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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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

Policymakers need to drive the rapid expansion of renewable energy technologies, and additionally channel 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? In this study, short-term energy scenarios are generated using the BenOpt model while considering both current and alternative policy instruments. The results are compared with long-term, cost-optimal energy scenarios in regard to the use of biomass. The analysis reveals that e.g. the GHG-quota instrument does not promote the use of biofuels in the hard-to-electrify areas of the transport sector, where they should be cost-optimally allocated according to long-term energy scenarios. This might lead to counterproductive developments in the passenger road sector, but at the same time helps to ramp up biofuel capacities required in shipping and aviation in the long term. In contrast, alternative policy scenarios show that the sole
instrument of a high CO₂-price is more conducive to direct electrification and at the same time displaces more fossil fuels until 2030 than the GHG-quota alone. This instrument also promotes the optimal use of biogas plants in the power sector according to long-term cost-optimal developments. However, a high CO₂-price alone is not sufficient in the heat sector, where additional instruments are required to scale up renewable technologies and use biomass efficiently instead of simply covering the base load demand.

**Keywords:** energy system analysis, bioenergy, RED II, optimization, policy evaluation

1 Introduction

Global climate change forces all nations to phase out fossil fuels for power, heat and transport energy generation; therefore, politicians need to establish strategies to drive the expansion of renewable energies forward. While energy from wind and photovoltaic (PV) in Germany must provide the lion’s share in the long term [1–6], the current picture is a far cry from envisioned future targets. Currently, bioenergy provides one of the larger shares of renewable energies in Germany, primarily through its decentralized consumption in the heating sector [7]. Unfortunately, biomass is often used inefficiently in private households for heating or in small-scale plants to provide base-load electricity; however, this is expected to change. Studies show that the limited potential of biomass in Germany should be used in areas that are difficult to electrify, for peak load coverage in the heat sector or for the flexible provision of electricity in the long term [3–6, 8–10]. The instances of hard-to-electrify sectors are high-temperature heat applications, aviation, shipping or heavy-duty vehicles. Furthermore, biomass can play an important role in hybrid heat supply concepts to cover peak load demand in the winter or for covering parts of the residual load as a flexibility option in the power sector. For all these applications, the alternatives are green H₂ (according to the national hydrogen strategy [11]), other PtX solutions, or, where feasible, costly direct electrification solutions. In this context, we should note that the national potential of biomass is limited. If there is a demand for biomass beyond the nationally sustainable available potential, this demand, according to the cornerstone paper on the national biomass strategy, should be covered by sustainable imports, taking into account telecoupled land-use change, socioeconomic and ecological effects in the countries of origin as well as fair global distribution [12–14]. These guidelines should also apply to the import of green H₂ and its derivatives. However, imports do always entail the risk for ecological damage [15, 16].

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 values for the share of renewable energies have been defined, which
are to be achieved with the implementation of a European trading of CO₂ certificates and the support measures for the produced electricity defined in the Renewable Energy Sources Act [17]. In the heating sector, there are target values for renewable shares, national CO₂ trading and investment subsidies in place. 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 share of renewable energies and to replace fossil energies. However, the question arises whether these instruments also promote the use of biomass in areas, in which it is particularly beneficial for the system or whether the valuable biomass is used less efficiently? Lead the implemented political instruments onto the cost-optimal transition path for biomass until 2050?

Of course, the implemented political instruments need to be constantly adjusted as they are regularly under discussion. Currently, a revision of the EU Renewable Energy Directive is under discussion (RED III) [18] and the European Parliament and Council just agreed on regulations for the use of greener fuels in the aviation and maritime sectors (part of the fit-for-55 package) [19, 20]. Additionally, due to the Russian war of aggression on Ukraine, the energy mix (e.g., the consumption of natural gas from gaseous to liquid form), and subsequently, energy prices have changed significantly, leading to an unpredictable development of energy trends until 2030.

With this study, via formulating the short-term scenarios in an optimisation setting, we show how the political instruments affect the cost-optimal distribution of biomass in the energy system until the next decade. Using numerous scenarios, which are intended to capture the uncertainties up to 2030, it is shown in detail where the limited biomass in Germany finds the cost-optimal use in the energy system under the current political 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 until 2050. These long-term scenarios have been outlined in former studies [9, 10].

\section{Methods}

For this analysis, the BenOpt model is used in order to model short-term energy scenarios. The BenOpt model and the used data on technologies, biomass resources, price assumptions and the future energy demand development were comprehensively described in former publications [9, 10, 21]. Consequently, in this method section only a brief overview of the model is given. The focus of this section is on the implementation of policies into the model, especially the integration of the GHG-quota in the transport sector. Further, details on the design of the scenarios and their varied parameters are described.

\subsection{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 [22]. The design of BenOpt follows best practice guidelines described by DeCarolis et al. [23]. BenOpt is focusing on analysing the
future role of the limited biomass potential within the future German energy system. Hence, the degree of detail in regards to biomass feedstocks, bioenergy technologies and the relevant demand sectors is high. BenOpt is modeling the competition in 19 heat sub-sectors, 8 transport sub-sectors and the provision of the residual load in the power sector. For each sub-sector representative fossil, bioenergy and alternative renewable options are defined to fulfill the demand [21]. Besides monovalent systems, also hybrid heat supply concepts were defined for the heat sector [24]. The limited biomass potential (over 30 types) is described in detail and can be freely allocated over all sectors within the optimization. As the research focus is on biomass and bioenergy, BenOpt relies in other details on data from external studies, e.g. the future energy demand developments in each sub-sector, infrastructure developments or the future expansion of wind and photovoltaic [1, 25]. Details on the design of the model are described in various former studies [9, 10, 26–28].

The model is fully deterministic and uses perfect foresight. The time horizon of the BenOpt model in this study is 11 years from 2020 until 2030, with a yearly resolution in the heat and transport sector and an up to hourly resolution in the power sector. As a programming environment GAMS is used in combination with MATLAB. Since BenOpt is a linear programming model, the CPLEX solver is chosen for GAMS.

In this study, we do not model long term cost-optimal transformation pathways under the condition of fulfilling the climate targets. In addition to identifying cost-optimal transformation pathways fulfilling the climate targets in 2045/2050, this analysis is about investigating the effect of political instruments on the role of biomass in the energy transition until 2030. For this purpose, political instruments had to be implemented into the model. For the heat and power sector minimum shares of renewable technologies are to be achieved, 2. This is simply implemented in the model: the production of all renewable technologies in these sectors needs to be greater or equal the target value. For the transport sector, however, this is not as simple, as there is a detailed procedure for accounting renewable fuels into the GHG-quotas. In this study, the focus lies on implementing the GHG-quota requirements according the RED II for the German road transport sector into the BenOpt model.

### 2.1.1 National implementation of the 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 others to effectively increase the share of renewable energies. The target values in RED II are shown in Tab. 1 reaching 25% in 2030. Additionally, maximum or minimum quotas are defined for the use of advanced biofuels, conventional biofuels, biofuels from used cooking oils (UCO) and animal fats, and for the use of PtL kerosene, see also Tab. 1. Conventional biofuels are produced using energy crops, which could also be used for food or feeding. In contrast, advanced biofuels are stemming from residues, wood or energy crops, which can not be used for food or feeding (e.g. perennial crops as Miscanthus).

The total GHG-quota is basically calculated from the ratio of the (real) emissions $\varepsilon_{\text{real}}$ in the transport sector (the numerator in the formula of Fig. 1) over a reference
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) [29, 30]. UCO = Used Cooking Oil; PtL = Power to Liquid

<table>
<thead>
<tr>
<th>Notation</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total GHG-quota (minimum quota)</td>
<td>$GHG_{\text{min}}$</td>
<td>7%</td>
<td>8%</td>
<td>9.25</td>
<td>10.5%</td>
<td>12%</td>
<td>14.5%</td>
<td>17.5%</td>
<td>21%</td>
</tr>
<tr>
<td>Advanced biofuels (minimum quota)</td>
<td>$BioAdv_{\text{min}}$</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0.4%</td>
<td>0.7%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.7%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Conventional biofuels (maximum quota)</td>
<td>$BioConv_{\text{max}}$</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Biofuels from UCO and animal fats (maximum quota)</td>
<td>$BioUCO_{\text{max}}$</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.9%</td>
</tr>
<tr>
<td>PtL kerosene (minimum quota)</td>
<td>$PTL_{\text{Kermin}}$</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>2.0%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
value $\varepsilon^{\text{ref}}$ (the denominator). The accounting of different fuel types varies, details of the formula and its explanation for calculating the total GHG-quota from 2022 onwards is shown in Fig. 1. Within the GHG-quota end of pipe emissions and the upstream emissions are considered.

The cornerstones stated in Tab. 1 and the formula for calculating the total GHG-quota in Fig. 1 are implemented in the BenOpt model according to eq. 1-7. 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, thus additional factors and variables like the amounts of biomass used and the efficiencies of the technologies had to be considered. 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. 1.

$$
\varepsilon^{\text{real}} \leq (1 - GHG_{\text{min}}) \cdot \varepsilon^{\text{ref}} \quad \forall t \in T
$$

$$
\varepsilon^{\text{real}} = \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{ref}} + \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{rel}} + \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{rel}} \quad \forall t \in T
$$

$$
\varepsilon^{\text{ref}} = 94.1 \cdot (L m_{t,s,b} \cdot \eta_{t,i,b} + L m_{t,s,b} \cdot \eta_{t,i,b} + L m_{t,s,b} \cdot \eta_{t,i,b}) \quad \forall t \in T
$$

$$
\sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{rel}} \leq \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \quad \forall t \in T
$$

$$
\sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{rel}} \geq \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \quad \forall t \in T
$$

$$
\sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{rel}} \geq \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \quad \forall t \in T
$$

$$
\sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \cdot \varepsilon^{\text{rel}} \leq \sum_t L m_{t,s,b} \cdot \eta_{t,i,b} \quad \forall t \in T
$$
Fig. 1 Formula for the accounting of different fuel types in the total GHG-quota from 2022 onwards [31].
The real emissions $\varepsilon_{\text{real}}$ are the sum of the fossil fuels, biofuels, direct electrification and power based fuels, each multiplied with the corresponding emission factor $\varepsilon_{\text{rel}}$ and in some cases a factor for multiple crediting. In regards to fossil fuels the use of petrol $m_{\text{Petrol}}$ and diesel $m_{\text{Diesel}}$ at each time point $t$ is multiplied by the given emission factors in Fig. 1. In terms of biofuels the sum over the used biomass types $b$ is multiplied with the efficiency $\eta_{b}$ and the emission factor $\varepsilon_{\text{rel}}^{i}$ of each technology $i$, see eq. 2. As there is different crediting for conventional biofuels $m_{\text{BioConv}}$, advanced biofuels $m_{\text{BioAdv}}$, advanced biofuels over-fulfilling the quota $m_{\text{BioAdv+}}$ and biofuels from UCO and animal fats $m_{\text{BioUCO}}$, these fuels are separately defined in eq. 2. For direct electrification, e.g. in battery electric vehicles, the use of electrivity from the German power mix $m_{\text{PowerMix}}$ and its corresponding emissions $\varepsilon_{\text{PowerMix}}$ are considered for each year $t$. Finally, the production of hydrogen $\Pi_{\text{H2}}$ or its PtX derivates $\Pi_{\text{PtX}}$ are considered. These quantities are summarized over all road sectors $s$. The reference emissions $\varepsilon_{\text{ref}}$ are calculated according to the same principle, see eq. 3, but without using the specific emission factor. Instead, a uniform reference value is used according to Fig. 1.

Eq. 4 - 7 represent the additional minimum or maxima quotas for the different fuel types defined in Tab. 1. For simplification, it is assumed that the minimum quota for advanced biofuels applies to the fuel production in the road transport sector $\Pi_{\text{TransRoad}}^{\text{min}}$, the quota for conventional biofuels and fuels from UCO and animal fats applies to the production in the complete transport sector $\Pi_{\text{Trans}}^{\text{min}}$ and the minimum quota for producing PTL kerosene applies to the production in the aviation sector $\Pi_{\text{TransAvia}}^{\text{min}}$.

2.2 Scenarios

The investigated scenarios consider current energy policies until 2030 and alternative policies, which are currently discussed. Additionally, current political crises (Ukraine war) and their effects on the energy market are taken into consideration. As a base for comparing the scenarios, the Trend scenario (Sc.1) is set up. The Trend scenario includes a likely trend of the CO$_2$ price development, the current energy price and demand developments until 2030. Already decided minimum shares of renewable energies in the power, heat and transport sector are considered and need to be fulfilled by the optimization model. In reality these targets need to be achieved through e.g. subsidies in the heat sector. The GHG-quota in the transport sector includes a variety of restrictions, which are described in section 2.1. Invest costs and efficiencies of the technologies are kept at the current level or in some cases conservative assumptions are made regarding the improvement until 2030. In regards to biomass, the available land for the cultivation of energy crops and the potential for importing conventional biofuels remain constant. In regards to biomass residues, it is assumed that not yet mobilised biomass residues can partially be activated and consequently the residues potential and the potential to import advanced biofuels will moderately increase.

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.
Table 2 Overview of the scenarios investigated in this study. 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.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CO₂-Price EU ETS in €/tCO₂ equiv.</th>
<th>CO₂-Price DE EHS in €/tCO₂ equiv.</th>
<th>Min. share renewable power</th>
<th>Min. share renewable heat</th>
<th>GHG-quota in transport</th>
<th>Land for energy crops</th>
<th>Import limit advanced biofuels</th>
<th>Import limit conventional biofuels</th>
<th>Invest costs (Technologies)</th>
<th>Efficiency (Technologies)</th>
<th>Fossil energy and power prices</th>
<th>Final Energy demand</th>
<th>Transport Turnaround</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc.1 Trend</td>
<td>90</td>
<td>129</td>
<td>129</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>2.3 Mha</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
</tr>
<tr>
<td>Sc.2 Only high CO₂ price</td>
<td>125</td>
<td>300</td>
<td>300</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>50% of the domestic potential of biomass residues</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
</tr>
<tr>
<td>Sc.3 Trend + high CO₂ price</td>
<td>80%</td>
<td>50%</td>
<td>25%</td>
<td>80%</td>
<td>50%</td>
<td>25%</td>
<td>2.3 Mha</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
</tr>
<tr>
<td>Sc.4 Ukraine</td>
<td>90</td>
<td>90</td>
<td>25%*</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>2.3 Mha</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
</tr>
<tr>
<td>Sc.5 Transport Turnaround</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>2.3 Mha</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
<td>Status 2020</td>
</tr>
</tbody>
</table>
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 is assumed that renewable technologies become more efficient and cheaper, where technological feasible, e.g. fossil technologies and conventional bioenergy technologies do not increase their performance in this case. All other parameters are kept the same as in the Trend scenario.

In the Ukraine scenario (Sc.4), the GHG-quota in transport, compared to the Trend scenario, was adjusted according to current proposals raised in the political debate [32]. This proposal includes the increase of the crediting within the GHG-quota for direct electrification (4x) and power based fuels (3x). Additionally, the maximum quota for conventional biofuels was decreased to zero in 2030 including the import of conventional biofuels, the maximum quota for biofuels from UCO is increased to 2.2% and the energy prices (fossil and electricity) are doubled in the scenario, in accordance with the developments of the last years.

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 stronger increase in the GHG-quota up to 35% in 2030, a stronger reduction in the final energy demand development in transportation and it is assumed that renewable technologies in the transport sector become more efficient and cheaper. An overview of all scenario parameters can be found in table 2.

3 Results

3.1 Short term scenario results

The aggregated model results of the power and heat sector are shown in Fig. 2 for Sc.1 and Sc.2 and in Fig. 3 the transport sector results 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 is changing considerably. In all investigated scenarios, the biomass potential is almost completely exploited in 2030, except for the import potential of conventional biofuels.

In the power sector, BenOpt models the competition of flexible bioenergy provision to other non fluctuating energy resources which are competing to fulfill the future residual load [33]. The expansion of wind and PV as well as the future power demand development 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 in 2030 is already fulfilled with 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 in Sc.2, see Fig. 2.
In the heat sector, the policies of Sc.1 and Sc.2 show a different effect. In the Trend scenario the share of renewable energy in 2030 is nearly double as high as in Sc.2, see Fig. 2. The biomass shares in this scenario are also proportionally higher than in Sc.2. Even with a strongly increasing CO$_2$-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 CO$_2$-price is therefore not sufficient in the heat sector to trigger a rapid transformation.

In the transport sector, the two different policies of Sc.1 (GHG-Quota) and Sc.2 (Only high CO$_2$-price) clearly lead to different results. Especially, the ratio between renewable fuels and direct electrification is changing considerably, see Fig. 3. The GHG-quota in the Trend scenario, and all other scenarios considering this instrument, promotes the use of biofuels and leads to higher shares of biofuels than today. Additionally, the share of battery electric vehicles 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 biofuel shares remain more or less constant. Interestingly, a combination of the ambitious political instruments of Sc.1 and Sc.2, which are integrated in Sc.3, lead to a stronger increase of renewable fuels until 2030 than in the two other scenarios, see Fig. 3 and 7. However, the fossil fuel shares are more or less identical in Sc.3 and Sc.2, but the share of direct electrification is lower in Sc.3.

In all scenarios, the SNG and HEFA shares increase, although to varying degrees. The shares of FAME and Bioethanol are slowly decreasing in all cases and biomethane is only temporarily competitive in the scenarios where a GHG-quota is introduced, see Fig. 3, 7 and 8. The switch from biomethane to SNG in all GHG-quota related scenarios can also be interpreted as a switch from the cultivation of maize to the cultivation of
Fig. 3 Aggregated BenOpt model results in the transport sector for all investigated scenarios. BtL = Biomass to Liquid; HEFA = Hydroprocessed Esters and Fatty Acids; FAME = fatty acid methyl ester; SNG/LSNG = (Liquified) Synthetic Natural Gas; BEV = Battery Electric Vehicles; PtG = Power to Gas; PtL = Power to Liquid; LPG = Liquefied Petroleum Gas; LNG = Liquefied Natural Gas; CNG = Compressed Natural Gas.

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. However, 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. 4. The GHG-quota instrument thus has a strong impact on the vehicle fleet, which looks identical for all scenarios considering this instrument. However, one has to consider that the fleet development in this analysis is purely driven by the fuel competition, infrastructure and vehicle investment costs are not considered. In all cases where the GHG-quota is applied, it 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 change in the power and heat sector compared to the Trend scenario. In contrast, considerably more biomass is used in the transport sector, see Fig. 3 and 8. From all scenarios investigated in this study, in Sc.4 the highest shares of biofuels are consumed in 2030. Especially, the cultivation of Miscanthus for the production of SNG and also smaller
shares of BtL for the use in diesel engines is strongly increased, leading to the highest use of land area for energy crop production between 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 changes in the power and heating sectors compared to Sc.1. Additionally, only little change on the absolute biofuel shares in the transport sector can be identified compared to the Trend scenario. The results show an earlier shift from biomethane to SNG, leading to a small increase of the SNG shares in 2030 compared to Sc.1. Instead, the applied measures in Sc.5 lead to a ramp-up of the hydrogen and PtL FT diesel shares, displacing battery electric vehicle (BEV) shares, see Fig. 3 and 8. This can be explained with an assumed increase of the efficiency and price drops of PtX and H2 technologies in this scenario. The strong reduction of the final end energy demand until 2030 in this scenario plays an essential role for reaching the lowest fossil fuel shares of all scenarios.

3.2 Short term vs. long term scenario results

With the BenOpt model, also long term energy scenarios until 2050 have been calculated and the results of these analyses are comprehensively presented and discussed in Jordan et al. [9], Meisel et al. [10]. The objective of the long term scenarios is not the evaluation of political instruments, but rather the identification of cost optimal transformation pathways until 2050, while fulfilling defined emission targets. In summary, these studies come to the conclusion that the limited potential of biomass is in the long term optimally used in areas, which are hard to electrify or in providing energy as
flexibility option. Solid domestic 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
an essential role within the energy transition by providing energy either as flexibil-
ity 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.

<table>
<thead>
<tr>
<th>2030 Scenarios (GHG-quota)</th>
<th>2050 Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passenger road transport:</strong></td>
<td><strong>Shipping:</strong></td>
</tr>
<tr>
<td>• BTG CNG Ligno (Miscanthus) <em>dominating in all scenarios</em></td>
<td>• BTG LNG Ligno (imported residues)</td>
</tr>
<tr>
<td>• Biomethane LNG (imported digestible residues) <em>small shares</em></td>
<td>• Biomethane LNG (imported digestible residues)</td>
</tr>
<tr>
<td>• HEFA Diesel (oily residues)</td>
<td>• HEFA SAF (oily residues)</td>
</tr>
<tr>
<td>• Biomethane CNG <em>temporarily</em></td>
<td>• BTL SAF Ligno (imported residues)</td>
</tr>
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</table>

Fig. 5 Comparison of the bioenergy technologies in the transport sector, identified as the cost opti-
mal options either in the short term scenarios (left) as well as 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; LNG=Liquified Natural Gas; CNG=Compressed Natural Gas; HEFA=Hydroprocessed Esters
and Fatty Acids; SAF=Sustainable Aviation Fuels.

The comparison of the two scenario approaches (2030 vs. 2050) shows whether the
current political measures promote the use of bioenergy in the areas in which bioenergy
should cost-optimally be used according to the long term scenario results. In concrete
terms, is the path of the long-term scenarios being followed through current political
measures? Especially, a comparison of the results in the transport sector reveals some
differences, see Fig. 5. The GHG-quota, applied in the short term scenarios (Sc.1/3/4/5), encourages the use of biofuels in the passenger road transport sector, which
according to the long term scenario results should cost-optimally be electrified. The
GHG-quota therefore initially appears counterproductive, as the findings in the liter-
ature are consistent in that if biomass is to be used in transport, it should be used
in those areas that are difficult to electrify in the long term. And these are the avia-
tion and shipping sectors and not the passenger road transport sector. However, the
biofuels promoted by the GHG-quota in road transport can easily be used in ship-
ping or processed into aviation fuels via suitable product developments. In Fig. 5, the
arrows indicate this process step, pointing on 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)* based on lignocellulosic biomass and *HEFA* based on oily biomass. *BTG CNG* (compressed natural gas) can easily be liquified to *BTG LNG* (liquified natural gas), and refineries producing *HEFA diesel* can be retrofitted to *HEFA SAF*. Consequently, the GHG-quota does not promote the use of biofuels in the long-term targeted sectors, but the promoted biofuel types can be used in the targeted sectors in the long term via suitable product developments. Fig. 6 actually shows that in the long-term scenarios HEFA is initially used as diesel and a switch to HEFA SAF only takes place after 2030, showing that the path of the long-term scenarios is being followed. In addition, Fig. 6 shows that in the case of the BTG fuel in Sc.2, the path of the long-term scenarios is already being followed and the liquefied variant of BTG is already being produced from the beginning.

![Fig. 6 Comparison of HEFA and SNG shares in transport between Sc.1/ Sc.2 of the 2030 scenarios and a long term energy scenario until 2050. SNG/LSNG=(Liquified) Synthetic Natural Gas; BtG=Biomass to Gas; LNG=Liquified Natural Gas; CNG= Compressed Natural Gas; HEFA=Hydroprocessed Esters and Fatty Acids; SAF=Sustainable Aviation Fuels.](image)

**4 Discussion**

The initial research gap in this paper raises the question whether current energy policies in Germany promote the use of biomass in areas where it is particularly beneficial to the system? For this purpose short term energy scenarios until 2030 considering current policies in Germany are compared with long term energy scenarios until 2050 identifying cost optimal allocation priorities for the use of biomass. Within this study, the short term policy scenarios until 2030 are calculated and the results are presented in section 3.1. The findings of the long term scenarios are presented
elsewhere in detail [9, 10], but summarized and compared to the short term scenarios in section 3.2.

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 long term energy scenarios. Biofuels are rather promoted in the passenger road transport than in the shipping or aviation sector. Nevertheless, it could be shown 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, but on the other hand, it does not provide the necessary incentives for the rapid electrification of the passenger road transport sector, which is the cost optimal solution in the long term under the assumptions used in our model. Accordingly, a modification of the multiple crediting factors within the GHG-quota is discussed and the effects of these modifications are being evaluated in Bannert et al. [34]. 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 [19, 20]. For example, these regulations are supposed to ensure a level playing field for sustainable air transport and will oblige aircraft fuel suppliers to gradually increase the share of SAF up to 70% in 2050. The impact of these measures on biofuels is difficult to estimate. European impact assessments project high amounts of biomass as a consequence in the aviation and maritime sector [35, 36]. Other sources come to varying conclusions [37]. However, the biomass potentials will not be enough to fulfill the complete renewable energy demands in aviation and PtL infrastructures need to be established anyway.

When biofuels are being 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 CO$_2$-price alone (Sc.2) is more conducive to direct electrification and at the same time displaces more fossil fuels until 2030 than the GHG-quota alone, see Fig. 3. 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 considerably higher biofuel shares, see Fig. 3. Interestingly, the GHG-quota influences the vehicle fleet development towards internal combustion engines and the high CO$_2$-price increases the biofuel share used in these vehicles in Sc.3. It is therefore debatable whether the GHG quota does not provide sufficient incentives for electric drives. In all cases, we see that, similar as today, a high share of the advanced biofuels used in the scenarios is stemming from imports.

In any case, it could be shown that the instrument GHG-Quota has a significant impact on the model results and promotes high shares of biofuels rather than a direct electrification. In the Ukraine-Scenario (Sc.4) this effect is even increased. One reason could be that fossil energies in the transport sector are the most expensive ones compared to fossil fuels in the power and heat sectors. Consequently, if fossil energy prices double, there is the greatest potential for cost savings from a systems perspective by
replacing fossil transport fuels with renewable fuels, in this case more biofuels are the optimal solution.

Surprisingly, the absolute biofuel shares in Sc.5 (Transport Turnaround) are not increased compared to Sc.1, although the GHG-quota is increased 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 end energy demand until 2030 leading to the lowest absolute fossil fuel shares of all investigated scenarios and realising the GHG-Quota of 35% with the same amount of biomass due to the increase in the relative bioenergy share.

This study reveals detailed findings on the use of biomass in the transport sector under 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 CO$_2$-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 subsidizing flexible power generation. Long term modeling results [9, 10] show, that biogas plants are one optimal solution to provide flexibility in the power sector. An increased CO$_2$-price until 2030 will help to retain the existing biogas plants (5.9 GW installed capacity in 2022 [38]) and incentivise retrofitting for flexible electricity supply.

For the heat sector, modelling has shown that the instrument of a high CO$_2$-price alone is not sufficient to achieve a rapid ramp-up of renewable technologies. The renewable shares in this scenario (Sc.2) are only half as high as in the Trend Scenario (Sc.1). Consequently, further political instruments, such as the currently applicable investment subsidies (federal funding for efficient buildings (BEG)) and the federal building energy act (GEG) are necessary [39]. The GEG specifies e.g. minimum shares for renewable energies in new buildings (65%) and minimum energy efficiency standards of the buildings. However, this act is controversially discussed and some institutions request higher standards, e.g. higher efficiency standards for poorly refurbished buildings or deleting the option to use fossil "H2-ready" technologies for heating [40]. The findings in our analysis are in line with these requests. The renewable energy share in new or refurbished buildings needs to increase, as the technology life times reach 20-30 years and climate neutrality in 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 for providing flexibility.

Limitations. The competitiveness in the transport sector within the model is purely driven by the different fuel types and does not consider investments for vehicles or infrastructure. In the modeling, for the heat and power sector political instruments are represented through minimum shares of renewable energy. These targets were set as a restriction in BenOpt. In reality these targets are supposed to be achieved through e.g. 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 [41]. Therefore, some high-value wood assortments were excluded from the model a priori.

5 Conclusions

The comparison of current and alternative policy scenarios until 2030 with cost optimal long term scenarios until 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 cost optimally be allocated according to long term energy scenarios. Biofuels are promoted to be used in the passenger road transport instead of the shipping or aviation sector. However, these biofuels can easily be used in shipping or processed into aviation fuels via suitable product developments and thus the GHG-quota helps ramping-up these technologies. Nevertheless, the GHG-quota might lead to counterproductive developments in the passenger road sector. On the one hand it promotes high shares of biofuels but on the other hand, it does not provide the necessary incentives for the ramp-up of battery electric vehicles, which would be the cost optimal solution in the passenger road sector according to the long term scenarios. In the Ukraine scenario, this effect is even more distinct. In alternative policy scenarios it is 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 until 2030 than the GHG-quota alone.

A high CO₂-price also leads to biogas plants being used more flexibly for balancing fluctuating renewable energies in the power sector, which is one optimal solution identified in 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 is not used to cover base load demand.

6 Declarations

• Ethics approval and consent to participate: Not applicable.
• Consent for publication: Not applicable.
• Availability of data and materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.
• Competing interests: The authors declare that they have no competing interests.
• Funding: The project on which this article is based on is an internal strategic project of the German Biomass Research Center.
• Acknowledgements: Thank you to Öko-Institut e.V. for sharing the heat demand data calculated with B-STar (Building Stock Transformation Model), which have been used in this study for the defined household, trade and commerce and district heating markets [25].
Fig. 7 Model resulting shares of renewable fuels in the transport sector in Sc.1 (Trend), Sc.2 and Sc.3. BtL=Biomass to Liquid; HEFA=Hydroprocessed Esters and Fatty Acids; FAME=fatty acid methyl ester; SNG/LSNG=(Liquified) Synthetic Natural Gas; BEV=Battery Electric Vehicles; PtG=Power to Gas; PtL=Power to Liquid; LPG=Liquefied Petroleum Gas; LNG=Liquified Natural Gas; CNG=Compressed Natural Gas.

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=Biomass to Liquid; HEFA=Hydroprocessed Esters and Fatty Acids; FAME=fatty acid methyl ester; SNG/LSNG=(Liquified) Synthetic Natural Gas; BEV=Battery Electric Vehicles; PtG=Power to Gas; PtL=Power to Liquid; LPG=Liquefied Petroleum Gas; LNG=Liquified Natural Gas; CNG=Compressed Natural Gas

7 Appendix

References


[4] Climate Paths 2.0: A Program for Climate and Germany's


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