fuels in various transport sectors in petajoules (PJ) under the SYN scenario when optimizing total system cost under 99.5% GHG abatement level. The dash lines illustrate the energy demand by each sub-sector considering energy efficiency improvement. PtL: Power-to-Liquid, 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.

enhance the practicality of this technology, it is imperative to explore alternative business models, such as utilizing the storage potential of electric vehicles. This shows that BESS should become cheaper to play an important role in the future German energy system. Furthermore, our analysis shows that the combined effect of growing intermittent renewable sources and increasing energy efficiency may create an emerging need for more deployment of BESS in the mid-term. When the fluctuation of renewable sources requires electricity storage, our optimization model uses stored electricity to produce hydrogen.

8 Necessity and appropriateness of the work performed

The work carried out and the resources expended on it were necessary and appropriate, as they corresponded to the planning set out in detail in the project

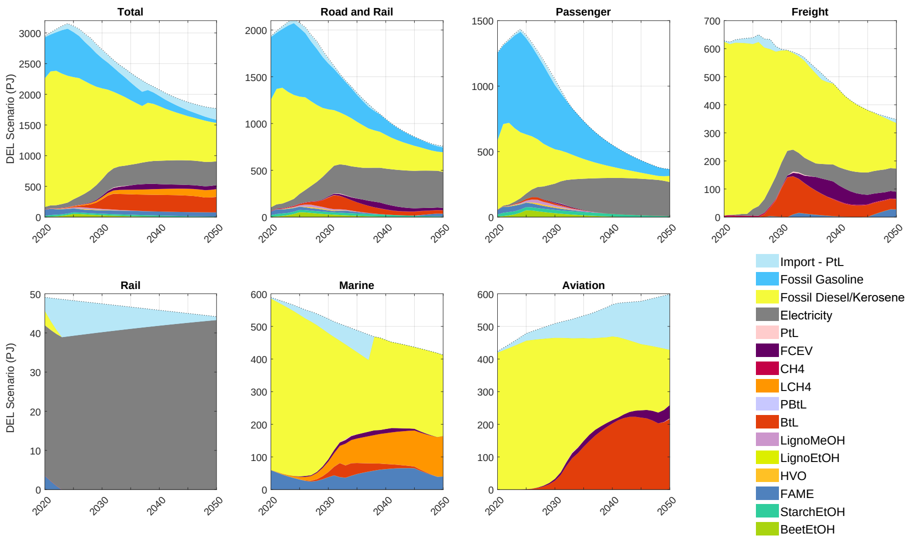

Figure 6: The distribution of alternative fuels in various transport sectors in petajoules (PJ) under the DEL scenario when optimizing total system cost under 99.5% GHG abatement level. The dash lines illustrate the energy demand by each sub-sector considering energy efficiency improvement. PtL: Power-to-Liquid, 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.

application and all the tasks formulated in the work plan were successfully completed. Beyond that, no additional resources had to be expended to carry out the project.

9 Usability of the results

The climate change problem has multiple facets touching many stakeholders with dissimilar and often conflicting interests and understanding; hence, experts from different disciplines should cooperate to capture techno-socioeconomic aspects. As such, the required diverse set of expertise for making robust decisions cannot be achieved by merely utilizing one model. Standalone models can optimize a subset of objectives while harming other targets. Therefore, the integration of discipline-specific models, which are highly advanced in capturing technological, social, and institutional dimensions can provide a holistic

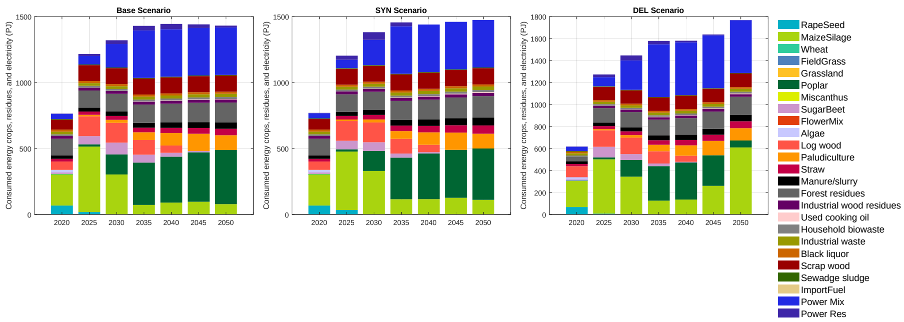

Figure 7: The consumption of feedstock (domestic energy crops and residues) and electricity in Germany under various scenarios.

view of the problem.

In this context, our developed system of models enables us to address intricate research inquiries pertaining to the demand-driven pressure arising from the future expansion of renewable electricity generated from wind and solar sources on land and biodiversity.

10 Progress at other sites

None known.

11 Published or submitted publications

Numerous conference and journal papers have been published, utilizing the developed methodology and presenting the obtained results. The list of published papers are in the reference section [2, 4, 5, 3]. Additionally, we have recently submitted a conference paper to the International Conference on European Energy Markets (EEM). We are pleased to announce that the paper submitted to the EEM conference has been accepted and published [16]. Furthermore, another manuscript has been submitted to the peer-reviewed journal, Transportation Research Part D, which is currently undergoing the review process [1].

12 Work that has not led to a solution

We also endeavored to tackle the hydrogen scenario using a similar approach (i.e., soft-linking REMix and BENOPTex models); however, the linking process for the base, SYN, and DEL scenarios consumed a substantial portion of our capacities, impeding us from successfully concluding the hydrogen scenario.

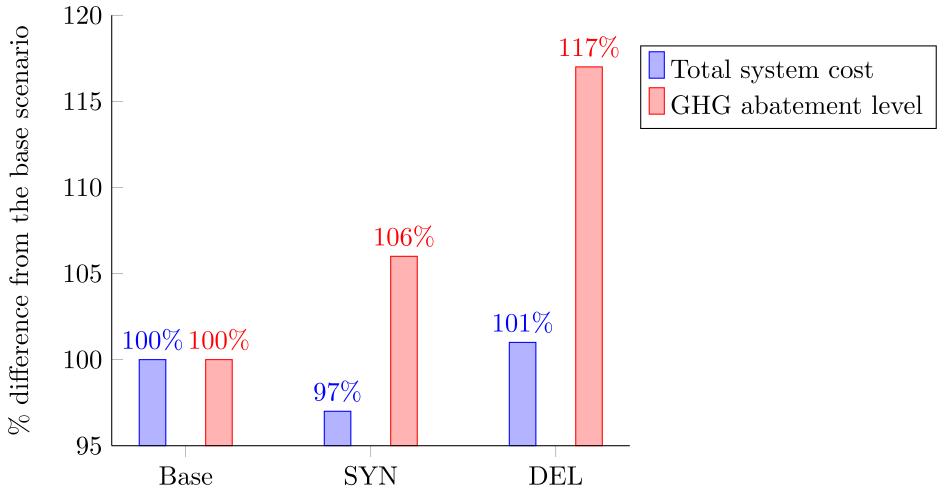

Figure 8: The cost and GHG abatement level differences among scenarios compared to the base scenario.

13 Presentation opportunities for potential users

Apart from the scientific meetings, we did not contact directly stakeholders. However, the outcomes of our WP were presented in the road-map meeting to policymakers and discussed by stakeholders.

14 Compliance with the cost and time planning

The project has been accomplished mostly on time. However, a portion of the travel funds and publication funds could not be consumed. The travel budget was not entirely expended due to the shift to online meetings and conferences in response to the COVID-19 pandemic. The restrictions imposed during this period necessitated a transition to virtual platforms, resulting in reduced travel requirements. It is important to note that only recently have the COVID-19 regulations been lifted in Germany, allowing for more in-person interactions and potential future use of the travel funds. Regarding the publication budget, we are committed to utilizing the remaining funds for open access publication of the paper submitted to the conference. Open access publication ensures wider accessibility to our research findings and facilitates knowledge dissemination among researchers, practitioners, and the general public. Additionally, we have unallocated personnel funds. These funds were not utilized within the project's scope.

A Performance review report

A.1 Contribution to funding policy

The project was funded by The Federal Ministry for Economic Affairs and Energy (BMWi), now known as The Federal Ministry for Economic Affairs and Climate Action (BMWK), has made significant strides in advancing our understanding of alternative fuel production pathways.

We have provided a comprehensive analysis of various scenarios in which multiple pathways for the production of alternative fuels are formulated. The competition and synergy between these pathways are captured respecting the latest developments in the political arena. The outcomes of this sub-project will assist policymakers to anticipate the required modifications in regulations or necessary investments through which the specified targets for the energy transition in Germany are successfully achieved.

This sub-project was the first of its own in which the entire bioenergy supply chain from biomass and renewable electricity to biofuels and alternative fuels is modeled. This will allow policymakers to find the theoretical limitation of technologies as well as resources.

A.2 Scientific-technical results

The results show that electricity generation from renewable sources is a limiting factor that should be addressed. We can import renewable electricity from neighboring countries or boost our investments in solar farms and wind turbines. Moreover, the import of synthetic fuel, especially for the aviation sector, will be required to reach the specified targets in FuelEU. Another significant outcome is related to the structure of the credit system in the GHG quota. The credit system will allow car manufacturers to produce ICE vehicles because the manufactured BEVs will credit them multiple times. This hypothesis is also supported by our colleagues who discussed this issue with manufacturers, who were reluctant to adjust their engine designs for a higher mixture of bioethanol; however, changing the designs to adopt a higher bioethanol mixture can relax the need for electricity and diversify the portfolio of technologies.

There has been a noticeable decrease in the consumption of rapeseed and sugar beet, which are typically used to produce biodiesel and bioethanol, respectively. This is due to new RED policies that limit conventional biofuels. On the other hand, in all scenarios, there has been an increase in the consumption of poplar as feedstock in the BtL technology to produce biodiesel and SAF for the road and aviation industries.

A.3 Updating of utilization plan

This sub-project does not involve any specific inventions or patents. Instead, its focus lies in conducting a comprehensive analysis and providing valuable insights into the production of alternative fuels and the associated bioenergy supply chain. By modeling various scenarios and considering the competition and synergy between different pathways, this research contributes to a better understanding of the theoretical limitations, technological capabilities, and resource requirements in the field of alternative fuel production. While the sub-project does not yield specific inventions or patents, its outcomes serve as a foundation of knowledge that can inform policymakers, researchers, and stakeholders in advancing the energy transition and driving innovation in the broader context of sustainable energy systems.

This sub-project does not focus on exploring specific economic prospects. Rather, its primary objective is to provide a comprehensive analysis of various scenarios and pathways for the production of alternative fuels within the bioenergy supply chain. The research aims to understand the techno-economic feasibility, regulatory implications, as well as resource requirements associated with these pathways, generating knowledge and insights to assist policymakers in making informed decisions. The findings and recommendations derived from this research can serve as a basis for future economic assessments and investment strategies, helping to shape a sustainable and economically viable energy transition in Germany.

We are actively advancing our research by utilizing the tools and methodology we have developed on multiple fronts. One important direction of our investigation is to assess the impact of widespread deployment of solar and wind farms on available lands and biodiversity. To accomplish this, we integrate the output from the REMix tool, which provides data on the capacity of renewable energy sources (RES) deployed in various regions of Germany. This RES capacity information is then fed into the model developed by the MultiplEE project, allowing us to determine the optimal placement of these plants. To estimate the electricity generated by the wind turbines in these specific locations, we employ a simulation tool known as the ReSTEP model. This model incorporates historical climate data to simulate the electricity output from the turbines. By considering past climate patterns, we can more accurately project the potential electricity generation from wind farms. Finally, the electricity generated from these renewable sources is integrated into the BENOPTex model. By leveraging these interconnected models and simulation tools, we can gain valuable insights into the feasibility, efficiency, and environmental impact of deploying solar and wind farms.

B Document control sheet

Document Control Sheet / Berichtsblatt

<table>
<tr><td>1. ISBN or ISSN
-</td><td colspan="2">2. type of document
Report</td></tr>
<tr><td colspan="3">3. title
Final report of the UFZ subproject for BEniVer – Accompanying research on energy transition in transport</td></tr>
<tr><td colspan="2" rowspan="3">4. author(s)
EsmaeiliAliabadi, Danial; Jordan, Matthias</td><td>5. end of project
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<tr><td>14. no. of tables
3</td></tr>
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8</td></tr>
<tr><td colspan="3">16. supplementary notes
-</td></tr>
<tr><td colspan="3">17. presented at (title, place, date)
-</td></tr>
<tr><td colspan="3">18. abstract
Decarbonizing the transport sector in Germany is of utmost importance due to its significant role in mitigating climate change. Transportation is a major contributor to greenhouse gas emissions, with road vehicles being the primary culprits. By transitioning to cleaner and more sustainable alternatives, Germany can significantly reduce its carbon footprint and work towards achieving its climate goals. However, it is crucial to recognize that there is no silver bullet solution to decarbonizing the transport sector. Each technology has its advantages and limitations, and a holistic approach is needed to address the complex challenges involved. The objective of this sub-project is to explore the competition between electricity-based fuels (e-fuels) and biofuels in meeting energy and GHG reduction targets within the German transportation sector. To accomplish this, we have extended the existing BENOPT to include relevant e-fuel options, thereby addressing four wh-questions of which fuel paths become relevant in which sectors, by when, and to what extent. Running in parallel with the REMix model, we investigate the competition between different e-fuels and biofuels in German energy and power systems using the BENOPT. Although both models overlap in objectives, they approach the problem from different angles. The BENOPT model considers the techno-economic and political aspects of the bio-economy in a bottom-up manner, whereas REMix is focused on the infrastructure needed to support the expansion of intermittent renewable energy sources such as wind and solar in the power sector. This includes examining the spatiotemporal distribution of renewable energy sources, their integration with existing infrastructure, and their overall potential to meet energy and climate goals. The BENOPT model incorporates a detailed cost and GHG analysis using an LCA approach. Furthermore, technological learning effects are considered exogenously, which reduces the investment and operation costs over time. Employing a flexible temporal resolution, BENOPT finds the most cost-efficient long-term strategy in order to meet the energy and GHG reduction targets under multiple scenarios. Deployment and GHG mitigation costs are determined and compared to electricity-based options. Extensive sensitivity analyses check the robustness of the results.
All in all, the following objectives have been achieved in the project:</td></tr>
</table>

- Extension of a bioenergy optimization model (i.e., BENOPTex) to include e-fuels.
    - The extension of the technology portfolio to include e-fuel processes.
    - Calculating the GHG reduction over time for four different scenarios, given the latest developments in policy.
- Analysis and comparison of GHG mitigation costs over time for four different scenarios.
- Modeling the optimal use of e-fuels and biofuels, based on energy and GHG mitigation costs.

19. keywords

Soft-coupling, bioenergy, synthetic fuel, renewable energy, Germany, transportation, optimization models

20. publisher

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Abschlussbericht des UFZ-Teilprojekts zu BEniVer - Begleitforschung zur Energiewende im Verkehr

4. Autoren:

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18. Kurzfassung

Die Dekarbonisierung des Verkehrssektors in Deutschland ist aufgrund seiner wichtigen Rolle bei der Abschwächung des Klimawandels von größter Bedeutung. Der Transportsektor ist ein Hauptverursacher von Treibhausgasemissionen, wobei Straßenfahrzeuge die Hauptverursacher sind. Durch die Umstellung auf umweltfreundlichere und nachhaltigere Alternativen kann Deutschland seinen Kohlenstoff-Fußabdruck erheblich verringern und auf das Erreichen seiner Klimaziele hinarbeiten. Es ist jedoch wichtig zu erkennen, dass es keine Patentlösung für die Dekarbonisierung des Verkehrssektors gibt. Jede Technologie hat ihre Vorteile und Grenzen, und es ist ein ganzheitlicher Ansatz erforderlich, um die komplexen Herausforderungen zu bewältigen.

Ziel dieses Teilprojekts ist es, den Wettbewerb zwischen strombasierten Kraftstoffen (E-Fuels) und Biokraftstoffen bei der Erreichung der Energie- und Treibhausgasminderungsziele im deutschen Verkehrssektor zu untersuchen. Um dies zu erreichen, haben wir das bestehende

BioEnergy Optimization Model (BENOPT) um relevante E-Kraftstoff-Optionen erweitert und damit vier Fragen beantwortet: Welche Kraftstoffpfade werden in welchen Sektoren, wann und in welchem Umfang relevant?

Parallel zum Modell Renewable Energy Mix (REMix) untersuchen wir mit BENOPT den Wettbewerb zwischen verschiedenen E-Fuels und Biokraftstoffen in deutschen Energie- und Stromsystemen. Obwohl sich beide Modelle in ihren Zielen überschneiden, gehen sie das Problem aus unterschiedlichen Blickwinkeln an. Das BENOPT-Modell betrachtet die technisch-ökonomischen und politischen Aspekte der Bioökonomie in einer Bottom-up-Methode, während REMix sich auf die Infrastruktur konzentriert, die benötigt wird, um den Ausbau von intermittierenden erneuerbaren Energiequellen wie Wind und Sonne im Stromsektor zu unterstützen. Dazu gehört die Untersuchung der räumlichen und zeitlichen Verteilung der erneuerbaren Energiequellen, ihrer Integration in die bestehende Infrastruktur und ihres Gesamtpotenzials zur Erreichung der Energie- und Klimaziele.

Das BENOPT-Modell umfasst eine detaillierte Kosten- und Treibhausgasanalyse unter Verwendung eines Lebenszyklus-Analyse (LCA)-Ansatzes. Darüber hinaus werden technologische Lerneffekte exogen berücksichtigt, was die Investitions- und Betriebskosten im Laufe der Zeit reduziert. Unter Verwendung einer flexiblen zeitlichen Auflösung findet BENOPT die kosteneffizienteste langfristige Strategie, um die Energie- und THG-Reduktionsziele unter verschiedenen Szenarien zu erreichen. Die Bereitstellungs- und THG-Minderungskosten werden ermittelt und mit strombasierten Optionen verglichen. Umfangreiche Sensitivitätsanalysen überprüfen die Robustheit der Ergebnisse.

Insgesamt wurden im Rahmen des Projekts die folgenden Ziele erreicht:

- Erweiterung eines Bioenergie-Optimierungsmodells (z.B. BENOPTex) zur Einbeziehung von E-Kraftstoffen.
    - Die Erweiterung des Technologieportfolios um E-Fuel-Verfahren.
    - Berechnung der Treibhausgasreduzierung im Laufe der Zeit für vier verschiedene Szenarien unter Berücksichtigung der neuesten politischen Entwicklungen.
- Analyse und Vergleich der Treibhausgasminderungskosten im Zeitverlauf für verschiedene Szenarien.
- Modellierung der optimalen Nutzung von E-Kraftstoffen und Biokraftstoffen auf der Grundlage der Energie- und Treibhausgasminderungskosten.

19. Schlagwörter	
Soft-Coupling, Bioenergie, synthetische Kraftstoffe, erneuerbare Energien, Deutschland, Verkehr, Optimierungsmodelle	
20. Verlag -	21. Preis -

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18. abstract

The transport sector is a major consumer of energy worldwide. Unfortunately, there is no silver bullet to de-fossilize the transport sector due to its intricacy; therefore, many concepts and technologies should be combined to have a noteworthy impact on this hard-to-abate sector. As such, the required diverse set of expertise for making correct decisions cannot be achieved by merely utilizing one model. In this study, we connect multiple datasets and models that employ various methodologies with different purposes to exhibit a pathway to a green transport sector. The extended bioenergy optimization (BENOPTex) and renewable energy mix (REMix) models are coupled iteratively to produce coherent results while considering different sets of constraints. The combined effects of bioenergy and synthetic fuel -- using renewable electricity -- on the German transport sector are investigated via a scenario. Two demand models are also used to capture the specificities of the energy demands of the mainly behavior-driven road transportation as well as technology-driven aviation sector. The outcome of the resulted soft-coupled model respects biomass availability, regulatory circumstances, techno-economic properties, and power sector expansion for the production of synthetic fuels.

19. keywords

Soft-coupling, bioenergy, renewable energy, transportation, optimization models

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A model for cost- and greenhouse gas optimal material and energy allocation of biomass and hydrogen

4. author(s) (family name, first name(s)) Millinger, Markus; Tafarte, Philip; Jordan, Matthias; Musonda, Frazer; Chan, Katrina; Meisel, Kathleen; EsmaeiliAliabadi, Danial	5. end of project May 2023 6. publication date 1 Dec 2022 7. form of publication Journal paper
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- Department of Space Earth and Environment, Chalmers University of Technology, 412 96, Göteborg, Sweden
- Department of Economics, Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany
- Faculty of Economics and Management Science, Institute for Infrastructure and Resources Management, University of Leipzig, Ritterstraße 12, 04109 Leipzig, Germany
- Department of Bioenergy Systems, Deutsches Biomasseforschungszentrum Gemeinnützige GmbH—DBFZ, Torgauer Straße 116, 04347 Leipzig, Germany

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5

16. supplementary notes
The online appendix includes 5 tables

17. presented at (title, place, date)
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18. abstract
BENOPT, an optimal material and energy allocation model is presented, which is used to assess cost-optimal and/or greenhouse gas abatement optimal allocation of renewable energy carriers across power, heat and transport sectors. A high level of detail on the processes from source to end service enables detailed life-cycle greenhouse gas and cost assessments. Pareto analyses can be performed, as well as thorough sensitivity analyses. The model is designed to analyse optimal biomass and hydrogen usage, as a complement to integrated assessment and power system models.

19. keywords
Biomass; Power-to-x; Energy system; LCA; Sector coupling; Industrial ecology; Systems perspective

20. publisher
Elsevier

21. price
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3. title
Electrofuels from excess renewable electricity at high variable renewable shares: cost, greenhouse gas abatement, carbon use and competition

4. author(s) (family name, first name(s))
Millinger, Markus; Tafarte, Philip; Jordan, Matthias; Hahn Alena; Meisel, Kathleen; Thrän, Daniela

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Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany • Department of Economics, Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany • Research Group MultiplEE, Faculty of Economics and Management Science, Institute for Infrastructure and Resources Management, University of Leipzig, Ritterstraße 12, 04109 Leipzig, Germany • University Leipzig, Institute for Infrastructure and Resources Management, Grimmaische Str. 12, 04109 Leipzig, Germany • Department of Bioenergy Systems, Deutsches Biomasseforschungszentrum Gemeinnützige GmbH—DBFZ, Torgauer Straße 116, 04347 Leipzig, Germany	10. reference no. 03EIV116F 11. no. of pages 16

12. sponsoring agency (name, address) Bundesministerium für Wirtschaft und Klimaschutz (BMWK) 53107 Bonn	13. no. of references 114 14. no. of tables 4 15. no. of figures 11

16. supplementary notes

-

17. presented at (title, place, date)

-

18. abstract

Increasing shares of variable renewable electricity (VRE) generation are necessary for achieving high renewable shares in all energy sectors. This results in increased excess renewable electricity (ERE) at times when supply exceeds demand. ERE can be utilized as a low-emission energy source for sector coupling through hydrogen production via electrolysis, which can be used directly or combined with a carbon source to produce electrofuels. Such fuels are crucial for the transport sector, where renewable alternatives are scarce. However, while ERE increases with raising VRE shares, carbon emissions decrease and may become a limited resource with several usage options, including carbon storage (CCS). Here we perform a model based analysis for the German case until 2050, with a general analysis for regions with a high VRE reliance. Results indicate that ERE-based electrofuels could achieve a greenhouse gas (GHG) abatement of 74 MtCO2eq yearly (46% of current German transport emissions) by displacing fossil fuels, at high fuel-cell electric vehicle (FCEV) shares, at a cost of 250–320 € per tCO2eq. The capital expenditure of electrolysers was found not to be crucial for the cost, despite low capacity factors due to variable ERE patterns. Carbon will likely become a limiting factor when aiming for stringent climate targets and renewable electricity-based hydrocarbon electrofuels replacing fossil fuels achieve up to 70% more GHG abatement than CCS. Given (1) an unsaturated demand for renewable hydrocarbon fuels, (2) a saturated renewable hydrogen demand and (3) unused ERE capacities which would otherwise be curtailed, we find that carbon is better used for renewable fuel production than being stored in terms of overall GHG abatement.

19. keywords

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20. publisher	21. price
Royal Society of Chemistry	1600 GBP

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Planned	publication

3. title	
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4. author(s) (family name, first name(s)) EsmaeiliAliabadi, Danial; Chan, Katrina; Wulff, Niklas; Meisel, Kathleen; Jordan, Matthias; Oesterle, Ines; Pregger, Thomas; Thrän, Daniela	5. end of project May 2023 6. publication date - 7. form of publication Journal paper
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18. abstract 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 must set boundaries for 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.	
19. keywords Renewable energy directive; German transport sector; biofuel; synthetic fuel; optimization; energy system models	
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