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Do current energy policies in Germany promote the use of biomass in areas where it is particularly beneficial to the system? Analysing short- and long-term energy scenarios

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Abstract

Background Policymakers are tasked with both driving the rapid expansion of renewable energy technologies and, additionally channelling the limited national potential of biomass into areas where it can provide the greatest benefit to the energy system. But do current policy instruments promote the use of biomass in these areas? As biomass is limited, its use must be sustainable without leading to further biodiversity loss or depleting forest or soil resources. In this study, short-term energy scenarios are generated using the BenOpt model, which take into account both current and alternative policy instruments under limited biomass utilisation. The results are compared with long-term, cost-optimal energy scenarios for the use of biomass.

Results The analysis reveals that the instrument of a GHG quota does not promote the use of biofuels in hard-to-electrify areas of the transport sector, where they should be cost-optimally allocated according to long-term energy scenarios. Biofuels are promoted for use in passenger road transport and not in the shipping or aviation sector. In contrast, alternative policy scenarios indicate that the sole instrument of a high CO2 price is more conducive to direct electrification and could displace more fossil fuels by 2030 than the GHG quota alone. This instrument also promotes the optimal use of biogas plants in the power sector in accordance with long-term cost-optimal developments.

Conclusions The instrument of a GHG quota might lead to counterproductive developments in passenger road transport, but it also helps to ramp up the biofuel capacities required in shipping and aviation in the long term. However, it does not provide the necessary incentives for the ramp-up of battery electric vehicles, which would be the cost optimal solution in passenger road transport according to the long-term scenarios. Even though alternative policy scenarios show that the sole instrument of a high CO2-price is more conducive to direct electrification, a high CO2 price alone is not enough (e.g. in the heat sector) to promote the efficient use of biomass instead of simply covering the base load demand.

Keywords Energy system analysis, Bioenergy, RED II, Optimisation, Policy evaluation

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Background

Global climate change is forcing all nations to phase out fossil fuel-based energy generation in the power, heat and transport sectors. As a result, politicians need to establish strategies to drive forward the expansion of renewable energies. In Germany, the lion's share of energy will have to be generated from wind and photovoltaics (PV) in the long term [1–6], however the current picture is a far cry from the envisioned future targets. Currently, bioenergy makes up a substantial proportion of the renewable energies in Germany, primarily because it is consumed on a decentralised basis in the heating sector [7]. Unfortunately, biomass is often used inefficiently to heat private households or it is used in small-scale plants to provide base-load electricity. This, however, is expected to change. Studies show that the limited biomass potential in Germany should be used in areas that are difficult to electrify, for peak load coverage in the heat sector, or for flexible provision of electricity in the long term [3–6, 8–10]. Hard-to-electrify sectors include high-temperature heat applications, aviation, shipping and heavy-duty vehicles. Furthermore, biomass can also play an important role in hybrid heat supply concepts to cover peak load demand in the winter or as a flexibility option in the power sector to cover part of the residual load. Alternatives to these applications are green H2 (in accordance with the national hydrogen strategy [11]), other PtX solutions, or, where feasible, costly direct electrification solutions. In this context, it should be noted that the national biomass potential is limited and its use must be sustainable without leading to further biodiversity loss or depleting forest or soil resources. According to the cornerstone paper on the national biomass strategy, if there is a demand for biomass beyond the nationally sustainable potential, this demand should be covered by sustainable imports. Here, telecoupled land-use change, socioeconomic and ecological effects, the impact of seasonality and climate change on yields in the countries of origin as well as fair global distribution need to be taken into account [12–15]. These guidelines should also apply to the import of green H2 and its derivatives. It should be noted, however, that imports always entail the risk of ecological damage [16, 17].

Thus, policymakers need to promote the rapid expansion of renewable energy technologies and simultaneously channel the limited national biomass potential into areas where it can provide the greatest benefit to the energy system. Various instruments have been established in Germany to achieve the ramp-up of renewable technologies. These instruments are generally open to all renewable technologies. Consequently, biomass and bioenergy are addressed by an abundance of instruments. In the electricity sector, target percentages have been established for renewable energies. These are to be achieved through the implementation of a European trading scheme for CO2 certificates and through support measures for the produced electricity as defined in the Renewable Energy Sources Act [18]. In the heating sector, target values are in place for shares of renewables, as well as national CO2 trading scheme and investment subsidies. In the road transport sector, a binding greenhouse gas (GHG) quota based on RED II has been implemented and, as in the heating sector, a national CO2 price has been set. These instruments all aim to increase the proportion of renewable energies and to replace fossil energies. However, the question arises as to whether these instruments also promote the use of biomass in areas which are particularly beneficial for the system, or whether the valuable biomass is used less efficiently? Do the implemented political instruments lead to a cost-optimal transition path for biomass by 2050?

Naturally, the implemented political instruments need to be constantly adjusted and are regularly under discussion. Currently, a revision of the EU Renewable Energy Directive is under discussion (RED III) [19] and the European Parliament and Council recently agreed on regulations for using greener fuels in the aviation and maritime sectors (part of the "Fit for 55" package) [20, 21]. Additionally, due to the Russian war of aggression on Ukraine, the energy mix (e.g. the consumption of natural gas), and as a consequence, energy prices, have changed significantly, leading to an unpredictable development of energy trends up to 2030.

The German Environmental Agency analysed the effects of current policies on the energy system and the development of future emissions [22]. With regard to the utilisation of biomass, the study concludes that the current instruments are causing demand for biomass to rise substantially and that imports of solid biomass in particular could increase significantly as a result. This study does not focus on the specific areas where these biomass quantities are being utilised. On the contrary, our study especially focuses on the question of whether these instruments channel biomass into the areas of application with the greatest benefit to the system. It does so by comparing them with long-term cost-optimal energy scenarios. By formulating short-term scenarios in an optimisation setting, it is shown how the political instruments affect the cost-optimal distribution of biomass in the energy system. Numerous scenarios, which are intended to capture the uncertainties up to 2030, reveal in detail where there is a cost-optimal use of the limited biomass in Germany in the energy system under the scenario settings. Furthermore, a detailed comparison is made between these short-term policy scenarios and the long-term energy scenarios, identifying the cost-optimal allocation priorities of biomass in the energy system up to 2050. These long-term scenarios have been outlined in previous studies [9, 10].

Methods

This study uses the Bioenergy Optimisation (BenOpt) model to analyse short-term energy scenarios. The BenOpt model, technology data, biomass resources, price assumptions and the development of future energy demands have been comprehensively described in previous publications [9, 10, 23–26]. The latest version of the model, which is also used in this study, has been described in [9]. Consequently, the Methods section will only provide a brief overview of the model and will focus on integrating policies into the model, especially the integration of the GHG quota in the transport sector. The design of the scenarios and their different parameters are also described in detail.

The BenOpt model and the implementation of current policies

BenOpt is a classic bottom-up energy system optimisation model, as they are used in many cases to provide policy insights [27]. The design of BenOpt follows the best practice guidelines described by [28]. BenOpt focuses on analysing the future role of the limited biomass potential within the future German energy system. Hence, the degree of detail with regard to biomass feedstocks, bioenergy technologies and the relevant demand sectors is high. BenOpt models the competition in 19 heat sub-sectors and, 8 transport sub-sectors as well as the provision of residual load in the power sector. For each sub-sector, representative options are defined for fossil, bioenergy and alternative renewable technologies to meet the demand [23, 29]; see also Sec. 2.2.1 in [9]. In addition to monovalent systems, hybrid heat supply concepts were also defined for the heat sector [30]. For further details on the sectors see Sec. 2.1 of [9]. The limited biomass potential (over 30 types of biomass) is described in detail in Sec. 2.1 and 2.2.2 of [9] and can be freely allocated over all sectors within the optimisation model. Market prices for the different types of biomass as well as for fossil fuels and other materials, were compiled from various statistical databases, details of which can be found in the supplementary material and in Sec. 2.3 of [9]. No differentiation was made between domestic and import market prices. As the research focus is on biomass and bioenergy, BenOpt relies on data from external studies for other aspects, such as the development of future energy demands in each sub-sector, infrastructure developments, and the future expansion of wind and photovoltaics [1, 31]. For further details, see Sec. 2.1 of [9].

The model is fully deterministic and uses perfect foresight. Total system costs from 2020 to 2030 are minimised, while fulfilling the demand and scenario constraints. The allocation of technologies, fuels and feedstocks is internally optimised. For further details see Sec. 2.1 of [9]. The time horizon of the BenOpt model in this study is 11 years (from 2020 to 2030) with a yearly resolution in the heat and transport sector and an up-to-hourly resolution in the power sector. GAMS is used as a programming environment in combination with MATLAB. Since BenOpt is a linear programming model, the CPLEX solver has been chosen for GAMS.

In this study, we do not model long-term cost-optimal transformation pathways under the condition of fulfilling the climate targets by 2045. Instead, we investigate the effect of political instruments on the role of biomass in the energy transition up to 2030. Thus, political instruments had to be implemented into the model. For the heat and power sector, minimum shares of renewable technologies are to be achieved; see Table 2. This is simply integrated into the model, with the production of all renewable technologies in these sectors needing to be greater or equal to the target value. However, this is not as straightforward for the transport sector, as there is a detailed procedure for accounting renewable fuels in the GHG quotas. In this study, the focus lies on integrating the GHG quota requirements defined by RED II into the BenOpt model for the German road transport sector.

National implementation of RED II

The government has defined clear targets in the road transport sector for the total GHG quota in Germany. In the proposed GHG quota instrument, multi-counting factors are pivotal components, through which policymakers rank the significance of one technology over another, thereby effectively increasing the share of renewable energies. Table 1 shows the target values defined by RED II which amount to 25% in 2030. Table 1 also lists the minimum and maximum quotas for advanced biofuels, conventional biofuels, biofuels from used cooking oils (UCO) and animal fats, and for the use of PtL kerosene. Conventional biofuels are produced from energy crops that can also be used for food or feed. In contrast, advanced biofuels are produced from residues, wood and energy crops that cannot not be used for food or feed (e.g. perennial crops such as Miscanthus).

The total GHG-quota is basically calculated from the ratio of the (real) emissions ε^{real} in the transport sector (the numerator in the formula of Eq. 1) over a reference value ε^{ref} (the denominator). A simplified version of the formula is shown in Eq. 1. The actual accounting of different fuel types varies, details of the formula and its explanation for calculating the total GHG-quota from 2022

Table 1 Cornerstones for the national implementation of RED II in Germany for the transport sector as a percentage of CO2 emissions (total GHG-quota) or energy quantities (all others) [32, 33]

	Notation	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total GHG-quota (minimum quota)	GHG^{min}	7%	8%	9.25	10.5%	12%	14.5%	17.5%	21%	25%
Advanced biofuels (minimum quota)	$BioAdv^{min}$	0.2%	0.3%	0.4%	0.7%	1.0%	1.0%	1.7%	1.7%	2.6%
Conventional biofuels (maximum quota)	$BioConv^{max}$	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%
Biofuels from UCO and animal fats (maximum quota)	$BioUCO^{max}$	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%
PtL kerosene (minimum quota)	PtL_Ker^{min}					0.5%	0.5%	1.0%	1.0%	2.0%

UCO used cooking oil, *PtL* power to liquid

Table 2 Overview of the scenarios investigated in this study

	Sc.1 Trend	Sc.2 Only high CO2 price	Sc.3 Trend + high CO2 price	Sc.4 Ukraine	Sc.5 Transport Turnaround
CO2-Price EU ETS in €/tCO2 equiv.	90	129	129	90	90
CO2-Price DE EHS in €/tCO2 equiv.	125	300	300	125	125
Min. share renewable power	80%	–	80%	80%	80%
Min. share renewable heat	50%	–	50%	50%	50%
GHG-quota in transport	25%	–	25%	25%*	35%
Land for energy crops	2.3 Mha				
Import limit advanced biofuels	50% of the domestic potential of biomass residues				
Import limit conventional biofuels	Status 2020	Status 2020	Status 2020	0	Status 2020
Invest costs (technologies)	Base	Base	Low	Base	Low (transport)
Efficiency (technologies)	Base	Base	High	Base	High (transport)
Fossil energy and power prices	Base	Base	Base	Double	Base
Final energy demand	Moderate reduction				Strong reduction in transport

The values are shown for the year 2030. The years between the status quo in 2020 and 2030 are linearly interpolated. *Power (4x) and power-based fuels (3x) get higher crediting within the GHG-quota

onwards are shown in Fig. 6. End-of-pipe emissions and upstream emissions are considered in the GHG quota:

$$GHG\text{-}quota \leq 100\% - \frac{\sum(E\,[GJ]\cdot EF\,[kg/CO_2\text{-}eq]\cdot f^{EF\_PT}\,[\text{-}]\cdot f^{MC}\,[\text{-}]) - UER}{\sum(E\,[GJ]\cdot f^{MC}\,[\text{-}])\cdot ReferenceValue\,[kg/CO_2\text{-}eq]}, \quad (1)$$

where E = energy quantity of used fuel option,
EF = emission factor of used fuel option,
f^{EF_PT} = factor for efficiency powertrain and
f^{MC} = factor for multi-counting.

The cornerstones stated in Table 1 and the formula for calculating the total GHG-quota in Eq. 1 and Fig. 6 are implemented in the BenOpt model in accordance with Eq. 2–8. The total GHG quota applies only to the production of fuels used in German road transport, but considers domestic and imported (bio)fuels. The implementation is adapted to the BenOpt model design. Therefore, additional factors and variables had to be considered, such as the quantities of biomass used and the technology efficiencies. The original formula of the total GHG quota had to be rearranged to avoid formulating a non-linear constraint in GAMS. The result is shown in Eq. 2:

$$\varepsilon_t^{real} \leq (1 - GHG_t^{min})\cdot \varepsilon_t^{ref} \qquad \forall t \in T \quad (2)$$

$$\begin{aligned}\varepsilon_t^{real} = & \sum_{s,b} \dot{m}_{t,s,b}^{Petrol} \cdot 93.3 + \sum_{s,b} \dot{m}_{t,s,b}^{Diesel} \cdot 95.1 + \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioConv} \cdot \eta_{t,i,b} \cdot \varepsilon_{t,i}^{rel} \\ & + \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioAdv} \cdot \eta_{t,i,b} \cdot \varepsilon_{t,i}^{rel} + 2 \cdot \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioAdv+} \cdot \eta_{t,i,b} \cdot \varepsilon_{t,i}^{rel} \\ & + \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioUCO} \cdot \eta_{t,i,b} \cdot \varepsilon_{t,i}^{rel} + 3 \cdot \sum_{s,b} \dot{m}_{t,s,b}^{PowerMix} \cdot 0.4 \cdot \varepsilon_t^{PowerMix} \\ & + 2 \cdot \sum_{i,s} \pi_{t,i,s}^{H2} \cdot 0.4 \cdot \varepsilon_{t,i}^{rel} + 2 \cdot \sum_{i,s} \pi_{t,i,s}^{PtX} \cdot \varepsilon_{t,i}^{rel} \qquad \forall t \in T\end{aligned} \tag{3}$$

$$\begin{aligned}\varepsilon_t^{ref} = & 94.1 \cdot (\sum_{s,b} \dot{m}_{t,s,b}^{Petrol} + \sum_{s,b} \dot{m}_{t,s,b}^{Diesel} + \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioConv} \cdot \eta_{t,i,b} \\ & + \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioAdv} \cdot \eta_{t,i,b} + 2 \cdot \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioAdv+} \cdot \eta_{t,i,b} + \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioUCO} \cdot \eta_{t,i,b} \\ & + 3 \cdot \sum_{s,b} \dot{m}_{t,s,b}^{PowerMix} + 2 \cdot \sum_{i,s} \pi_{t,i,s}^{H2} + 2 \cdot \sum_{i,s} \pi_{t,i,s}^{PtX}) \qquad \forall t \in T\end{aligned} \tag{4}$$

$$BioAdv_t^{min} \cdot \sum_{i,s} \pi_{t,i,s}^{TransRoad} \leq \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioAdv} \cdot \eta_{t,i,b} \qquad \forall t \in T \tag{5}$$

$$BioConv_t^{max} \cdot \sum_{i,s} \pi_{t,i,s}^{Trans} \geq \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioConv} \cdot \eta_{t,i,b} \qquad \forall t \in T \tag{6}$$

$$BioUCO_t^{max} \cdot \sum_{i,s} \pi_{t,i,s}^{Trans} \geq \sum_{i,s,b} \dot{m}_{t,i,s,b}^{BioUCO} \cdot \eta_{t,i,b} \qquad \forall t \in T \tag{7}$$

$$PtL\_Ker_t^{min} \cdot \sum_{i,s} \pi_{t,i,s}^{TransAvia} \leq \sum_{i,s} \pi_{t,i,s}^{PtL\_Ker} \qquad \forall t \in T. \tag{8}$$

Real emissions ε_t^{real} are the sum of the fossil fuels, biofuels, direct electrification and power-based fuels, each multiplied by the corresponding emission factor ε^{rel}[1] and in some cases a factor for multiple crediting. With regard to fossil fuels, the use of petrol $\dot{m}_{t,s,b}^{Petrol}$ and diesel $\dot{m}_{t,s,b}^{Diesel}$ at each time point t is multiplied by the emission factors listed in Fig. 6. In terms of biofuels, the sum over the used biomass types b is multiplied by the efficiency $\eta_{t,i,b}$ and the emission factor $\varepsilon_{t,i}^{rel}$ for each technology i; see Eq. 3. As there is different crediting for conventional biofuels $\dot{m}_{t,i,s,b}^{BioConv}$, advanced biofuels $\dot{m}_{t,i,s,b}^{BioAdv}$, advanced biofuels over-fulfilling the quota $\dot{m}_{t,i,s,b}^{BioAdv+}$ and biofuels from UCO and animal fats $\dot{m}_{t,i,s,b}^{BioUCO}$, these fuels are separately defined in Eq. 3. For direct electrification, e.g. in battery electric vehicles, the use of electricity from the German power mix $\dot{m}_{t,s,b}^{PowerMix}$ and its corresponding emissions $\varepsilon_t^{PowerMix}$ are considered for each year t. Finally, the production of hydrogen $\pi_{t,i,s}^{H2}$ or its PtX derivates $\pi_{t,i,s}^{PtX}$ are considered. These quantities are summarised for all road sectors s. The reference emissions ε_t^{ref} are calculated according to the same principle (see Eq. 4) but without using the specific emission factor. Instead, a uniform reference value is used in accordance with Fig. 6.

Equations 5–8 represent the additional minimum or maximum quotas for the different fuel types defined in Table 1. For simplification, it is assumed that the minimum quota for advanced biofuels applies to the fuel production in the road transport sector $\pi_{t,i,s}^{TransRoad}$, the quota for conventional biofuels and fuels from UCO and animal fats applies to the production in the total transport sector $\pi_{t,i,s}^{Trans}$ and the minimum quota for producing PtL kerosene applies to the production in the aviation sector $\pi_{t,i,s}^{TransAvia}$.

Scenarios

The investigated scenarios take into account existing energy policies up to 2030 as well as alternative policies which are currently being discussed. Additionally, current political crises (the war in Ukraine) and their effects on the energy market are also taken into consideration. The Trend Scenario (Sc.1) was established as a basis for comparing the scenarios and includes the likely development of CO2 prices, the current energy prices, and developments in demand up to 2030. Already determined minimum percentages of renewable energies in the power, heat and transport sectors are considered and

[1] The emission factor for biofuels depends on whether they meet the RED criteria or their national implementation. If they do not, they receive the fossil factor. Since there are no such biofuels on the market today, they were not taken into account in the model.

need to be fulfilled by the optimisation model. In reality, these targets need to be achieved, for example, through subsidies in the heat sector. The GHG quota in the transport sector includes a variety of restrictions which are described in Sect. "The BenOpt model and the implementation of current policies". Investment costs and technology efficiencies are kept at the current level or, in some cases, conservative assumptions are made regarding improvements by 2030. In terms of biomass, the land available for cultivating energy crops and the potential for importing conventional biofuels remain constant. With regard to biomass residues, it is assumed that biomass residues that have yet to be mobilised can partially be activated and consequently the residues' potential and the potential to import advanced biofuels will moderately increase.

Sc.2 is an alternative policy scenario that assumes a significantly higher increase in the CO2 price development, but has no sector-specific quotas. All other parameters are set identical to the Trend Scenario.

Sc.3 combines the more ambitious political instruments from Sc.1 and Sc.2. Additionally, it assumes that, where technologically feasible, renewable technologies will become cheaper and more efficient, i.e. the performance of fossil technologies and conventional bioenergy technologies will not increase. All other parameters are identical to the Trend Scenario.

In the Ukraine Scenario (Sc.4), the GHG quota in transport was adjusted in relation to the Trend scenario in line with current proposals raised in the political debate [34]. This proposal includes increased crediting within the GHG quota for direct electrification (4x) and power-based fuels (3x). Additionally, the maximum quota for conventional biofuels (including the import of conventional biofuels) was lowered to zero in 2030, the maximum quota for biofuels from UCO was raised to 2.2%, and the energy prices (fossil and electricity) were doubled in the scenario in accordance with recent developments.

Sc.5 assumes an increased turnaround in transport, which currently shows the lowest share of renewable energy compared with the power and heat sector in Germany. In concrete terms, this means a rise in the GHG quota to 35% in 2030, a strong reduction in final energy demand in transport, and the assumption that renewable technologies in the transport sector will become cheaper and more efficient.

An overview of all scenario parameters can be found in Table 2. The parameters, which are only described qualitatively can be found in supplementary material to this paper, with the exception of the demand development. In terms of the heat demand development, all scenarios are based on the values of the Reference Scenario in the Building-STar Model [31]. In the power and transport sector, demand developments are based on the GreenLate-Scenario in [1], except for the transport sector in Sc.5, which relies on the GreenSurpreme-Scenario in [1].

Results

Short-term scenario results

The aggregated model results for the power and heat sector are shown in Fig. 1 for Sc.1 and Sc.2, and in Fig. 2 the results for the transport sector are shown for all analysed scenarios. The results show that the different policies have a diverse impact in each sector. A high CO2-price in Scenario 2, for example, results in more flexible renewable electricity provision. In the heat sector, this results in lower renewable shares than in the Trend Scenario, while in the transport sector, the ratio between renewable fuels and direct electrification changes considerably. In all investigated scenarios, the biomass potential is almost completely exploited by 2030, except for the import potential of conventional biofuels.

In the power sector, BenOpt models the competition between flexible bioenergy provision and other non-fluctuating energy resources which are competing to fulfil the future residual load [35]. The expansion of wind and PV as well as the development of future power demands are taken from existing studies [1] as an input to calculate the residual load. The results in the Trend Scenario show that the renewable electricity expansion target of 80% renewable electricity by 2030 is already fulfilled through the assumed expansion of renewable energy from wind and PV. Consequently, in this scenario setting, there is no stimulus for the provision of flexible renewable power and fossil technologies cover all residual load in this scenario. On the other hand, in Sc.2 a higher CO2 price leads to the competitiveness of biogas technologies (see Fig. 1).

In the heat sector, the policies of Sc.1 (minimum shares of renewable heat) and Sc.2 (only high CO2 price) show a different effect. In the Trend Scenario the share of renewable energy in 2030 is nearly twice as high as in Sc.2; see Fig. 1. The shares of biomass in this scenario are also proportionally higher than in Sc.2. Even with a significantly increasing CO2 price in Sc.2, low-cost natural gas is the dominant energy source in the heating sector (buildings and industry) and prevents the rapid ramp-up of renewable technologies. The sole instrument of CO2 price is therefore not enough to trigger a rapid transformation in the heat sector.

In the transport sector, the two different policies of Sc.1 (GHG quota) and Sc.2 (only high CO2 price) clearly lead to different results. In particular, the ratio between renewable fuels and direct electrification changes considerably; see Fig. 2. The GHG quota in the Trend Scenario, and in all other scenarios that include this instrument

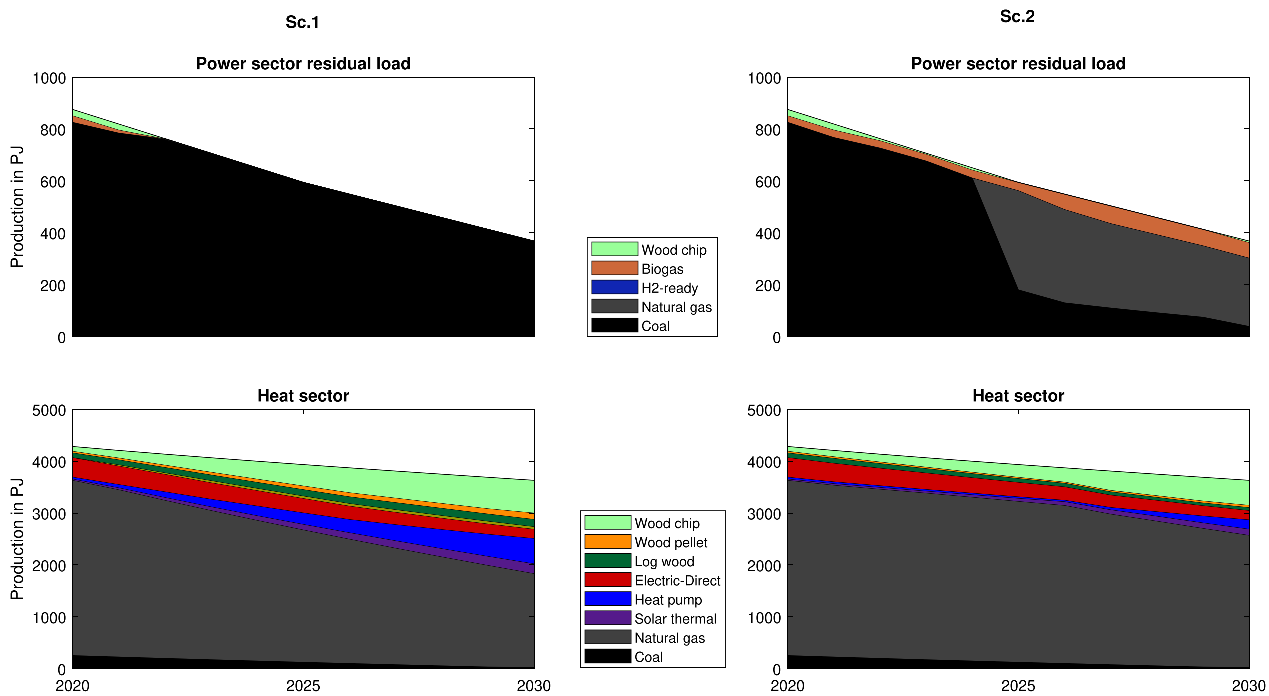

Fig. 1 Aggregated BenOpt model results in the power (residual load coverage) and heat sector for Sc.1 and Sc.2

promotes the use of biofuels and leads to higher shares of biofuels than today. The proportion of battery electric vehicles also increases. However, the policies in Sc.2 lead to a faster and higher direct electrification and fossil displacement rate in the transport sector compared to Sc.1, while the share of biofuels remains more or less constant. Interestingly, a combination of the ambitious political instruments of Sc.1 and Sc.2, which are integrated in Sc.3, leads to a stronger increase in renewable fuels by 2030 than in the two other scenarios; see Figs. 2 and 7. The fossil fuel shares are more or less identical in Sc.3 and Sc.2, however the share of direct electrification is lower in Sc.3.

In all scenarios, the shares of SNG and HEFA increase, although to varying degrees. The shares of FAME and bioethanol slowly decrease in all cases and biomethane is only temporarily competitive in the scenarios where a GHG-quota is introduced; see Figs. 2, 7 and 8. The switch from biomethane to SNG in all scenarios containing the GHG quota can also be interpreted as a switch from the cultivation of maize to the cultivation of Miscanthus or as a switch from conventional biofuels to advanced biofuels. In general, biofuels are used in all sub-sectors of the transport sector except in aviation. A high share of the biofuels used in the scenarios stems from imports (~50%); however, this is almost completely composed of advanced biofuels. When a GHG quota is in place, the highest shares of biofuels are used in (passenger) road transport, especially in CNG and LNG vehicles; see Fig. 3. As an instrument, the GHG quota thus has a strong impact on vehicle fleets. This impact is identical for all scenarios that take this instrument into account. However, one has to consider that fleet development in this analysis is purely driven by fuel competition; infrastructure and vehicle investment costs are not considered. In all cases where the GHG quota is applied, the quota is exactly met and not exceeded.

In the Ukraine scenario (Sc.4) the effect of increased power and fossil energy prices as well as political adjustments are investigated. The model results show no significant change in the power and heat sector compared to the Trend Scenario. In contrast, considerably more biomass is used in the transport sector, see Figs. 2 and 8. Of all scenarios investigated in this study, the highest shares of biofuels are consumed in Sc.4 in 2030. In particular, the cultivation of Miscanthus for the production of SNG and smaller quantities of BtL for use in diesel engines is strongly increased, leading to the highest use of land area for energy crop production of all investigated scenarios.

Sc.5 presents a hypothetical scenario for an accelerated energy transition in transport. All enhanced measures are applied to the transport sector only, which in this case lead to no significant changes in the power and heating sectors compared to Sc.1. Additionally, only little change in the absolute biofuel shares in the transport

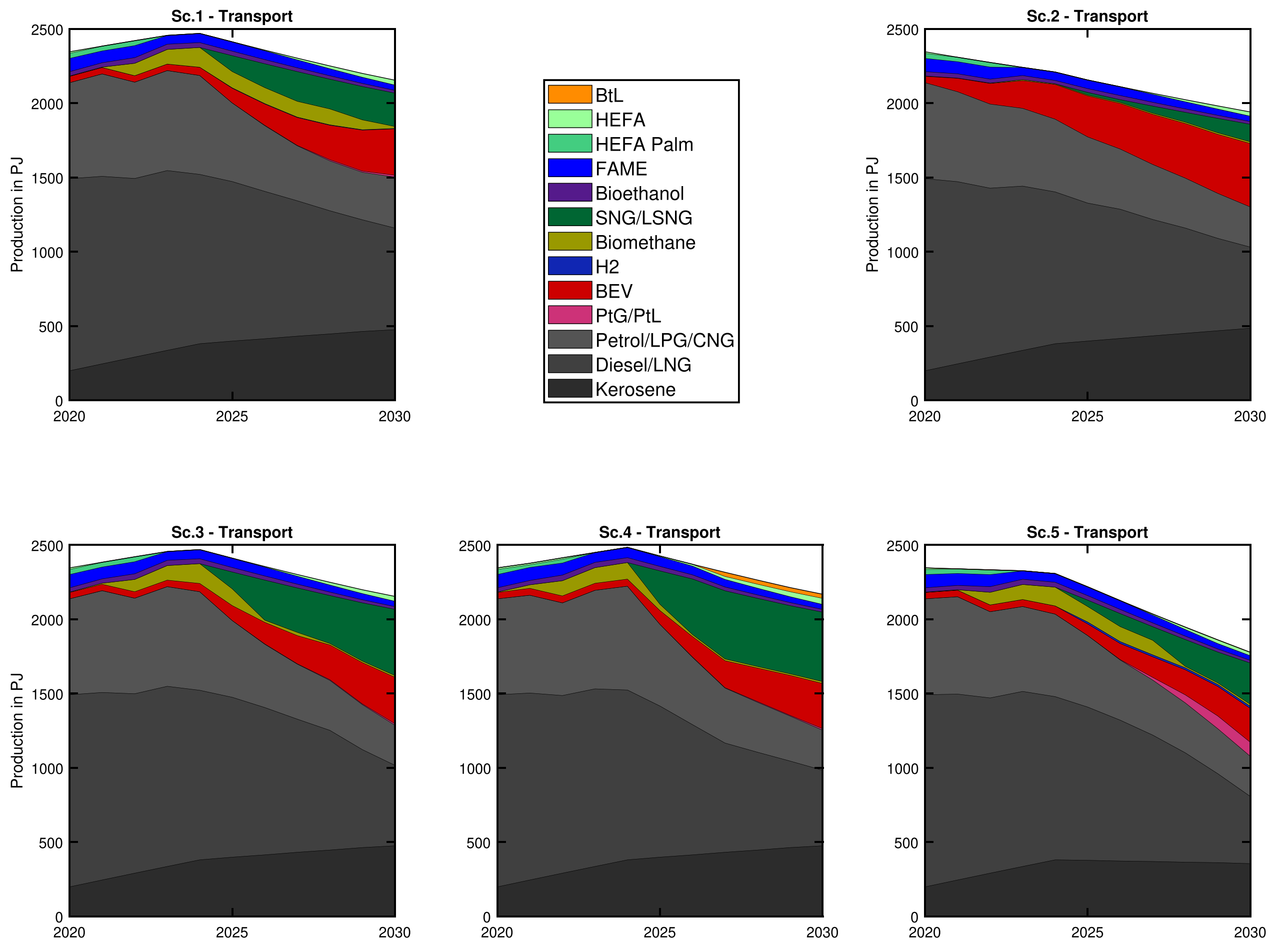

Fig. 2 Aggregated BenOpt model results in the transport sector for all investigated scenarios. *BtL* (lignocellulosic) biomass to liquid (gasification + Fischer–Tropsch synthesis), *HEFA* hydroprocessed esters and fatty acids, *FAME* fatty acid methyl ester, *SNG/LSNG* (liquified) synthetic natural gas (gasification of lignocellulosic biomass), *BEV* battery electric vehicles, *PtG* power to gas, *PtL* power to liquid, *LPG* liquefied petroleum gas, *LNG* liquified natural gas, *CNG* compressed natural gas

sector can be identified compared to the Trend Scenario. The results show an earlier shift from biomethane to SNG, leading to a small increase in the shares of SNG in 2030 compared to Sc.1. Instead, the applied measures in Sc.5 lead to a ramp-up of hydrogen and PtL FT diesel shares, displacing battery electric vehicles (BEV) shares; see Figs. 2 and 8. This can be explained by an assumed increase in the efficiency as well as price drops for PtX and H2 technologies in this scenario. A strong reduction in the final energy demand by 2030 in this scenario plays an essential role in reaching the lowest proportion of fossil fuel of all scenarios.

Short-term vs. long-term scenario results

The BenOpt model was also used to calculate long-term energy scenarios up to 2050. The results of these analyses are presented and discussed in detail in [9] and [10]. Long-term scenarios are not used to evaluate political instruments, but rather to identify cost-optimal transformation pathways up to 2050 while meeting defined GHG emission targets. In summary, these studies come to the conclusion that the limited potential of biomass is optimally used over the long term in areas which are hard to electrify or as a way of providing energy as a flexibility option. Domestic solid biomass potentials are prioritised in medium- to high-temperature heat applications. Advanced biofuel imports and domestic oily biomass potentials (UCO and animal fats) are prioritised in the shipping and aviation sector (HEFA and SNG). Finally, the domestic potential of digestible residues can play a key role in the energy transition by providing energy either as flexibility option in the power sector (biogas) or in hard-to-electrify areas of the heat sector (biomethane). The amount of biomass used in each of these sub-sectors is strongly dependent on the availability of biomass residues, energy crops and biofuel imports.

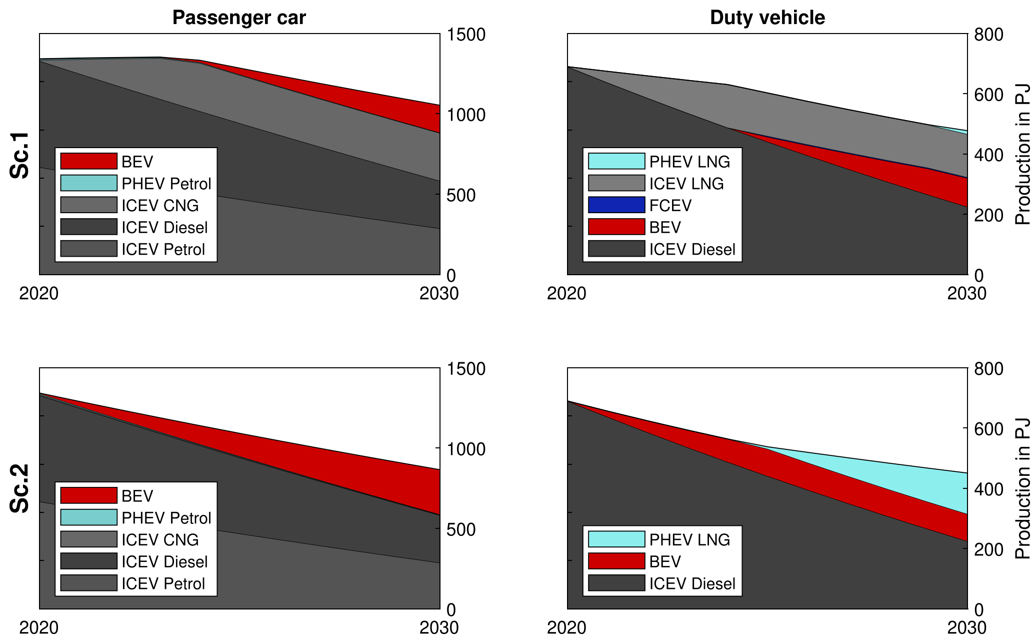

Fig. 3 Vehicle fleet development in Sc.1 and Sc.2 for the passenger road and duty vehicle sectors. The vehicle fleet development is identical for all scenarios that take into account the GHG quota. *BEV* battery electric vehicles, *PHEV* plug-in hybrid electric vehicles, *ICEV* internal combustion engine vehicles, *LNG* liquified natural gas, *CNG* compressed natural gas, *FCEV* fuel cell electric vehicles

A comparison of the short-term and long-term scenarios (up to 2030 vs. 2050) shows whether the current political measures promote the use of bioenergy in areas in which it should be cost-optimally used according to the long-term scenario results. In concrete terms, are current political measures following the path of the long-term scenarios? In particular, a comparison of the results in the transport sector reveals some differences;

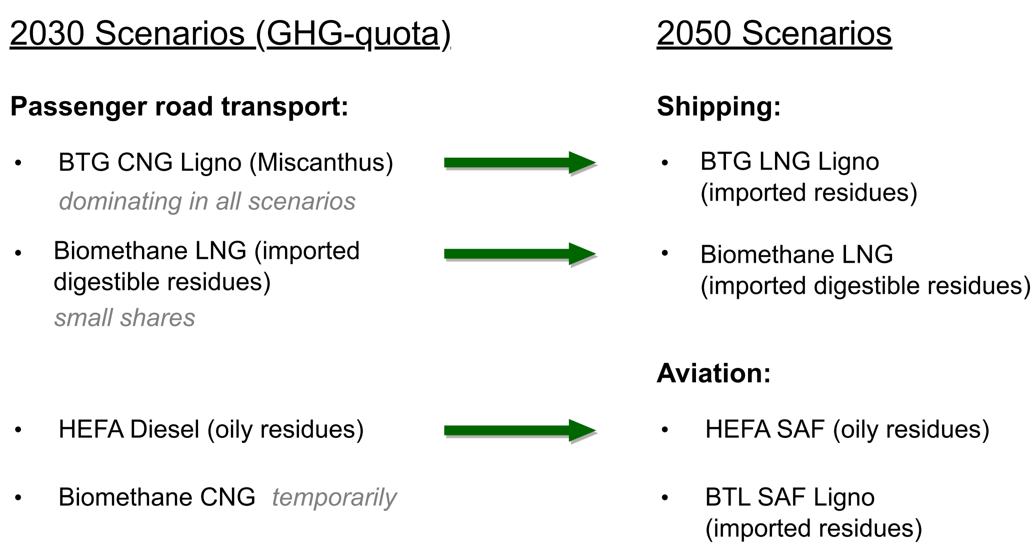

Fig. 4 Comparison of the bioenergy technologies in the transport sector, identified as the cost-optimal options either in the short term scenarios (left) or in the long-term scenarios (right). The GHG-quota, applied in the short-term scenarios, encourages the use of biofuels in sectors that should be electrified at optimal cost in the long term (passenger road transport). However, they can easily be used in shipping or processed into aviation fuels via suitable product developments. *BtG* biomass to gas (gasification of lignocellulosic biomass), *BtL* (lignocellulosic) biomass to liquid (gasification + Fischer–Tropsch synthesis), *LNG* liquified natural gas, *CNG* compressed natural gas, *HEFA* hydroprocessed esters and fatty acids, *SAF* sustainable aviation fuels

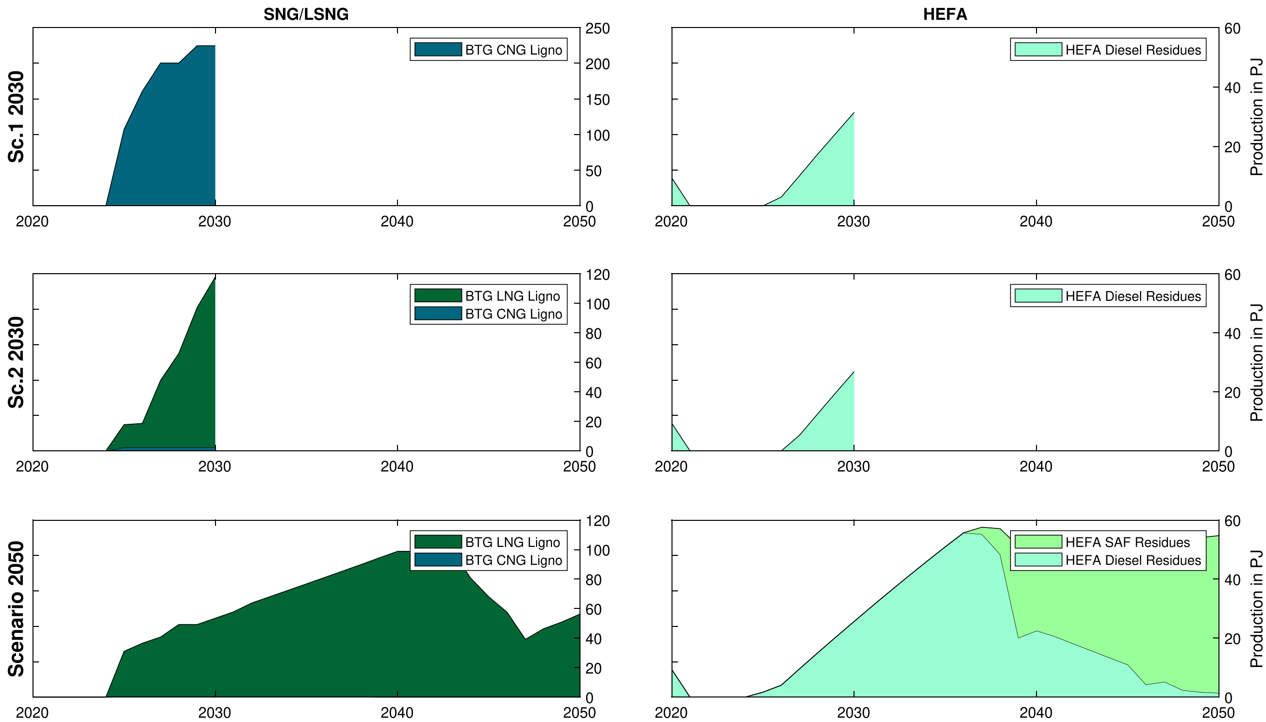

Fig. 5 Comparison of HEFA and SNG (BtG LNG or BtG CNG) shares in transport between Sc.1/ Sc.2 of the 2030 scenarios and a long-term energy scenario until 2050. *BtG* biomass to gas (gasification of lignocellulosic biomass), *LNG* liquified natural gas, *CNG* compressed natural gas, *HEFA* hydroprocessed esters and fatty acids, *SAF* sustainable aviation fuels

see Fig. 4. The GHG quota applied in the short-term scenarios (Sc.1/3/4/5) encourages the use of biofuels in passenger road transport, which, according to the long-term scenario results, should be cost-optimally electrified. The GHG quota therefore initially appears counterproductive, as the findings in the literature show that if biomass is to be used in transport, it should be used in areas that are difficult to electrify in the long term. These areas are aviation and shipping, not passenger road transport. However, the biofuels promoted by the GHG quota in road transport can easily be used in shipping or processed into aviation fuels via suitable product developments. In Fig. 4, the arrows indicate this process step, pointing to the competitive biofuels identified in the long-term energy scenarios. The largest shares in terms of volume are accounted for by the synthetic fuel biomass to gas (BTG) which is based on lignocellulosic biomass, and HEFA based on oily biomass. From a technical point of view, BTG CNG (compressed natural gas) can easily be liquified to BTG LNG (liquified natural gas), something which is common practice [36]. Of course, the costs for investment and operation will be higher, but the market value will also be higher. Refineries producing HEFA diesel can be retrofitted to produce HEFA SAF [37], the technical feasibility of which has been proven [38]. This is a one-time investment that results in identical operating costs but a final product of higher value. Consequently, the GHG quota does not promote the use of biofuels in the long-term targeted sectors, however the promoted biofuel types can be used in these sectors in the long term if suitable product developments are made. Figure 5 shows that, in the long-term scenarios, HEFA is initially used as a diesel and a switch to HEFA SAF only takes place after 2030. This demonstrates that the long-term scenario pathway is being followed. In addition, Fig. 5 shows that in the case of the BTG fuel in Sc.2, the long-term scenario pathway is already being followed and the liquefied variant of BTG has been produced from the beginning.

Discussion

The initial research gap investigated by this paper raises the question of whether current energy policies in Germany promote the use of biomass in areas where it is particularly beneficial to the system. To do this, short-term energy scenarios up to 2030, which take into account current policies in Germany, are compared with long-term energy scenarios up to 2050, and cost-optimal allocation priorities for the use of biomass are identified. This study investigates the short-term policy scenarios up to 2030 and the results are presented in Sect. "Short term scenario results". The findings of the long-term scenarios are presented in detail elsewhere [9, 10], but summarised and compared to the short-term scenarios in Sect. "Short term vs. long term scenario results".

The comparison shows that the current political instruments do not promote the use of biofuels in areas or sub-sectors of the transport sector in which they should cost-optimally be allocated according to the long-term energy scenarios. Instead, biofuels are promoted in passenger road transport rather than in shipping or aviation. Nevertheless, it could be argued that these biofuels can easily be used in shipping or processed into aviation fuels via suitable product developments. Consequently, the GHG quota ensures the necessary ramp-up of biofuels required in the long term, however, it does not provide the necessary incentives for the rapid electrification of the passenger road transport sector, which is the long-term cost-optimal solution under the assumptions used in our model. Accordingly, [39] discuss a modification of the multiple crediting factors within the GHG quota and evaluate the effects of these modifications. Thinking one step further, the question arises as to what should replace the GHG-quota instrument in 2030 in order to redirect biofuels from road transport to aviation and shipping. In 2023, the European Parliament and Council agreed on regulations for the use of greener fuels in the aviation and maritime sectors [20, 21]. These regulations are supposed to ensure a level playing field for sustainable air transport and will oblige suppliers of aircraft fuel to gradually increase the proportion of SAF to 70% by 2050. The impact of these measures on biofuels is difficult to estimate. European impact assessments project high amounts of biomass in the aviation and maritime sector as a consequence [40, 41]. Other sources come to varying conclusions [42], however, biomass potentials will not be enough to completely meet renewable energy demands in aviation, and PtL infrastructures will nevertheless need to be established.

Once biofuels are redirected to the aviation and maritime sectors after 2030, how can the passenger road transport sector catch up with or significantly expand direct electrification? Alternative policy scenarios show that the instrument of a high CO2 price alone (Sc.2) is more conducive to direct electrification and at the same time displaces more fossil fuels by 2030 than the GHG quota alone; see Fig. 2. A combination of the two instruments (Sc.3) leads to a similarly high degree of fossil fuel displacement as in Sc.2, but this combination leads to a considerably higher share of biofuels; see Fig. 2. Interestingly, the GHG quota influences vehicle fleet development towards internal combustion engines and the high CO2 price increases the share of biofuels used in these vehicles in Sc.3. It is therefore debatable whether the GHG quota provides a sufficient incentive for electric drives. In all cases, we see that, similar as today, a high share of the advanced biofuels used in the scenarios stems from imports.

Overall the instrument of a GHG quota is shown to have a significant impact on model results and promotes a high proportion of biofuels rather than direct electrification. This effect is even stronger in the Ukraine Scenario (Sc.4). One reason could be that fossil energies in the transport sector are more expensive than fossil fuels in the power and heat sectors. Consequently, if fossil energy prices double, the potential for cost savings is greatest from a systems perspective when fossil fuels are replaced with renewable fuels in transport. In this case, more biofuels are the optimal solution.

Surprisingly, the absolute share of biofuels in Sc.5 (Transport Turnaround) does not increase compared to Sc.1, even though the GHG quota increases from 25% to 35% (see Table 2). In this scenario, the assumed cost and efficiency benefits of PtX technologies lead to additional competitive market shares of PtX fuels. However, the key factor in this scenario is the strong reduction of the final energy demand by 2030, leading to the lowest absolute share of fossil fuels of all investigated scenarios. Here, the GHG quota of 35% is achieved with the same amount of biomass due to the increase in the relative share of bioenergy.

This study reveals detailed findings on the use of biomass in the transport sector using current political instruments. The results in the power and heat sectors, on the other hand, can be summarised quickly as the variations in Sc.3, Sc.4 and Sc.5 have a negligible influence on the results in the power and heat sector. In the power sector, it could be shown that a higher CO2 price than the current trend is necessary to create incentives for renewable flexibility options in addition to fossil options unless the government is willing to continue subsidising flexible power generation. Long-term modelling results [9, 10] show that biogas plants are one optimal way of providing flexibility in the power sector. An increased CO2 price by 2030 will help to retain the existing biogas plants (5.9 GW installed capacity in 2022 [43]) and incentivise retrofitting for flexible electricity supply.

For the heat sector, the modelling has shown that the instrument of a high CO2-price alone is not enough to achieve a rapid ramp-up of renewable technologies. The share of renewables in this scenario (Sc.2) is only half as high as in the Trend Scenario (Sc.1). Consequently, further political instruments, such as the investment subsidies currently being applied (Federal Subsidy for Efficient Buildings (BEG)) and the Federal Building Energy Act (GEG) are necessary [44]. The GEG specifies, for example, minimum shares for renewable energies in new buildings (65%) and minimum energy efficiency standards for the buildings. However, this act is controversially discussed and some institutions are calling for higher standards, e.g. higher efficiency standards for poorly refurbished buildings or doing away with the option to use fossil ”H2-ready” technologies for heating [45]. The findings of our analysis are in line with these demands. The share of renewable energies in new or refurbished buildings needs to increase, as technology life times reach 20–30 years and climate neutrality by 2045 can only be achieved if the installation of 100% renewable technologies starts now. Additionally, the findings in the long-term scenarios demonstrate once more that green hydrogen is an expensive option, which should only be used in areas that are hard to electrify or to provide flexibility.

Limitations

The competitiveness within the model in all sectors is driven by the technologies, fuels and feedstocks and does not consider infrastructure measures like an expansion of the power grid, hydrogen grid, gas grid or district heating network. Additionally, the competitiveness in the transport sector is purely driven by the different fuel types and does not consider investments in vehicles. Other approaches take these costs into account, e.g. the TCO (total cost of ownership) approach. Therefore, a simplification was made in this model by assuming that there are no differences in investment costs for future competing vehicles, as the German government already subsidises electric vehicles to harmonise investments. However, many factors are being taken into account within this modelling approach which cannot be considered using a TCO approach. For the heat and power sector, political instruments are represented through minimum shares of renewable energy. These targets were set as a constraint in BenOpt. In reality, these targets are supposed to be achieved through, for example, subsidies in the heat sector, which might have slightly changed the allocation priorities. The emission factors for biomass were chosen on the basis of political conventions and do not correspond to the real net emission factors, especially for wood [46]. Therefore, some high-value wood assortments were excluded a priori from the model.

Conclusions

A comparison of current and alternative policy scenarios up to 2030 with long-term cost-optimal scenarios up to 2050 identifies some commonalities and some contradictions. For one, it shows that the instrument of the GHG quota does not promote the use of biofuels in areas or sub-sectors of the transport sector in which they should be cost-optimally allocated according to the long-term energy scenarios. Biofuels are promoted in passenger road transport instead of in shipping and aviation. However, these biofuels can easily be used in shipping or processed into aviation fuels via suitable product developments and thus the GHG quota can help to ramp up these technologies. Nevertheless, the GHG quota could lead to counterproductive developments in passenger road transport. It does promote high shares of biofuels; however, it does not provide the necessary incentives for ramping up battery electric vehicles, which would be the cost-optimal solution in passenger road transport according to the long-term scenarios. This effect is even more distinct in the Ukraine Scenario. In alternative policy scenarios it has been shown that the instrument of a high CO2 price alone (Sc.2) is more conducive to direct electrification and, at the same time, displaces more fossil fuels by 2030 than the GHG quota alone.

A high CO2 price also leads to a more flexible use of biogas plants in order to balance fluctuating renewable energies in the power sector. This is one optimal solution identified by the long-term scenarios. Consequently, it will help to retain existing capacities of biogas plants and incentivise retrofitting for flexible electricity supply. However, in the heat sector the sole instrument of a high CO2 price is not enough to ramp-up renewable technologies. Further instruments are required to quickly replace fossil fuels, yet these instruments must be designed in such a way that biomass is used efficiently in areas that are difficult to electrify and not used to cover base load demand.

Appendix

See Figs. 6, 7, 8.

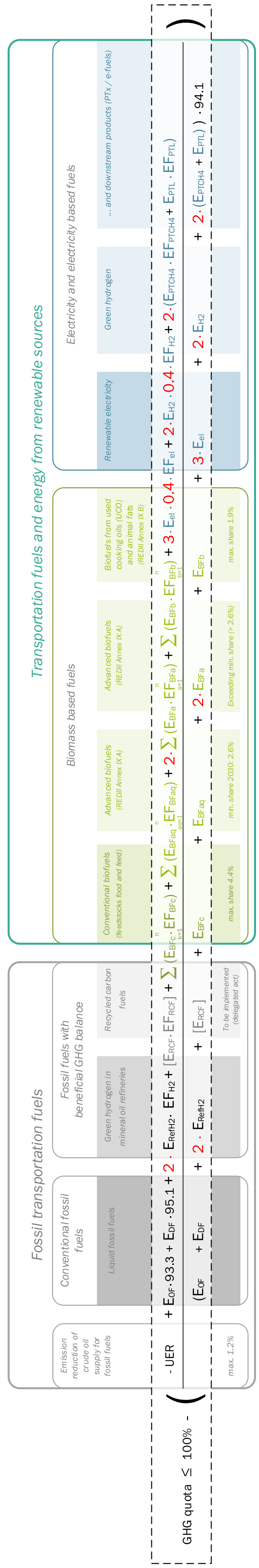

Fig. 6 Formula for the accounting of different fuel types in the total GHG-quota from 2022 onwards [47]

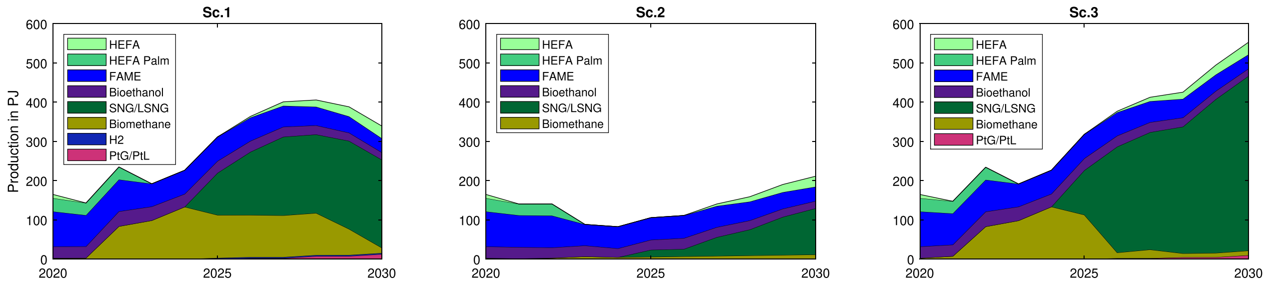

Fig. 7 Model resulting shares of renewable fuels in the transport sector in Sc.1 (Trend), Sc.2 and Sc.3.*HEFA* hydroprocessed esters and fatty acids, *FAME* fatty acid methyl ester, *SNG/LSNG* (liquified) synthetic natural gas (gasification of lignocellulosic biomass), *PtG* power to gas, *PtL* power to liquid

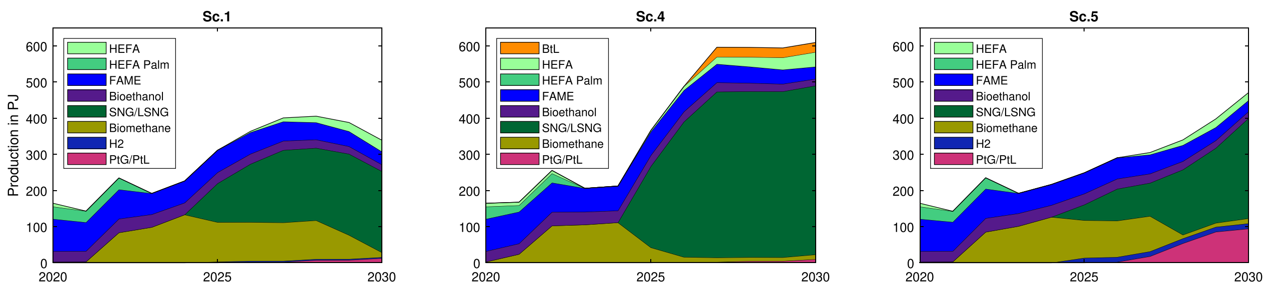

Fig. 8 Model resulting shares of renewable fuels in the transport sector in Sc.1 (Trend), Sc.4 (Ukraine) and Sc.5 (Transport Turnaround). *BtL* (lignocellulosic) biomass to liquid (gasification + Fischer–Tropsch synthesis), *HEFA* hydroprocessed esters and fatty acids, *FAME* fatty acid methyl ester, *SNG/LSNG* (liquified) synthetic natural gas (gasification of lignocellulosic biomass), *PtG* power to gas, *PtL* power to liquid

Supplementary Information

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Supplementary Material 1.

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Availability of data and materials
The datasets used and/or analysed in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Competing interests
The authors declare that they have no competing interest

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References

1. Purr K, Günther J, Lehmann H, Nuss P (2019) Resource-efficient pathways towards greenhouse-gas-neutrality: RESCUE: summary report. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/rescue_kurzfassung_eng.pdf
2. Deutschland auf dem Weg zur Klimaneutralität 2045: Szenarien und Pfade im Modellvergleich (2021) https://ariadneprojekt.de/publikation/deutschland-auf-dem-weg-zur-klimaneutralitat-2045-szenarienreport/
3. Towards a Climate-Neutral Germany by 2045: How Germany can reach its climate targets before 2050: Executive summary (2021) https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_04_KNDE45/A-EW_213_KNDE2045_Summary_EN_WEB.pdf
4. Climate Paths 2.0: A Program for Climate and Germany's Future Development (2021) https://english.bdi.eu/publication/news/climate-paths-2-0-a-program-for-climate-and-germanys-future-development/
5. Langfristszenarien für die Transformation des Energiesystems in Deutschland 3 (2021) https://www.langfristszenarien.de/enertile-explorer-de/
6. dena-Leitstudie: Aufbruch Klimaneutralität (2021) https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf

7. Erneuerbare Energien in Deutschland 2022: Daten zur Entwicklung im Jahr 2022 (2023) https://www.umweltbundesamt.de/publikationen/erneuerbare-energien-in-deutschland-2022
8. Klepper G, Thrän D (2019) Biomass: striking a balance between energy and climate policies: Strategies for sustainable bioenergy use. https://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/PDFs/ESYS_Position_Paper_Biomass.pdf
9. Jordan, M, Meisel K, Dotzauer M, Schröder J, Cyffka K-F, Dögnitz N, Schmid C, Lenz V, Naumann K, Daniel-Gromke J, Paiva GC, Schindler H, Aliabadi DE, Szarka N, Thrän D (2023) The controversial role of energy crops in the future German energy system: The trade offs of a phase-out and allocation priorities of the remaining biomass residues. Energy Rep 10: 3848–3858 https://doi.org/10.1016/j.egyr.2023.10.055
10. Meisel K, Jordan M, Dotzauer M, Schröder J, Lenz V, Naumann K, Cyffka K-F, Dögnitz N, Schindler H, Daniel-Gromke J, Costa de Paiva G, Schmid C, Szarka N, Majer S, Thrän D (2023) Quo vadis, biomass? Long-term scenarios of an optimal energetic use of biomass for energy transition. Int J Energy Res
11. The national hydrogen strategy (2020) https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile &v=6
12. Eckpunkte für eine Nationale Biomassestrategie: NABIS (2022) https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/nabis-eckpunktepapier-nationale-biomassestrategie.html
13. Welfle AJ, Almena A, Arshad MN, Banks SW, Butnar I, Chong KJ, Cooper SG, Daly H, Garcia Freites S, Güleç F, Hardacre C, Holland R, Lan L, Lee CS, Robertson P, Rowe R, Shepherd A, Skillen N, Tedesco S, Thornley P, Verdía Barbará P, Watson I, Williams OSA, Röder M (2023) Sustainability of bioenergy—mapping the risks and benefits to inform future bioenergy systems. Biomass Bioenergy 177: 106919. https://doi.org/10.1016/j.biombioe.2023.106919
14. Wu F, Pfenninger S (2023) Challenges and opportunities for bioenergy in Europe: National deployment, policy support, and possible future roles. Bioresour Technol Rep 22: 101430. https://doi.org/10.1016/j.biteb.2023.101430
15. Sadr M, Esmaeili Aliabadi D, Avşar B, Thrän D (2024) Assessing the impact of seasonality on bioenergy production from energy crops in Germany, considering just-in-time philosophy. Biofuels Bioprod Biorefining. https://doi.org/10.1002/bbb.2602
16. Egenolf V, Schüngel J, Bringezu S, Schaldach R (2023) The impact of the German timber footprint on potential species loss in supply regions. Sci Total Environ 901: 165897. https://doi.org/10.1016/j.scitotenv.2023.165897
17. Wang S, Chen B, Sun Z, Long X, Xue M, Yu H, Sun M, Wang Y (2023) The booming non-food bioeconomy drives large share of global land-use emissions. Glob Environ Change 83: 102760. https://doi.org/10.1016/j.gloenvcha.2023.102760
18. Bundesministeriums der Justiz und für Verbraucherschutz: Gesetz für den Ausbau erneuerbarer Energien: Erneuerbare- Energien-Gesetz - EEG 2017 (30.06.2017) http://www.gesetze-im-internet.de/eeg_2014/EEG_2017.pdf
19. Revision of the Renewable Energy Directive (2021) https://www.europarl.europa.eu/legislative-train/carriage/revision-of-the-renewable-energy-directive/report?sid=7201
20. European Commission: Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC. Accessed 17 February 2023 (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:562:FIN
21. Parliament European (2021) Annexes to the proposal for a regulation of the European parliament and of the council on ensuring a level playing field for sustainable air transport. Technical report, Publications office of the European Union, Luxembourg
22. Projektionsbericht 2023 für Deutschland (2023) https://www.umweltbundesamt.de/publikationen/projektionsbericht-2023-fuer-deutschland
23. Dotzauer M, Radtke KS, Jordan M, Thrän D (2024) Advanced SQL-Database for bioenergy technologies—a catalogue for bio-resources, conversion technologies, energy carriers, and supply applications. Heliyon 10(3):25434. https://doi.org/10.1016/j.heliyon.2024.e25434
24. Millinger M, Tafarte P, Jordan M, Musonda F, Chan K, Meisel K, Aliabadi DE (2022) A model for cost- and greenhouse gas optimal material and energy allocation of biomass and hydrogen. SoftwareX 20: 101264. https://doi.org/10.1016/j.softx.2022.101264
25. Jordan M, Lenz V, Millinger M, Oehmichen K, Thrän D (2019) Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach. Energy 189: 116194. https://doi.org/10.1016/j.energy.2019.116194
26. Jordan M, Millinger M, Thrän D (2022) Benopt-Heat: an economic optimization model to identify robust bioenergy technologies for the German heat transition. SoftwareX 18: 101032. https://doi.org/10.1016/j.softx.2022.101032
27. Welfle A, Thornley P, Röder M (2020) A review of the role of bioenergy modelling in renewable energy research & policy development. Biomass Bioenergy 136: 105542. https://doi.org/10.1016/j.biombioe.2020.105542
28. DeCarolis J, Daly H, Dodds P, Keppo I, Li F, McDowall W, Pye S, Strachan N, Trutnevyte E, Usher W, Winning M, Yeh S, Zeyringer M (2017) Formalizing best practice for energy system optimization modelling. Appl Energy 194: 184–198. https://doi.org/10.1016/j.apenergy.2017.03.001
29. Dotzauer M (2023) Bioenergy-Technology-Database (BET.db). https://doi.org/10.5281/zenodo.7632246
30. Lenz V, Jordan M (2019) Technical and economic data of renewable heat supply systems for different heat sub-sectors. https://doi.org/10.17632/v2c93n28rj.2 .
31. Koch M, Hennenberg K, Hünecke K, Haller M, Hesse T (2018) Role of bioenergy in the electricity and heating market until 2050, taking into account the future building stock (Rolle der Bioenergie im Strom- und Wärmemarkt bis 2050 unter Einbeziehung des zukünftigen Gebäudebestandes). https://www.energetische-biomassenutzung.de/fileadmin/Steckbriefe/dokumente/03KB114_Bericht_Bio-Strom-W%C3%A4rme.pdf Accessed 04.06.2019
32. Bundesregierung Deutschland: Gesetz zur Weiterentwicklung der Treibhausgasminderungs-Quote (2021) https://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl &start=%2F%2F%2A%5B%40attr_id=%27bgbl121s4458.pdf%27%5D#__bgbl__%2F%2F*%5B%40attr_id%3D%27bgbl121s4458.pdf%27%5D__1697788198261
33. Beschlossene Anpassungen der Treibhausgasminderungsquote (THG-Quote) (2023) https://www.bmuv.de/media/beschlossene-anpassungen-der-treibhausgasminderungsquote-thg-quote
34. Kurzpapier: Maßnahme zur Verringerung des Anteils von Biokraftstoffen aus Nahrungs- und Futtermittelpflanzen in Folge des Ukraine-Krieges (2023) https://www.klimareporter.de/images/dokumente/2023/01/230118-arbeitspapier-eckpunkte-agrokraftstoffe.pdf
35. Millinger M, Tafarte P, Jordan M, Hahn A, Meisel K, Thrän D (2021) Electrofuels from excess renewable electricity at high variable renewable shares: cost, greenhouse gas abatement, carbon use and competition. Sustain Energy Fuels 5(3):828–843. https://doi.org/10.1039/D0SE01067G
36. Baccioli A, Antonelli M, Frigo S, Desideri U, Pasini G (2018) Small scale bio-LNG plant: comparison of different biogas upgrading techniques. Appl Energy 217: 328–335 https://doi.org/10.1016/j.apenergy.2018.02.149
37. Müller-Langer F, Oehmichen K, Dietrich S, Zech KM, Reichmuth M, Weindorf W (2019) PTG-HEFA hybrid refinery as example of a SynBioPTx concept-results of a feasibility analysis. Appl Sci 9(19):4047. https://doi.org/10.3390/app9194047
38. Neste Rotterdam, Netherlands: Press Release (2022) https://www.safinvestor.com/project/141929/neste-rotterdam-netherlands/ Accessed 27.03.2024
39. Bannert J, Schütte C, Düsterlho J-E (2023) Increasing the share of renewable energy in the transport sector â€ "effects of modified multiple crediting factors in the German environmental economic instrument GHG Quota ("THG-Minderungsquote"). In: 2023 19th International Conference on the European Energy Market (EEM), pp. 1–11. https://doi.org/10.1109/EEM58374.2023.10161865
40. IMPACT ASSESSMENT: Accompanying the Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport (2021). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2021:0635:FIN:EN:PDF
41. IMPACT ASSESSMENT: Accompanying the Proposal for a Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport (2021) https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021SC0633 &from=EN
42. Esmaeili Aliabadi D, Chan K, Wulff N, Meisel K, Jordan M, Österle I, Pregger T, Thrän D (2023) Future renewable energy targets in the EU: Impacts on

the German transport. Transport Res Part D Transport Environ. https://doi.org/10.1016/j.trd.2023.103963
43. Installierte elektrische Leistung der Biogasanlagen in Deutschland in den Jahren 2001 bis 2022 (2023) https://de.statista.com/statistik/daten/studie/167673/umfrage/installierte-elektrische-leistung-von-biogasanlagen-seit-1999/
44. Bundestag: Gesetz zur Vereinheitlichung des Energieeinsparrechts für Gebäude und zur Änderung weiterer Gesetze (2020) https://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl &bk=Bundesanzeiger_BGBl &start=//*#__bgbl__%2F%2F*%5B%40attr_id%3D%27bgbl120s1728.pdf%27%5D__1694766811876
45. WWF stellt Leitplanken für das Heizungsgesetz vor (2023) https://www.wwf.de/2023/juni/wwf-stellt-leitplanken-fuer-das-heizungsgesetz-vor
46. Lundgren T (2008) The economics of biofuels. Int Rev Environ Resour Econ 2(3):237–280. https://doi.org/10.1561/101.00000017
47. Naumann K, Meisel K, Schröder J, Müller-Langer F, Majer S, Schmieder U (2021) Further development of the German greenhouse gas reduction quotA. https://www.dbfz.de/fileadmin/user_upload/Referenzen/Statements/Background_Paper_GHG_Quota.pdf

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