Transformation scenarios towards a low-carbon bioeconomy in Austria

Keywords: Low-carbon economy, Bioeconomy, Scenario, Decarbonisation, Biomass

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Abstract:

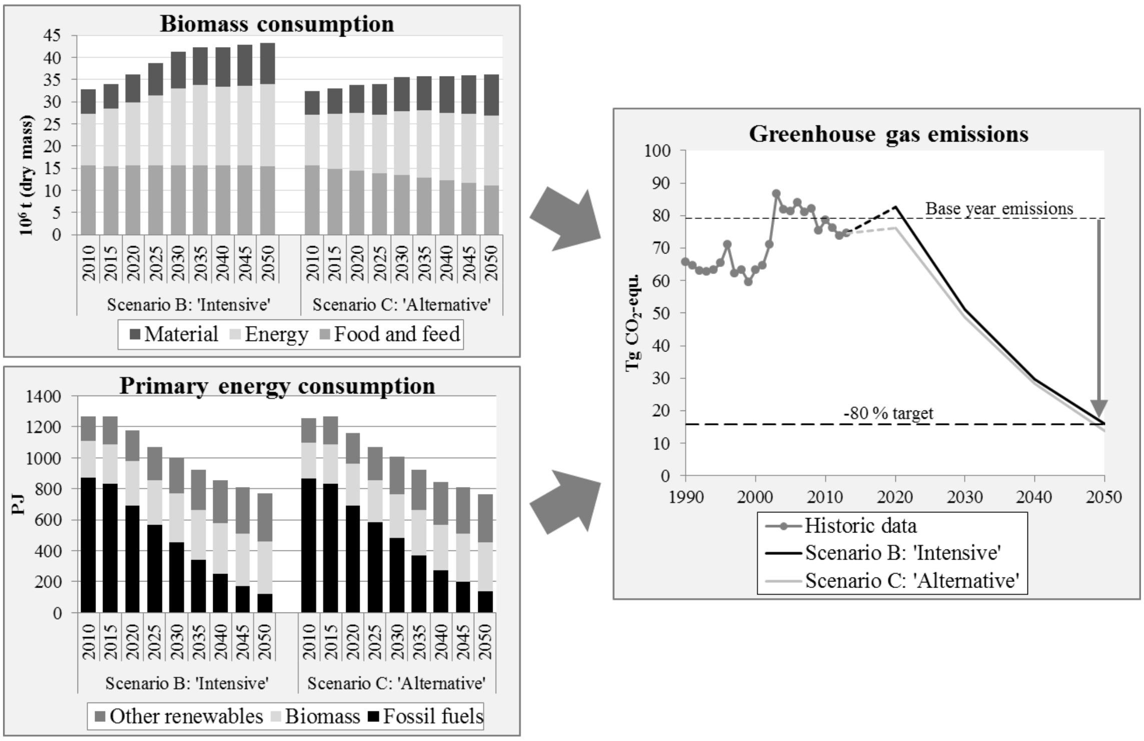
The transformation towards a low-carbon bioeconomy until 2050 is one of the main strategic long-term targets of the European Union. This work presents transformation scenarios for the case of Austria with GHG reduction to about 20% of Kyoto baseline. The scenarios are developed with an optimization model integrating the energy sector, land use and biomass flows. Focus is on investigating possible developments in domestic biomass supply and use. Biomass is crucial for (largely) decarbonising the energy system and replacing fossil-based and energy-intensive materials. Domestic biomass use (dry mass) increases by 32% in an ‘intensive’ and 11% in an ‘alternative’ transformation scenario, while total energy consumption decreases by 40%. Transformation to a low-carbon bioeconomy could be accomplished without additional biomass imports.

Highlights:

- Transformation scenarios to a low-carbon bioeconomy in Austria
- Optimization model integrating the energy sector, land use and biomass flows
- 2 Pathways to GHG emission levels of about 20% of Kyoto baseline in 2050
- Biomass use increases by 11% in one and 32% in the other scenario (2010 to 2050)
- Transformation is technically feasible without additional biomass imports

Graphical abstract:

Scenarios to a low-carbon bioeconomy in Austria



1 Introduction

1.1 Background

With its 2011 ‘Low Carbon Roadmap’ [1], the European Union has committed itself to establish a low-carbon economy until 2050. Starting with 1990 as base year, the roadmap shows a pathway towards an 80% reduction in domestic greenhouse gas (GHG) emissions by 2050. Furthermore, in February 2012 the EU launched a strategy for “A Bioeconomy for Europe” [2], which aims at driving the transition from a fossil-based economy to a sustainable bioeconomy. This strategy addresses crucial societal challenges such as food security, natural resource scarcity, dependence on fossil resources, climate change and sustainable economic growth. The ‘bioeconomy’, according to the strategy, encompasses ‘the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy’ [2].

Biomass will be of crucial importance for reducing GHG emissions and the dependence on fossil resources; not only in energy supply – as the EU’s ‘Energy Roadmap 2050’ [3] and the National Renewable Energy Action Plans indicate (cf. [3,4]) – but also with regard to the replacement of energy- and carbon-intensive products. Already today forestry and the wood processing industries are key elements of Austria’s economy. Biomass is currently the most important renewable energy source [5] and is usually considered to be of high importance for the establishment of a sustainable energy system (cf. [6,7]).

A transformation towards a bioeconomy might lead to rising demand for biogenic resources and increasing pressure on land; it might promote land use change and result in environmentally harmful intensification of agriculture, possibly resulting in an increase in non-energy related GHG emissions and a decline of natural carbon stocks (cf. [8]). It is therefore essential to apply a model with full carbon accounting (cf. [9], [10,11,12]) and consider all relevant GHG sources and sinks, namely emissions from agriculture, land use, land use change and forestry (LULUCF) as well as artificial carbon stocks like wood products.

1.2 Research question

While EU documents and accompanying studies provide some insight into transformation pathways for the EU, there is currently little knowledge on the feasibility and implications of transformation on a smaller scale (i.e. on national level) and the possible contribution of locally available biomass resources. This work aims at contributing to fill this research gap by answering the following core question: To what extent can domestic biomass contribute to the establishment of a low-carbon bioeconomy in Austria until 2050?

To this end, it is investigated whether pathways leading to a reduction of GHG emissions by at least 80 % are feasible without an increase in biomass net imports. Austria’s base year emissions under the Kyoto Protocol, which correspond to the historical GHG emissions in 1990 without consideration of LULUCF, are considered as the reference level. Apart from an 80 % reduction of GHG emissions, a significant increase in biomass use as material as well as enhanced cascading utilization chains are envisaged, in order to justify the term ‘bioeconomy transformation’ (cf. [2]).

2 Methodology

2.1 Modelling environment and approach

The model is implemented in the programming environment of ‘TIMES-VEDA’ (cf. [13,14,15]). The TIMES model generator (**T**he **I**ntegrated **M**ARKAL-**E**FOM **S**ystem) was developed for deriving long term energy scenarios and conduct energy and environmental analyses. It uses linear programming to generate a least-cost energy system, optimized according to certain constraints, in order to explore possible energy futures based on scenarios [13].

The optimization target of the presented modelling approach is to minimize GHG emissions, while economics are ignored. This approach is appropriate for deriving scenarios with maximum emission reduction without the necessity to assume concrete policy measures and highly uncertain parameters like fuel and raw material prices or cost developments for conversion technologies. The resulting scenario are, on the other hand, not cost-optimal; they might, for example, result in vast employment of high-cost bioenergy technologies (cf. section 5).

In the resulting scenarios, biomass is utilized in a way that is most efficient in reducing GHG emissions under the given constraints. Certain constraints are equal in all scenarios, such as dynamic constraints on technology diffusion, on fuel switch and market diffusion of individual bio-based products. Others are scenario-specific parameters (see section 3.2).

The time resolution of the model is 5 years, with three time slices for the seasonal and two for the day-night level (cf. [15]). These ‘sub-annual’ time slices are, however, only implemented in the electricity and the district heat sector, where generation profiles (especially from fluctuating renewable energy sources) and consumption patterns (load profiles) are relevant for capacity utilization and plant deployment.

Agricultural biomass supply and use in the scenarios is to a large extent determined by food and feed requirements. Yield development and dietary habits are the main factors determining the agricultural land resources available for growing crops for bioenergy and material uses. How the remaining land and biomass resources are utilized is determined endogenously based on GHG balances of the value chains and their fossil-based counterparts.

2.2 Data sources and model calibration

The model comprises two main elements: An ‘energy module’, which is a representation of the Austrian energy system, and a ‘biomass module’, which includes all relevant aspects of biomass supply, processing and consumption. The two modules are interlinked in several ways: through biomass being used in the energy sector (i.e. being converted from mass to energy flows), through biofuel plants producing animal feedstuff as by-product or industrial energy demand depending on developments in wood processing industries.

The scope of the biomass module goes beyond technical uses of biomass (i.e. for energy or materials) but also considers biomass flows induced by food consumption. For this purpose, specific per capita diets, such as vegetarian or reduced meat diet have been defined according to dietary guidelines [16] as well as their relative shares within the population (cf. supplementary material). As for other categories this final demand is converted into a corresponding demand for primary biomass, based on different conversion factors, in particular feed balance sheets. Primary biomass supply is linked to representations of agricultural land use, land use change and forest management.

The base year is 2010. Biomass flows and foreign trade streams, energy supply and consumption, installed plant capacities, land use structure etc. are calibrated to statistical data. The main data sources for the energy module include the national energy balance [5], the ‘useful energy analysis’ [17] and statistical data provided by the Austrian energy regulator [18]. Data used for calibration of the biomass module are from foreign trade statistics [19], commodity balances [20] statistics on agricultural production [21], on wood supply and consumption [22] and many more. Sources regarding biomass flows are to a large extent identical to the data used to map biomass flows in Austria in [23]. A complete list of data sources is provided in this publication.

Data for 2015 have not been available at the time the simulations were carried out. However, certain developments from 2010 to 2015 have been defined exogenously based on projections derived from developments until 2014. This approach ensures that relevant trends which took place after 2010 are represented in a realistic way. The following sectors and flow data are predetermined until 2015: the bioenergy sector (generation capacities and utilization), wood flows (production and consumption of the wood processing industries), bio-based product supply and consumption (biopolymers, bio-based insulation material etc.) as well as individual parameters in other sectors. Data on life-cycle emissions of conventional and bio-based products have been adopted from publicly available databases ([24,25]), scientific publications ([26,27]) and environmental product declarations ([28,29]). Energy technology data (like typical conversion efficiencies and utilization factors) and assumptions regarding future developments are based on previous studies [30,31] and literature [24,25,32,33,34,35]; and are calibrated to statistical data [5,18]. Assumed technology development in bioenergy is characterized by moderate efficiency increases for well-established technologies and large-scale commercial availability of ‘second generation’ biofuel technologies and thermochemical biomass gasification after 2020. Relatively immature technologies like algae-based pathways are disregarded.

Forest management scenarios are calculated with the dynamic forest succession simulator PICUS v1.4 [36,37]. The simulation results – time series for wood removals (differentiated by wood qualities) and forest stock development (and corresponding net carbon sequestration or emissions) – are exogenous parameters to the optimization model.

The structure of arable land use (crop shares) is endogenous, but subject to constraints imposed by natural conditions and requirements of crops. The data on natural conditions are generated with a GIS-based approach [38] and subsequent clustering of the present agricultural land into classes with specific suitability profiles. GIS data have been obtained from the Digital Soil Map of Austria (cf. [39,40]) and climate data from the project ‘Safe our Surface’ [41]. Crop requirements are based on the FAO’s ‘Ecocrop database’ [42]. Land use change between agricultural land (arable land, extensive and intensive grassland, mountain pastures), forest land and settlement areas is predetermined exogenously, based on historic developments (cf. supplementary material).

Energy demand in the various sectors is also mostly predetermined exogenously on the level of final energy consumption, based on a scenario developed in the context of

Austria’s GHG reporting obligation (see section 3.1). Exceptions are: Industrial energy demand in certain sectors, where it is linked to production of the wood-processing industries; and low-temperature heat consumption in the residential and the services sector, which is determined on the level of useful heat (since boiler efficiencies for different fuel types must be taken into account in case of endogenous fuel switch).

2.3 Greenhouse gas accounting

GHG emissions are evaluated according to the IPCC’s common reporting framework (CRF). The CRF categories represented in the model are CRF1A (Energy; excluding fugitive emissions), CRF3 (Agriculture) and CRF4 (LULUCF). GHG accounting is partly implemented in the biomass module and partly in the energy module. Following a ‘full carbon accounting principle’, the GHG balance of biomass utilization is calculated as the balance of GHG removals (due to carbon sequestration in forest wood, agricultural crops etc.) and emissions (from biomass combustion and natural decay). Carbon sequestration or emissions due to carbon stock changes in forests and artificial carbon pools are therefore fully incorporated, and accounting of harvested wood products according to IPCC Guidelines [43] is obsolete. GHG emissions/removals due to land use changes are calculated based on functions that consider typical amounts of carbon stored in biomass and soil per unit area. These functions are calibrated with information from [44] and [45]. Calculation of GHG emissions from agriculture (manure management, enteric fermentation, soils etc.) is based on emission factors derived from [44] and linked to livestock and crop production. Options for reducing specific GHG emissions (per livestock unit etc.) by changing agricultural practices are thereby neglected. Default emission factors according to IPCC Guidelines [46] are applied in the energy module.

With regard to “forests land remaining forest land” (cf. [43]), only CO_2 emissions resulting from carbon stock changes are considered. Non-CO_2 emissions like N_2O and CH_4 emissions from wildfires are assumed to remain negligible (cf. [44]). According to Decision 2/CMP.7 [47], accounting of forest management in the second commitment period of the Kyoto Protocol shall be done on the basis of a Forest Management Reference Level (FMRL) [43]. The FMRL is a value of net emissions/removals against which the actual net emissions/removals are compared. Since no FMRL has been defined for the timeframe beyond 2020 (cf. [48]), it is not possible to calculate emissions/removals from forest management for scenarios until 2050 in a way consistent with IPCC Guidelines. Instead, a “stock-difference method” is applied (cf. [43]) for calculating average annual CO_2 emissions/removals (equation 1). The carbon stock in the base year 2010 is used as reference:

$$EMI_t^{FM} = 3.67 \cdot \frac{CS_t - CS_{2010}}{t-2010} \qquad \text{for } t = 2015, 2020, \ldots 2050 \qquad (1)$$

EMI_t^{FM} denotes the emissions from forest management (or forest carbon stock changes) and CS_t the carbon stock in year t. 3.67 is the mass conversion factor from C to CO_2 [49]. It is reasonable to determine average values, because carbon stock changes often vary considerably from one simulation period to the next. Net emissions/removals in the target year 2050 would therefore not be representative if only the stock change from the previous to the respective period were considered.

3 Exogenous scenario assumptions

Numerous exogenous scenario assumptions and developments are adopted from an existing scenario titled ‘WAM plus’, which has been developed in the context of Regulation (EU) 525/2013 [50]. (The scenario name suggests that it is even more ambitious than a scenario **w**ith **a**dditional **m**easures.) The rationale behind this approach is to facilitate direct comparability with national scenarios which are widely accepted, to be able to focus on biomass-related issues and not overburden the present scenario development with the whole spectrum of possible developments in the energy sector.

3.1 The ‘WAM plus scenario’

Although developed in the context of Austria’s GHG reporting obligation, the WAM+Scenario is not included in the official report [51], but described in a separate document in German language only [52]. Data tables on exogenous scenario developments and underlying sector-specific storylines and modelling approaches are therefore provided in the supplementary material.

Exogenous scenario assumptions and developments adopted from the WAM+Scenario include energy demand, economic and population development as well as future deployment of renewable energy technologies with the exception of bioenergy. The scenario assumes very ambitious energy efficiency and renewable energy policies, rising environmental awareness and a general trend to sustainable development.

In contrast to significant growth of most renewable energy technologies like wind and solar power, biomass consumption for energy declines considerably until 2050 in the WAM+Scenario. This is partly explained with an increasing biomass demand for material uses. However, considering that bioenergy in Austria is largely based on by-products and residues, and the fact that the share of biomass ending up in products is relatively small in comparison to total biomass use (cf. [23]), increasing consumption of bio-based products may well be accompanied by a growing bioenergy sector. This has not been investigated in detail in the WAM+Scenario, as its focus was on the energy sector. With the integrated modelling approach presented here, it is possible to carry out in-depth analyses regarding future pathways for biomass production and utilization. Therefore, developments in bioenergy use are not adopted from the WAM+Scenario but are subject to the model’s optimization algorithm, and fossil fuel substitution and GHG mitigation in the energy sector can differ significantly in the WAM+ and the scenarios presented here.

3.2 Scenario-specific exogenous assumptions

Three scenarios are presented. Since bioeconomy transformation in the context of this work is intended to be established without additional biomass imports, a general assumption for all scenarios is that imports of each biomass commodity remain constant at the level of the respective calibration year. The same assumption is made for exports, meaning that the external trade balance of each biomass commodity remains constant. This assumption is considered suitable for investigating the core questions of this paper.

The scenarios differ in terms of six influencing parameters relevant for the future supply potential and demand for domestic biomass. The developments of these parameters include trend extrapolations and business as usual assumptions on the one hand, and more speculative assumptions considered feasible in case of targeted policy intervention on the other. These exogenous parameters are developments in dietary habits, land use change, forest management, average crop yields, food losses and assumptions regarding bioenergy production from crop by-products (which represent a considerable unused potential for energy production).

Scenario A (‘Reference’) is considered a most-likely scenario with regard to these parameters: It is assumed that the main trends will continue until 2050, no serious initiatives or policy intervention take place to reduce food losses, change dietary habits and to utilize crop by-products for energy; average crop yields continue to increase, albeit only moderately. In scenario B (‘Intensive’) higher agricultural yield increases and additional wood removals from small private forests are assumed, and crop by-products are assumed to be available as bioenergy source. Scenario C (‘Alternative’) is characterized by the aim to avoid intensification in biomass production. This is implemented as a more pronounced shift to healthy and no- or low-meat diets compared to Scenario A and B, reduced land use change after 2020, reduced food losses, constant average crop yields and forest management with longer rotation periods. These exogenous scenario parameters are summarized in Table 1.

Table 1. Scenario-specific exogenous parameters

Exogenous scenario parameters	Scenario A: ‘Reference’	Scenario B: ‘Intensive’	Scenario C: ‘Alternative’
Dietary habits	Trend (slight reduction in average meat consumption)		More pronounced shift to healthy and no/low-meat diets
Land use change (between forest, arable land, grassland types and settlements)	Trend (cf. supplementary material)		LUC reduced by 50 % during 2021 to 2030; no more LUC between land categories after 2030
Forest management	‘Business as usual’	Increased removals from small private forests	Longer rotation periods than in BAU
Average crop yields	Moderate increase	Significant increase	constant
Food losses	Constant		Reduction by 50% until 2050
Crop by-products used for energy	NO	YES	NO

4 Results

The results described in the following sections include the developments of GHG emissions, primary energy consumption and biomass consumption for energy, material and as food and feed. Results regarding electricity and district heat supply are presented in the supplementary material.

4.1 Greenhouse gas emissions

The CRF categories represented in the model are CRF1 (Energy), CRF3 (Agriculture) and CRF4 (LULUCF). These categories accounted for about 47 Tg CO_2-equ. in Austria's Kyoto base year 1990 and between 55 to 64 Tg CO_2-equ./a during the latest ten years available in statistics [53]. Around 75 % of Austria's total GHG emissions are attributable to these categories.

In Scenario A they decrease to 38.6 Tg CO_2-equ. in 2030 and 11.8 Tg in 2050 (Figure 1, left). This corresponds to a reduction by 17 % and 75 %, respectively, compared to 1990. In Scenario B the emission reduction in the considered CRF categories in 2050 is 87 % and in Scenario C 92 %. By comparison, the reduction achieved in the WAM+Scenario until 2050 is approximately 50 %.

Assuming GHG emission developments in CRF1B, CRF2 and CRF5 according to the WAM+Scenario (cf. [52]), pathways for total GHG emissions are derived (Figure 1, right). In 2030 total emission reductions relative to the Kyoto base year emissions [54] are in the range of 34 to 38 %. In 2050 they are 72 % in Scenario A, 80 % in Scenario B and 83 % in Scenario C. Hence, the intended emission reduction target is achieved in the 'intensive' as well as in the 'alternative' scenario.

In contrast to the WAM+Scenario, Scenario A, B and C show a temporary increase of GHG emissions until 2020. This comes from the forestry sector and is due to the age structure of Austrian forests in combination with management practices assumed in the simulations with PICUS. Due to different scenario-specific assumptions regarding management practices, net GHG emissions/removals in 2020 vary between the scenarios, but in every case harvesting rates are projected to temporarily exceed the wood increment around 2020. Such a trend is also assumed in the FMRL projection [48]. On the longer term, forests again become a net GHG sink in all scenarios.

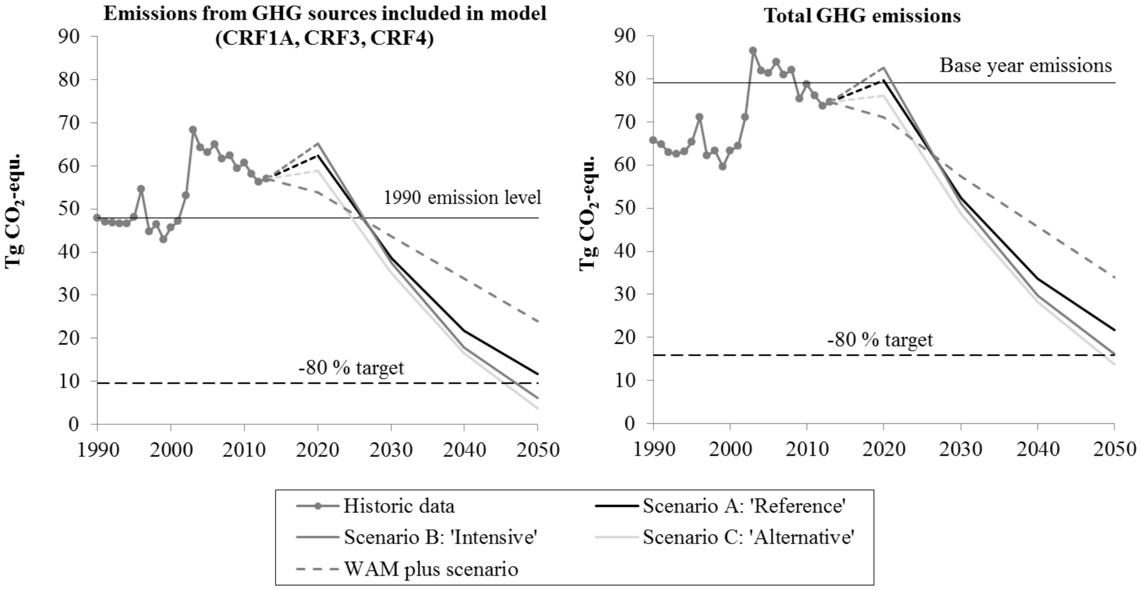


Figure 1. Development of GHG emissions in the scenarios

4.2 *Primary energy consumption*

Due to high energy efficiency gains assumed, all three scenarios show a significant reduction in primary energy consumption after 2015 (Figure 2): From about 1,270 PJ to 770 PJ in 2050. In Scenario A the share of biomass increases from 20 % in 2015 to 34 % in 2050. In Scenario B and C the biomass share in 2050 is 44 % and 41 %, respectively. Liquid fossil fuels and natural gas show the most pronounced decrease in absolute numbers; partly due to reduced energy consumption and partly due to fuel substitution with biomass. Replacement of natural gas with bio-based gases is clearly higher in Scenario B and C than in Scenario A (cf. Figure 4), because more arable land is available for energy crop production in these cases. Coal is practically phased out in all scenarios, while the overall share of the renewable energy sources hydropower, ambient energy, wind and solar power increases to more than 40 % in all scenarios. The decline of the non-biomass fraction of municipal solid waste (MSW) is especially pronounced in Scenario B and C, as fossil-based products and material is replaced with bio-based equivalents (cf. Figure 5), creating a shift in the structure of MSW.

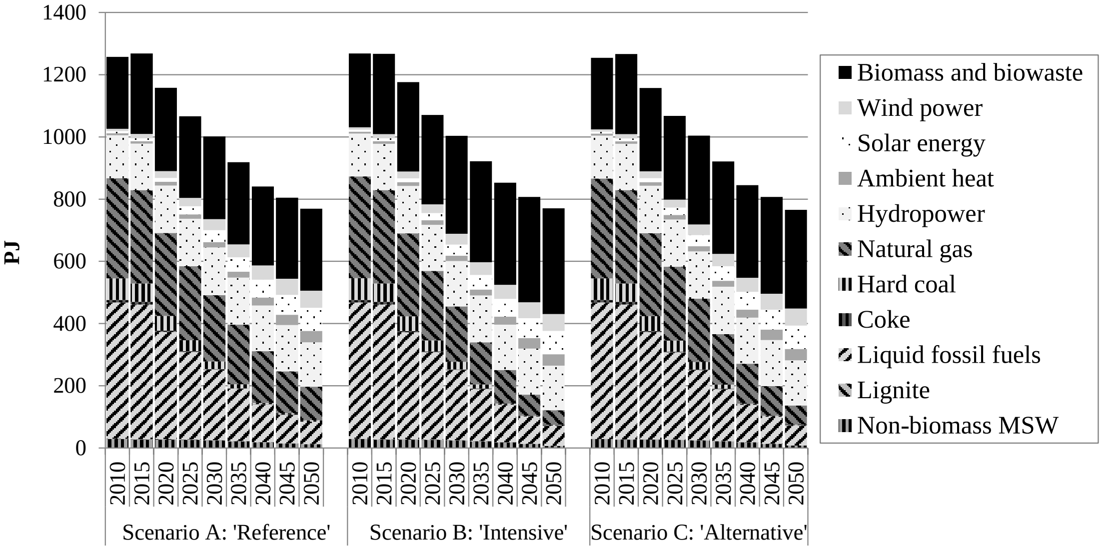


Figure 2. Development of primary energy consumption for in the scenarios (Following the IEA/Eurostat convention, primary energy from hydropower, wind etc. corresponds to the amount of electricity produced. Ambient heat includes any renewable heat utilized by heat pumps as well as directly used geothermal energy.)

4.3 *Biomass use*

Figure 3 shows the development of total domestic biomass use as food, feed, energy and material (see [23] for a detailed analysis of the status quo of biomass use in Austria). “Food” includes all biomass intended for direct human consumption, so the reduction in food losses in Scenario C is reflected in the figure. “Feed” is broken down by field crops being directly used as animal feed, biomass from grassland and by-products (like press cake or ethanol by-products). In Scenario A and B small reductions in average meat consumption are compensated by population growth, so total biomass consumption for food and feed remains almost constant. Scenario C shows a decrease in feed consumption by about 30 %, due to a greater shift towards no- and low-meat diets.

Biomass used for energy is broken down by forest wood-based fuels and other resources (biogenic waste, agricultural crops and by-products) in Fig. 3; the increase in bioenergy is almost exclusively based on the latter in all scenarios. Wood processing residues are partly diverted to material uses (mainly the production of insulating boards), resulting in a relatively constant consumption of forest wood for energy.

The share of material in total biomass consumption increases from 17 % in 2010 and 2015 to 23 % in Scenario A, 21 % in Scenario B and 26 % in Scenario C until 2050. As a consequence of more resource efficient diets and reductions in food losses, the total increase in biomass consumption is significantly smaller in the ‘alternative’ scenario than in the ‘intensive’ scenario. This result underlines the high resource efficiency of no-meat and ‘healthy’ diets in comparison to the meat-rich diet of an average Austrian. Dietary habits could apparently be an important lever to reduce pressure on land use intensification in a bioeconomy transformation.

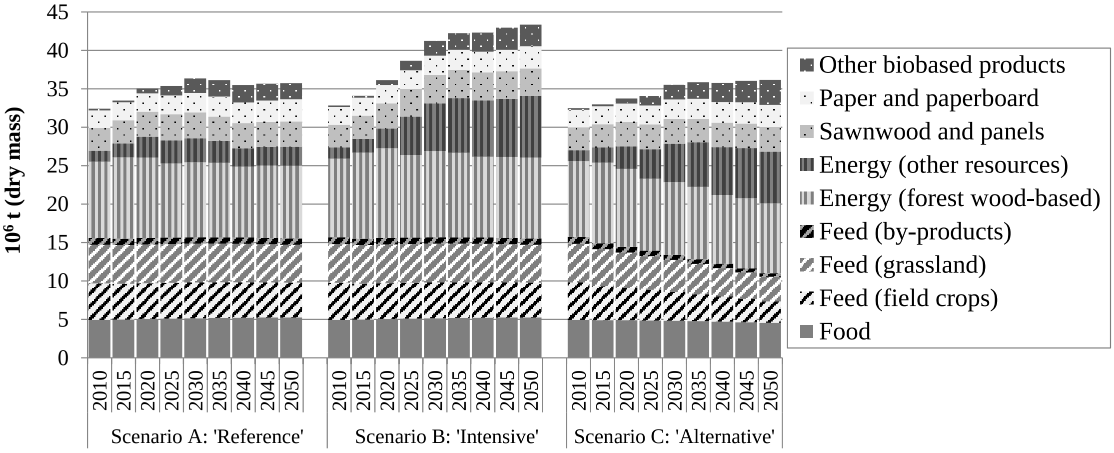


Figure 3. Development of total biomass use in the scenarios

The following figures show the developments in domestic biomass consumption for energy (Fig. 4) and material uses (Fig. 5) in more detail. Regarding bioenergy, a prominent trend common to all scenarios is the shift towards higher refined fuels such as lignocellulose-based transport fuels and natural gas substitutes (biomethane from anaerobic fermentation, synthetic natural gas from biomass gasification), while the shares of ‘wood log‘ and ‘wood waste’ (forest wood chips, industrial wood residues etc.) decline significantly. The main reason is that conventional biomass use for residential heating is becoming less important due to rapidly improving thermal quality of the building stock, and biomass is increasingly used for fuel substitution in the transport and industry sectors.

Biogenic natural gas substitutes injecting into the grid provide an opportunity to make use of existing infrastructures and facilities (especially in industry) and improve the flexibility of bioenergy (temporally and in terms of application fields). Liquid second generation biofuels primarily replace fossil fuels used in heavy-duty transport, where options for electrification and modal shift are most limited. Conventional liquid biofuels are almost entirely replaced by second generation biofuels on the longer term in all scenarios. The bioenergy developments in the three scenarios mainly differ regarding the contribution of biomethane and in terms of the amount of black liquor and straw used for energy.

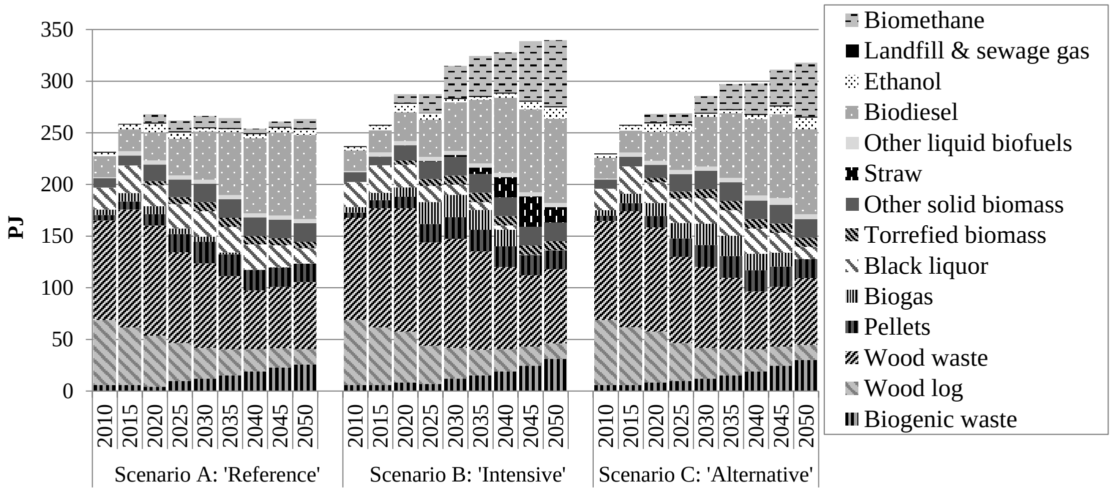


Figure 4. Development of biomass use for energy in the scenarios

Material use of biomass is currently dominated by conventional wood uses (sawnwood and wood panels) in building construction, packaging, furniture manufacturing etc. as well as paper and paperboard. In the scenarios other uses become increasingly important, especially insulation material and bioplastics made from sucrose and glucose. Further applications, which are less relevant in terms of raw material consumption, include plant oil used as lubricant, for detergents and surfactants, lignin used as asphalt binder and different conventional uses of starch (as additive in paper production and other manufacturing processes). Figure 5 shows the development of domestic consumption for these applications. The relative increase in total biomass used as material until 2050 ranges from 50 % in Scenario A to about 70 % in Scenario B and C. The main differences between the scenarios arise from domestic wood supply and availability of arable land for biomaterial production.

‘Material substitution’ is often highly efficient in reducing GHG emissions (cf. [55, 56, 57, 58]). The carbon storage effect and the fact that cascading biomass use (e.g. energetic use of bio-based products ending up as biogenic waste) is usually more efficient in GHG mitigation than direct combustion of biomass are the main reasons why growth rates in material uses are generally higher than in bioenergy in the scenarios.

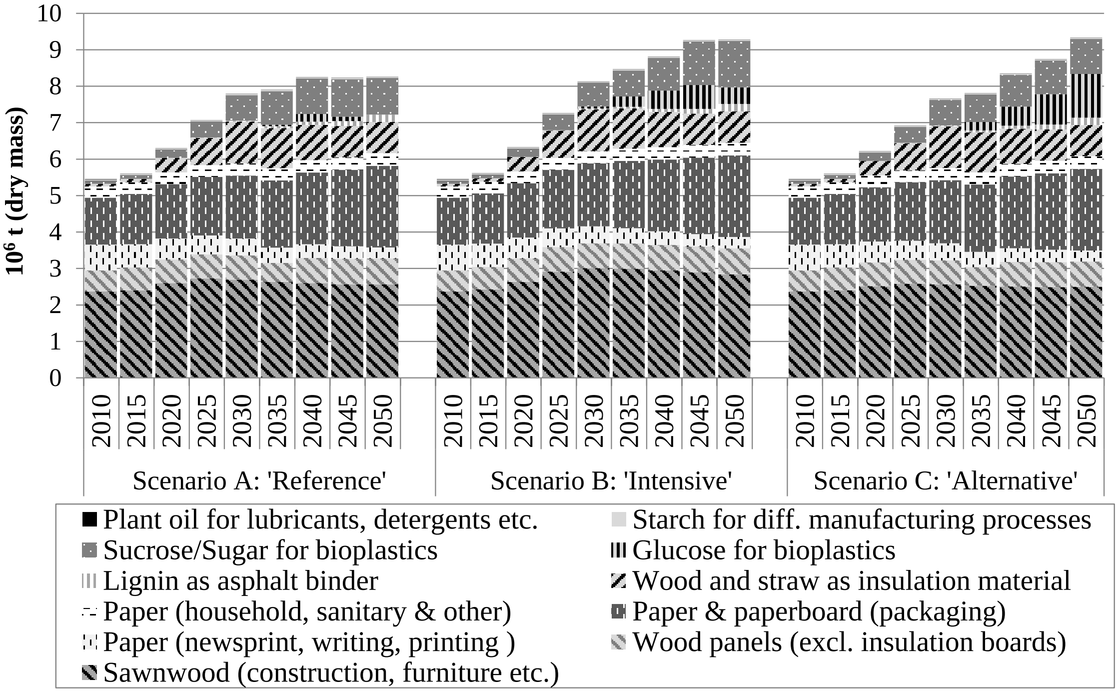


Figure 5. Development of biomass consumption for material uses in the scenarios

5 Discussion and interpretation

The scenarios B and C illustrate pathways to a low carbon economy. All three scenarios are characterized by increased material use for conventional and novel applications as well as enhanced cascading biomass use. Therefore, the scenarios B and C can be described as transformation paths to a low-carbon bioeconomy.

The results illustrate that transformation is feasible from a bio-physical and technical perspective without increasing biomass net imports. However, the requirements in terms of energy efficiency improvements, application of advanced biomass conversion technologies and other renewable energy sources are high; without massive policy intervention in all these fields, the necessary developments are highly unlikely from today’s point of view.

With the definition of GHG emissions (instead of aggregated costs) as optimization target, economic aspects are disregarded in scenario development. Hence, technologies and value chains which are effective in reducing GHG emissions are deployed regardless of their economic performance. Several conversion technologies which are vastly applied in the scenarios would certainly require considerable financial support, even if strong technological progress is achieved (cf. [8]) and fossil fuel prices rise significantly (e.g. the production of natural gas substitutes and second generation biofuels). A critical aspect with regard to competitiveness of such technologies is the relatively high share of feedstock costs in total production costs (cf. [30]) – In the context of a bioeconomy transformation with rising demand for biomass for various applications, it is questionable whether biomass or fossil fuel prices will grow at a higher rate. A strong fiscal instrument in the form of a general GHG tax could be an effective way to overcome this difficulty and maybe stimulate a development similar to the presented scenarios. If or how such an instrument could actually be implemented is beyond the scope of this work; but there are several obvious reasons that implementation on a purely national level is not realistic.

Considering the sheer number of technologies, applications and products, it is clear that the presented modelling approach is only feasible at a high aggregation level and that it is not possible to consider all types of products and value chains. The aim was to focus on those which are likely to be of some significance from a quantitative point of view; the identification and selection of such value chains is a challenge by itself and does of course have an impact on model outcomes. Especially with regard to material uses, the results presented here are intended as a first, yet very important step towards bioeconomy scenario development on a national level. Only with such an integrated approach it is possible to capture the complexities and sectoral interdependencies that are inherent to strategic bioeconomy research.

6 Summary

The transformation towards a low-carbon bioeconomy is one of the core strategic long-term targets of the European Union. Furthermore, the EU aims to establish a bioeconomy until 2050, in order to meet crucial societal challenges such as food security, natural resource scarcity and dependence on fossil resources. This work presents transformation scenarios for Austria with an 80 % reduction of GHG emissions, a significant increase in biomass use as material as well as enhanced cascading utilization.

The scenarios are developed with an integrated model developed in the programming environment TIMES-VEDA. The focus is on domestic biomass supply and utilization, due to its central role for energy generation and material substitution as well as interrelations of biomass production and utilization with non energy-related greenhouse gas emissions (i.e. from agriculture, land-use change and forestry). The optimization target is to minimize GHG emissions. Since the bioeconomy transformation is achieved without additional biomass imports, a general assumption is that net imports of each biomass commodity remain constant. Energy consumption is assumed to decline significantly in all scenarios, following a scenario developed in the context of Austria’s GHG reporting obligation.

Influencing parameters relevant for the future supply potential and demand for domestic biomass are varied exogenously. They include developments in dietary habits, land use change, forest management, average crop yields etc. Based on different settings for these parameters three scenarios are developed. Scenario A (‘Reference’) is a most-likely scenario with regard to these parameters and in Scenario B (‘Intensive’) more biomass is mobilized through intensification. Scenario C (‘Alternative’) demonstrates that intensification is not a necessity to achieve a bioeconomy transformation – at least not from a technical and bio-physical point of view and for the specific case of Austria – in case of a stronger shift towards ‘healthy’ and low-meat diets, if less food is wasted and land-use change is reduced.

The scenarios B and C can be described as transformation paths to a low-carbon bioeconomy, as GHG emissions decrease to about 20 % of the Kyoto base year emissions until 2050 and material as well as cascading use of biomass increase significantly. Total domestic biomass use, measured in dry mass, increases by 32 % in Scenario B and 11 % in Scenario C (2010 to 2050). The share of material in total biomass consumption increases from 17 % in 2010 and 2015 (about 5.5 million tons dry mass) to 21 % in Scenario B and 26 % in Scenario C (both 9.3 Mt_{dry}) in 2050. The share of biomass used for energy rises from 35 % to 43 % (B) and 44 % (C) in the same time frame, while total primary energy consumption decreases by about 40 % in all scenarios. Increase in bioenergy is almost exclusively based on non-forest biomass like biogenic waste and agricultural crops

These scenarios illustrate that transformation to a low-carbon bioeconomy is technically feasible until 2050 if energy consumption is reduced significantly, other renewable energy sources are employed intensively and biomass and bioenergy are utilized in an efficient way.

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Supplementary material

Contents

1 Energy demand

1.1 General storyline of the WAM+scenario

The WAM+scenario is a highly ambitious energy efficiency and renewable energy scenario. General framework conditions assumed in the WAM+scenario include (adopted from Krutzler et al. [1]):

- Binding energy and climate targets for 2030, 2040 and 2050
- Stimulation of sustainable economic development
- Rising environmental awareness, trend towards sustainable lifestyles and consumption patterns
- Formation of a common social vision with sustainable business and financing models

Detailed data for the most relevant energy demand sectors are provided in the following sections. Quantitative information is supplemented by narrative bulletpoints describing the storyline and providing insight into how the assumed trends in energy consumption are expected to be achievable. All this information is adopted from [1], with additional quantitative information provided by the authors via personal communication.

A direct comparison with data provided in [1] reveals several small differences to data presented below. These discrepancies are due to differences in classification, different statistical items being used (final/useful energy), and certain consumption categories in the transport sector being disregarded (namely aviation and shipping; see section 1.3).

Energy demand developments presented in the following sub-sections are not entirely predetermined exogenously, because fuel switch is implemented as endogenous flexibility to reduce GHG emissions. It is, however, only possible to switch between fuel types or systems which can be considered to be perfect substitutes (‘equivalent fuels/systems’). The assumed sector-specific options for fuel switch are described below. Fuel switch is generally subject to dynamic constraints (maximum rates of change from one simulation period to the next), and upper bounds on annual deployment of bioenergy plants (e.g. biomethane or torrefaction plants) are also implemented.

1.2 Low-temperature heat and hot water

Trends in this field are mainly determined by developments in the building sector. They are characterized by measures to achieve

- very high obligatory thermal building standards,
- compact settlement structures,
- standards of nearly zero energy buildings in new construction and
- an obligation to use renewable energy sources or district heat (in urban areas).

The following tables present the model input regarding useful energy demand for heating and hot water in the residential and the services sector. These data have been generated with the model 'Invert/EE-Lab', which is an engineering-based bottom-up model augmented by statistical bottom-up elements [2].

Table S2. Useful energy demand for heating & hot water in the services sector

TJ	2010	2015	2020	2025	2030	2035	2040	2045	2050
District heat	36,607	31,090	31,524	30,480	27,109	22,724	19,081	15,724	13,704
Electricity	10,066	11,820	7,351	5,546	4,655	4,168	3,713	3,493	3,385
Solar thermal	1,617	1,424	1,504	1,560	1,606	1,634	1,675	1,788	1,900
Ambient energy	1,120	1,506	2,271	3,225	3,745	3,882	3,776	3,874	4,188
Natural gas[a]	26,035	25,003	23,503	19,448	15,105	11,708	8,960	6,192	3,548
LPG*	1,988	837	649	342	217	125	78	46	24
Gasoil*	5,152	10,443	8,488	4,512	2,786	1,603	998	590	310
Heating oil*	2,110	424	173	53	16	9	6	3	2
Coal*	185	178	55	35	20	35	25	17	10
Wood log	575	590	580	315	277	264	253	279	287
Wood chips	1,320	1,726	3,279	4,081	3,782	3,343	2,943	2,894	2,768
Wood pellets*	852	1,429	2,839	3,834	3,842	3,511	3,214	3,285	3,408

Comments:

Endogenous fuel switch between fuels marked with an asterik (*) is possible after 2015. Hence, pellet boilers can replace oil-, gas- and LPG-fired boilers and vice versa. This is considered realistic because these heating systems are installed in similar building types, and space requirements and heat distribution systems are very similar.

a) Fuel switch from natural gas to biomethane is also possible.

Table S3. Useful energy demand for heating & hot water in the residential sector

TJ	2010	2015	2020	2025	2030	2035	2040	2045	2050
District heat	29,262	30,704	32,929	37,531	38,264	36,765	34,569	32,264	31,437
Electricity	17,424	18,071	15,290	12,849	11,681	10,974	10,478	10,577	11,236
Solar thermal	4,619	4,934	6,302	8,870	10,130	10,933	11,933	13,384	14,896
Ambient energy	4,364	5,867	7,190	8,978	10,557	11,786	12,805	14,555	16,986
Gas	49,707	48,685	47,611	43,096	38,213	33,361	27,947	22,454	17,308
LPG*	1,741	1,584	1,505	962	656	475	363	271	174
Gasoil*	39,822	34,202	29,165	18,879	13,088	9,512	7,287	5,438	3,495
Heating oil*	1,021	1,404	758	283	110	47	21	9	4
Coal*	1,604	1,655	501	106	29	26	20	14	8
Wood log	36,906	34,427	30,100	21,921	17,323	14,025	11,804	9,756	7,274
Wood chips	3,957	4,196	4,151	5,476	4,939	4,272	3,764	3,216	2,314
Wood pellets*	3,149	4,685	8,378	11,568	11,665	10,715	9,689	9,268	9,129

*) see comments to Table S1

1.3 Transport sector

The storyline for the transport sector is characterized by:

- Significant increase in transport fuel prices resulting from crude oil price increases and (EU-wide) increased taxation
- Reduced passenger and freight transport
- Modal shift of passenger transport towards public transport, bicycle and walking

- Modal shift of freight transport from road to rail and ship
- Reduced degree of motorization
- Significant increase in electric mobility

The final energy demand in the transport sector is presented below. Aviation and shipping are not included because international aviation and maritime transport are not subject to the reduction commitments under the Kyoto Protocol, and inland aviation and shipping are negligible. The negligible quantities of hydrogen used as transport fuel in the WAM+scenario have been disregarded.

Table S4. Final energy demand for in transport sector (aviation and shipping not included)

TJ	2010	2015	2020	2025	2030	2035	2040	2045	2050
Gasoline (fossil)	71,538	69,622	included in 'gasoline equivalents' for 2020 - 2050						
Diesel (fossil)	245,987	263,455	included in 'diesel equivalents" for 2020 - 2050						
Bioethanol / Bio-ETBE	3,270	2,779	included in 'gasoline equivalents' for 2020 - 2050						
Biodiesel	18,512	20,509	included in 'diesel equivalents" for 2020 - 2050						
Natural gas	199	131	included in 'natural gas equivalents' ' for 2020 - 2050						
Biomethane	0	34	included in 'natural gas equivalents" for 2020 - 2050						
Plant oil	612	1,172	1,059	1,015	973	949	913	883	857
LPG	199	131	200	265	325	397	463	530	596
Electricity (rail and road)	7,358	7,233	9,015	13,582	19,068	22,622	25,011	25,717	25,285
Gasoline equivalents	-	-	60,159	45,752	33,284	22,828	17,106	15,997	17,618
Diesel equivalents	-	-	228,663	209,986	191,891	170,677	150,963	134,737	120,260
Natural gas equivalents	-	-	252	334	408	499	582	666	750
Total	348,368	365,521	299,338	270,673	245,627	217,578	194,578	178,004	164,772

1.4 Industry

The WAM+scenario assumes highly efficient use of materials and fuels in industry and manufacturing. A trend to long-lived, high-quality products resulting in waste reduction, as well as increased environmental awareness, more targeted and combined environmental and economic support and technological progress are mentioned as preconditions in the storyline of the WAM+scenario [1].

Final energy demand in the industry according to the WAM+scenario is presented in Table S4, as well as the respective ‘equivalent biomass fuels’ to fossil fuels.

Table S5. Final energy demand of the industry sector in the WAM+scenario

TJ	2010	2015	2020	2025	2030	2035	2040	2045	2050	Equivalent biomass fuel (substitute)
Hard coal	4,726	4,574	4,489	4,434	4,284	3,232	2,310	1,455	631	Torrefied biomass
Lignite	1,748	1,613	1,789	1,595	1,387	1,131	915	721	541	Torrefied biomass

TJ	2010	2015	2020	2025	2030	2035	2040	2045	2050	Equivalent biomass fuel (substitute)
Coke	8,014	8,478	7,798	6,746	6,563	6,085	5,659	5,267	4,902	Torrefied biomass
Gasoline	203	190	195	204	208	208	205	196	176	Bioethanol
Petroleum	8	8	8	8	8	8	8	7	7	Bioethanol
Diesel	12,591	12,078	12,330	12,843	13,111	13,052	12,886	12,341	11,104	Biodiesel
Gasoil	3,216	2,954	3,221	3,407	3,550	3,028	2,557	2,095	1,605	Biodiesel
Heating oil	7,726	6,348	5,798	5,180	4,604	3,733	2,952	2,232	1,560	Biodiesel
LPG	3,078	1,822	1,875	1,874	1,854	1,676	1,516	1,355	1,178	Bioethanol
Other refinery products	2,014	1,859	1,862	1,843	1,805	1,685	1,588	1,495	1,392	-
Refinery gas	131	93	99	104	107	100	94	88	81	-
Natural gas	105,707	108,089	109,680	108,765	108,550	100,505	93,042	86,239	79,033	Biomethane
Furnace gas	1,652	1,606	1,411	1,142	1,088	535	509	486	452	-
Coke oven gas	3,129	2,903	2,903	2,903	2,903	2,505	2,352	2,220	2,077	-
Wastes (non-renewable)	13,769	12,914	13,596	13,943	14,303	13,628	13,054	12,460	11,743	Wood waste
Wood log	1,202	594	649	675	688	652	617	580	539	-
Biogenic fuels excl. wood log	52,137	51,455	54,286	55,940	56,528	54,312	52,647	51,170	49,477	-
Ambient heat	90	149	151	147	166	624	1,031	1,400	1,739	-
District heat	10,407	11,753	12,562	12,957	13,243	12,563	11,943	11,311	10,609	-
Electricity	97,319	99,757	102,346	102,912	100,490	101,629	102,975	103,852	103,848	-
Total	328,867	329,239	337,049	337,622	335,439	320,891	308,859	296,969	282,695	

2 Demand drivers for food and material

The main demand drivers are population and economic development. Both have been adopted from Krutzler et al. [1]. Fig. S1 shows the assumed developments.

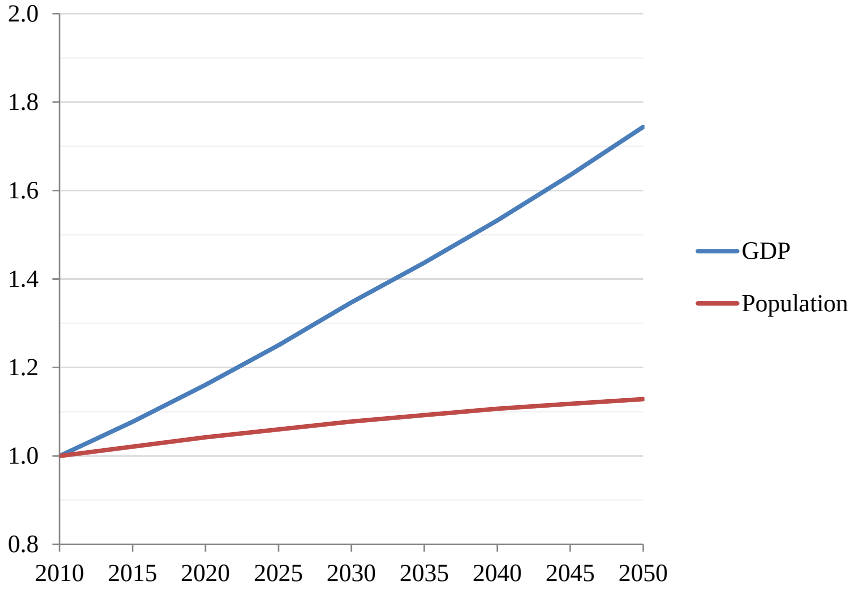

Figure S6. Relative growth of the main demand drivers GDP and population

Based on plausibility considerations, demand developments of certain commodities are directly linked to GDP or population growth. For example, demand for packaging material is directly linked to GDP development, whereas population development is assumed to determine the demand for hygienic paper, solvents, surfactants etc.; and of course of food demand.

For other demand commodities, specific trends are assumed to play a major role: Paper demand for newsprint and printing and writing paper are assumed to further decline due to increasing usage of portable electronic devices. Demand for virgin asphalt material (and asphalt binder; lignin is assumed to be a substitute for bitumen) is expected to decline as a consequence of enhanced recycling of reclaimed asphalt. Statistical data have been obtained from annual reports of the Austrian paper and pulp industry [3] and the European Asphalt Pavement Association [4], respectively, and extrapolated to 2050.

The demand driver for construction material is floor space of newly constructed buildings and building conversions and extensions. According data are available from the national statistical authority [5]. Projections to 2050 have been derived on the assumption of a linear correlation between population growth and additional floor space. Further demands, which are practically negligible in the overall context, include feed demand for horses and other (pet) animals, and raw material consumption for miscellaneous material uses not specified in supply balances [6]. Material consumption for these applications is assumed to remain constant.

3 Scenario-specific exogenous developments

3.1 Forest management

Forest management scenarios are calculated with the hybrid forest gap model PICUS v1.4 [7,8]. The simulation results are time series for wood removals (differentiated by wood assortment classes) and forest stock development (and associated net carbon sequestration or emissions). These time series are exogenous parameters to the optimization model.

The simulation model PICUS combines the abilities of a 3D gap model [7] in simulating structurally diverse forest stands with process-based estimates of stand level primary production. PICUS builds on a 3-D structure of 10 x 10 m patches, extended by crown cells of 5 m height. Population dynamics emerge from growth, mortality and reproduction of individual trees. In addition, the simulation framework integrates a management module, a detailed regeneration module, and forest disturbance modules (e.g, for barkbeetle and wind damages). PICUS is driven by time series data of temperature, precipitation, radiation and VPD at monthly or daily resolution.

Simulation results based on three different forest management strategies have been used as model input: The reference scenario (A) is a ‘Business as usual’ approach emulating current forest management practices in Austria. It consists of multiple forest management programmes tailored to different forest mixture and forest owner type. A total of 48 management programmes were simulated, including inter alia simple clear-cut systems in spruce dominated forests, shelterwood systems in broadleaved forests, and stripwise selection systems in mixed mountain forests. The forest management of small scale private owners was simulated with reduced thinning intensities and a reduced set of simpler silvicultural measures. In addition, a small part of the privately owned forest was not actively managed (approx. 6% of the area). For Scenario B ('Intensive'), we assumed that all forested areas were actively managed. Scenario C ('Alternative') aimed for climate change mitigation through forest carbon stock increase by extending rotation periods by 20 years for all stands above 1,200 m altitude.

3.2 *Land use and LUC*

The structure of agricultural land use in the base year 2010 is based on statistical data [9]. Developments until 2050 are derived from the relevant historical trends in land use change (LUC) according to the national inventory report [10]. In Scenario A and B it is assumed that the trends observed during 1990 to 2010 continue until 2050. In Scenario C it is assumed that targeted measures to reduce LUC are successful, resulting in a 50 % reduction of annual LUC after 2020 and agricultural land remaining constant after 2030 (Fig. S2).

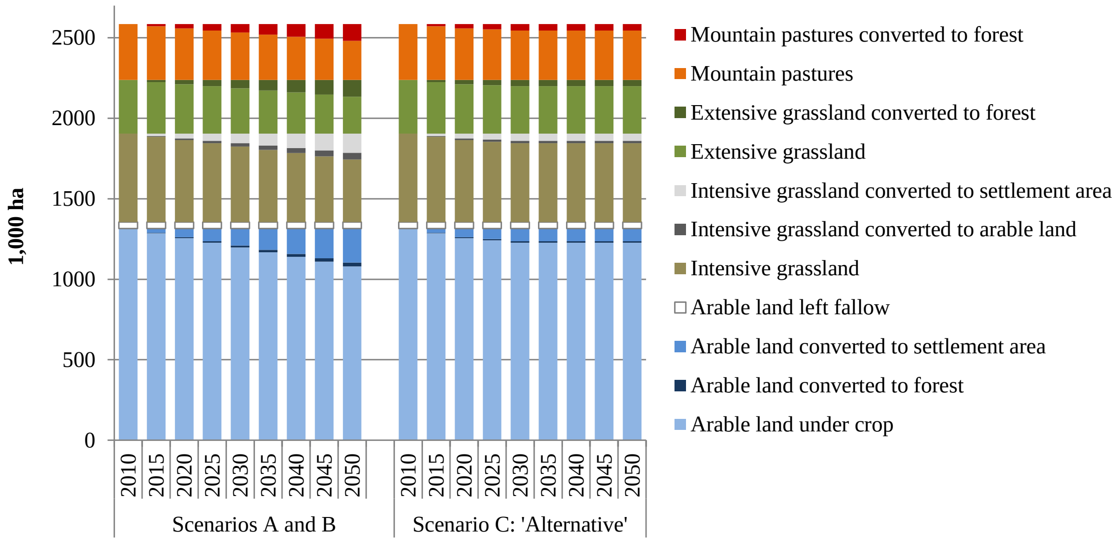

Figure S7. Agricultural land use and LUC in the scenarios

GHG emissions and removals resulting from LUC are implemented according to functions that consider typical amounts of carbon stored in biomass and soil per unit area in the biomass module, following the approach of [11]. These functions consider transition times required to reach the values for the new land use starting from the values of the previous land use and were calibrated with information from [12]. Carbon sequestration on agricultural land converted to forest is modelled with a generic growth function (from [13]).

3.3 *Dietary habits*

Dietary habits refer to the average actual food intake per capita and year, differentiating 48 food products. Baseline per capita diets in 2010 are derived by combining data on domestic food supply according to Austrian commodity balances [9] with literature derived data on food losses in sectors outside the system boundary of commodity balances, in particular households [14]. Average per capita intake is allocated to four broad types of diets: Based on USDA dietary guidelines [15], we differentiate three healthy diets – including meat, vegetarian and vegan – and one meat-rich diet to which all remaining food is allocated (Table S5). Assumed shares of diets in 2010 are based on a study for the UK [16] and a survey on purchases of animal products [17].

Future scenarios are based on a shift of relative shares of diets (Table S5). Based on trends in dietary habits during the last years and decades, a shift towards more healthy diets is assumed as baseline (in Scenario A and B): The shares of the ‘healthy’ diet types are assumed to increase by a factor of two until 2050. In Scenario C a more pronounced trend towards ‘healthy’ diets with meat and vegetarian diets is assumed. The part of the population eating meat-rich diets is assumed to decline to 20 %. Shares between 2010 and 2050 are interpolated linearly.

Table S6. Assumed shares of diet types in 2010 and 2050

		2050	
Diet types	2010	Scenario A and B	Scenario C
Meat-rich	82.5%	65.0%	20.0%
'Healthy' with meat	14.0%	28.0%	69.0%
'Healthy' vegetarian	3.0%	6.0%	10.0%
'Healthy' vegan	0.5%	1.0%	1.0%

Diet types and developments in average food intake in 2010 and 2050 according to the scenarios (i.e. resulting from the relative share of diet types shown in Table S5) are illustrated in Fig. S4. Developments in per capita meat and dairy products consumption are shown in Fig. S5.

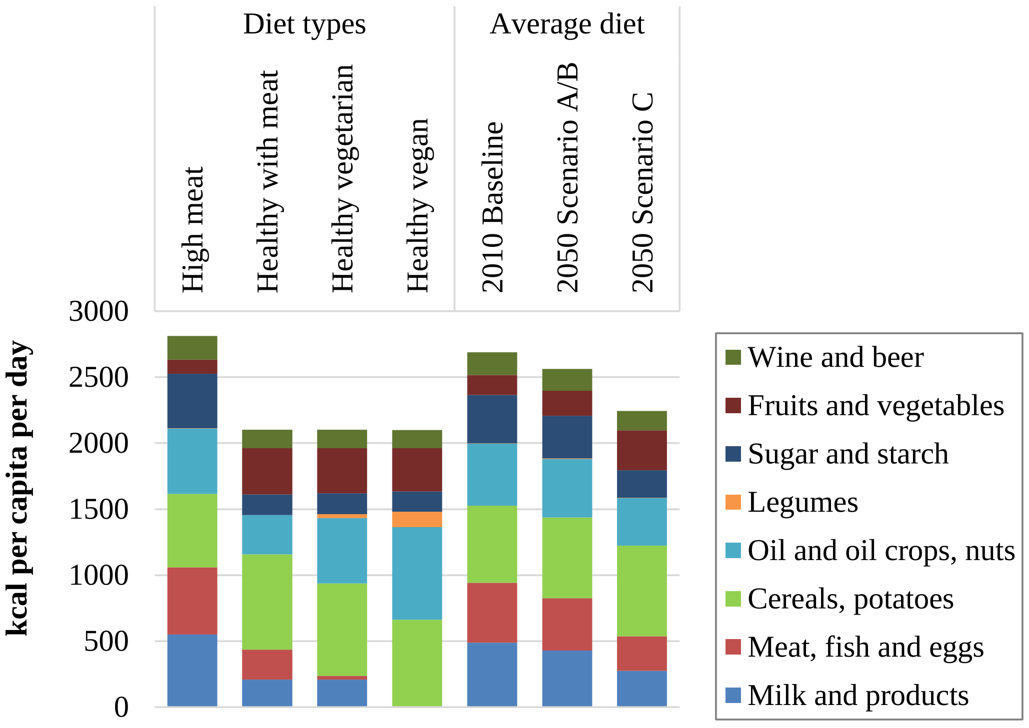

Figure S8. Diet types in kcal per capita and day, and average per capita diets in 2010 and 2050, resulting from the relative share of diet types shown in Table 5

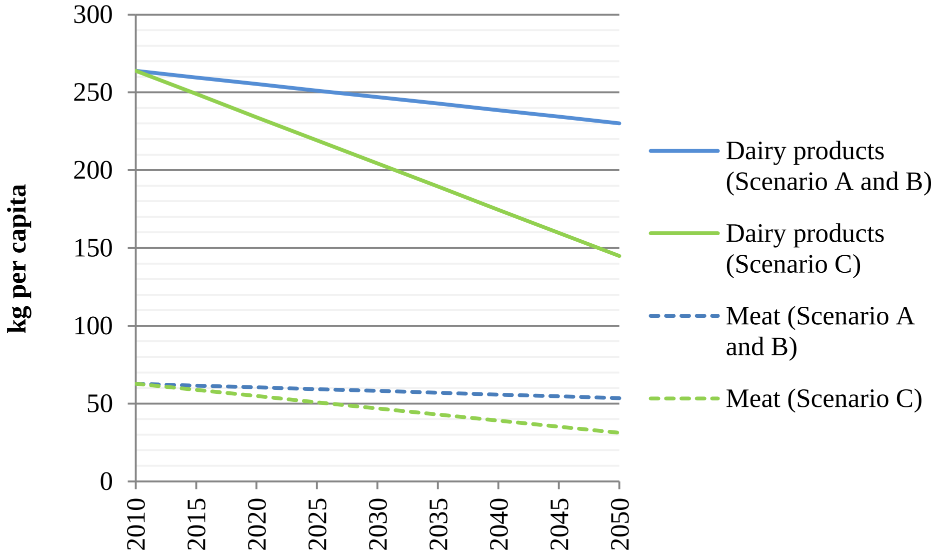

Figure S9. Per capita meat and dairy products consumption in the scenarios Comments: Dairy products are measured in raw milk equivalents. Actual human consumption is shown, i.e. food losses are not included.

3.4 Agricultural yields

Agricultural yields for the base year in 2010 are derived from agricultural statistics [9]. Our assumptions for the future development of agricultural yields are based on the following considerations:

In Scenario B (‘Intensive’), it is assumed that there are strong efforts to further increase crop yields along the path of the last decades. Crop yields in this scenario are based on a linear extrapolation of past trends of crop yields in conventional agriculture to 2050. In order to ensure that such an extrapolation doesn’t result in unrealistically high yields, we cross-checked crop yields in 2050 against yields already achieved in controlled field trials today [18]. This showed that such a continuation of linearly growing crop yields might be feasible in the case of Austria, albeit this is linked to certain ecological (and possibly social) costs.

In Scenario C (‘Alternative’), agricultural yields are assumed to remain constant throughout the whole simulation period. As yield increases are quite likely (at least for some of the most relevant crops), this assumption may be interpreted as yield increases being compensated by a structural shift towards organic farming. Grassland yields and yields for forage crops, such as Alfalfa, are assumed to remain constant in all scenarios.

For Scenario A it is assumed that only 50 % of the potential yield increases (i.e. of the increase assumed in Scenario B) are realized.

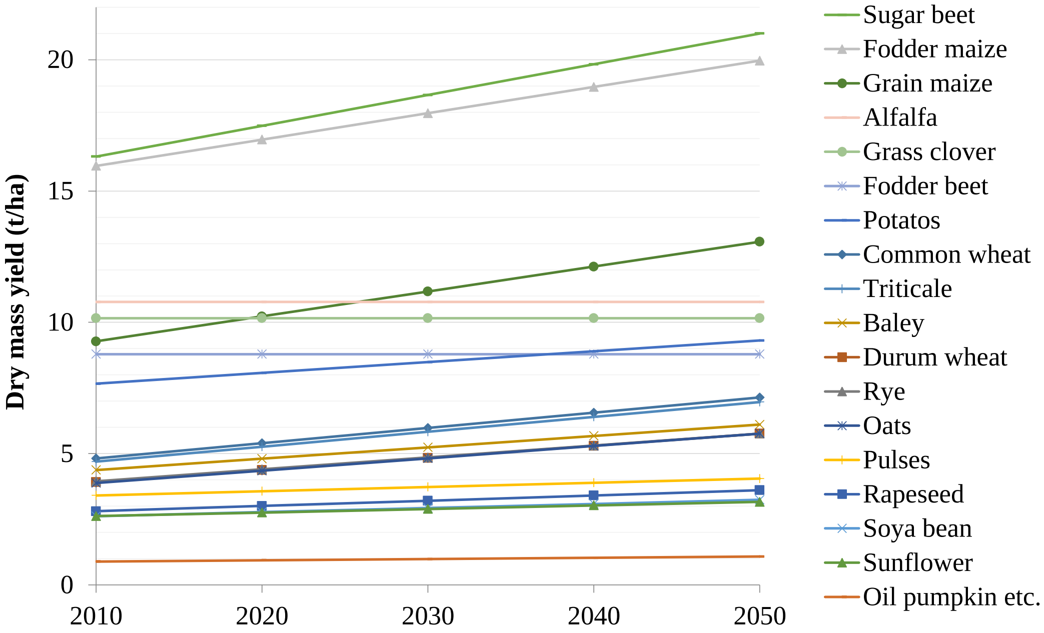

Figure S10. Development of dry mass yields in Scenario B ‘Intensive’

4 Further selected simulation results

The following figures show selected simulation results for the energy sector: The development of electricity and district heat supply. Both developments are characterized by a decline of fossil-based energy generation. The only non-renewable fuel which remains relevant for electricity and district heat generation until 2050 is the non-biogenic fraction of municipal solid waste being combusted in CHP plants.

Electricity imports and exports are evaluated on a sub-annual time slice level consisting of three seasonal and two day-night time slices; this is why (net) imports as well as (net) exports may occur in a certain years. In other words: They represent net trade in terms of the sub-annual time resolution and not on an annual basis (this is why ‘net’ is set in brackets). Due to this time resolution, they are not comparable with cross-border electricity exchange as stated in energy statistics [19].

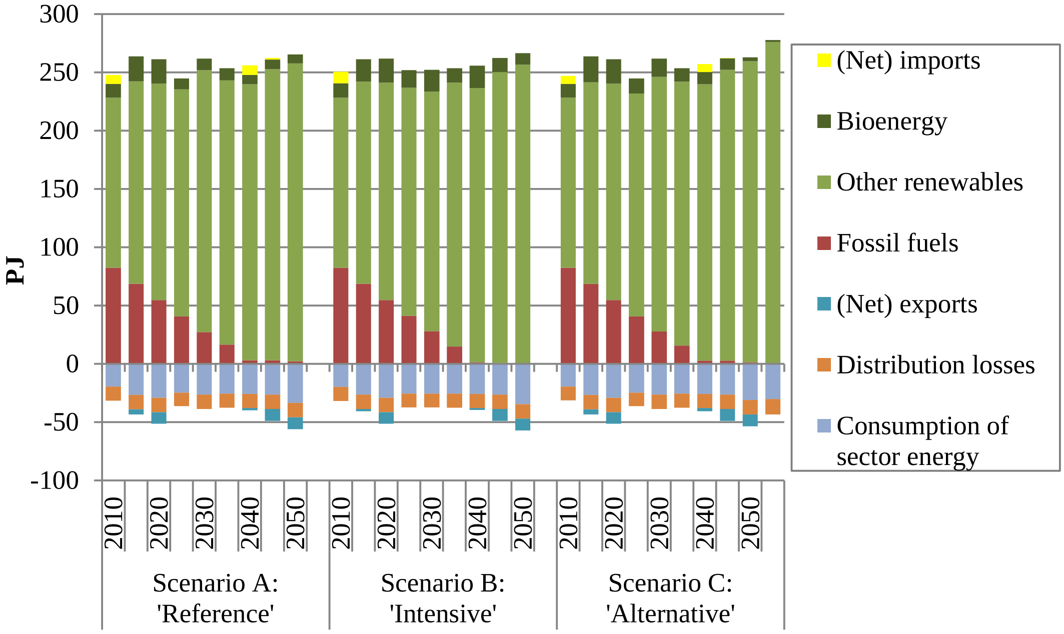

Figure S11. Development of electricity supply in the scenarios A, B and C

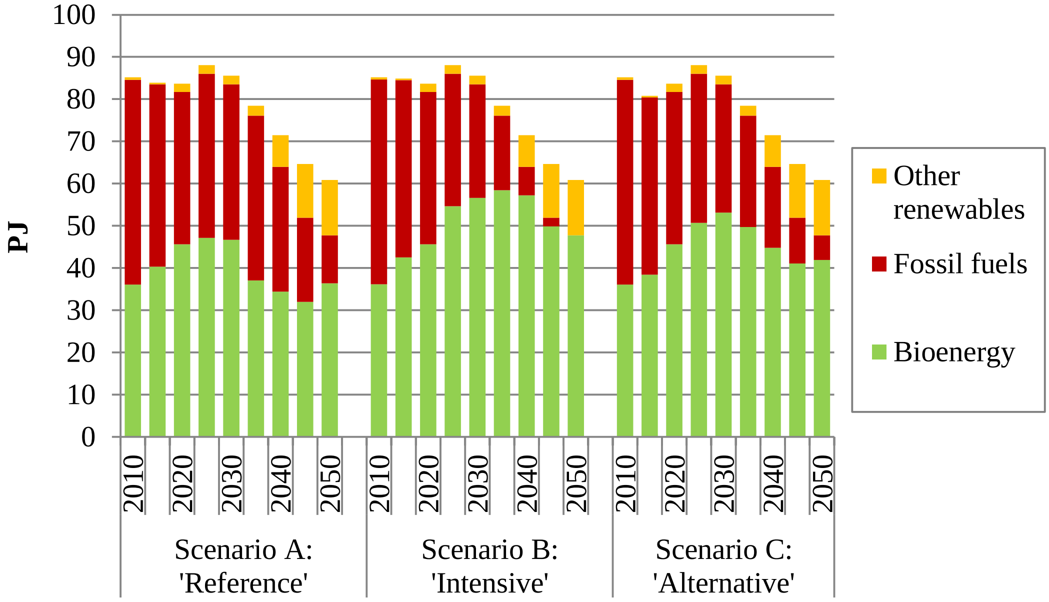

Figure S12. Development of district heat supply in the scenarios A, B and C

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