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Original Research Article

The socioeconomic optimal energetic use of biomass in Austria up to 2050

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ABSTRACT

Biomass for energy use is a limited resource that will play a critical role in achieving carbon neutrality, yet its optimal allocation across sectors remains uncertain. This study develops dynamic modelling scenarios to identify economically optimal biomass utilization pathways for Austria until 2050. The major new contribution and research gap closed is that a holistic multidisciplinary approach is applied, considering economic, carbon life-cycle aspects and sustainability of potentials simultaneously. The results show that the use of biomass for energy services is primarily allocated to individual heating and small district heating systems, where it remains the least-cost option both today and in future projections. However, this bottom-up cost perspective may conflict with broader decarbonization priorities. From a societal viewpoint biomass may need to be increasingly directed toward sectors with limited renewable alternatives particularly for high-temperature applications in industry. The findings highlight a potential misalignment between market-driven biomass allocation and long-term climate objectives. Consequently, future biomass governance may require policy frameworks that prioritize system-level decarbonization benefits over purely cost-based allocation. Eventually, regarding the quantity of sustainable primary bioenergy sources a major finding is that up to 2050 a total quantity of about 250 PJ will be available while the expected demand in the chosen scenario will be about 255 PJ. Hence, this is only a moderate gap which could be closed by imports or by more ambitious efficiency improvements.

KEYWORDS

Biomass-based energy carriers, costs, economics, sustainability, end uses.

INTRODUCTION

Bioenergy from forests play an important role in achieving long-term targets of reducing greenhouse gas emissions while ensuring security of supply in the transition to a carbon-neutral economy. Yet, currently the energetic use of biomass is at least under discussion because of issues of sustainability. Climate-related disturbances such as bark-beetle outbreaks and storms increasingly endanger the sequestration function of forests, emphasizing the need for climate-adapted forest management and optimized biomass utilization strategies. Therefore, it is key to identify the perfect balance between biomass availability, usage and costs to enhance the competitiveness of bioenergy.

The optimal allocation and role of biomass within low-carbon energy systems has been a long-standing topic in energy system research. Early work on a global level by Kraxner et al [1] and by Havlík et al [2] have drawn global bioenergy scenarios for future forest development, land-use implications, and trade-offs. In addition, global land-use implications of first and second generation biofuel targets have been discussed

On a European level Bentsen (2014) [3] has examined how biomass resources can be optimally deployed within the European Union to minimize greenhouse gas (GHG) emissions. The study emphasizes that biomass is a limited resource and should therefore be strategically allocated across sectors to maximize emission reductions rather than used indiscriminately for energy production. It highlights the importance of system-level optimization, suggesting that the climate benefits of biomass depend strongly on how and where it is utilized within the broader energy system.

A European wide analysis of the quantities of biomass that could in principle be used for energy purposes can be found in the report "How much bioenergy can Europe use without harming the environment" by the European Environment Agency [4]. This report analyzes how much biomass could be used for purely technical energy purposes without causing additional harm to the environment. To this end, a series of environmental criteria for energy production from biomass is drawn up, which are subsequently used for modeling the primary potentials. These criteria were developed across Europe.

Building on this earlier perspective, more recent research by Millinger et al. (2025) [5] adopts a sector-coupled European energy system model to analyze near-optimal pathways for achieving net-zero and net-negative emissions targets. The study reinforces the notion of biomass scarcity but advances the discussion by showing that the primary value of biomass lies in providing biogenic carbon, rather than simply serving as an energy source. This carbon can be used for carbon capture and storage (CCS) or as feedstock for synthetic fuels, which are crucial for hard-to-electrify sectors.

Kalt, Kranzl, & Haas [6], stated that to improve the commercial viability of bioenergy and the associated reduction in CO_2 emissions, measures to promote heat generation and, to a lesser extent, electricity generation in combined heat and power plants are both sensible and necessary. This may be an option to overcome the barriers to a broader market penetration of biomass in Europe as analysed by McCormick and Kaberger [7]. In their research "Key barriers for bioenergy in Europe: Economic conditions, know-how and institutional capacity, and supply chain coordination, Biomass and bioenergy." they ultimately conclude that there can be consistent strategies and suitable political interventions to overcome all relevant barriers. Lim & Lam [8] analyse the biomass supply chain optimisation via novel biomass element life cycle analysis. An also optimization-based analysis regarding decision workflow for designing regional renewable energy systems is provided by Pimentel et al [9] 2026. Knapek et al. [10] present an approach that shows a complex assessment of the energetic and economic evaluation of agricultural biomass for various applications, such as biomethane, electricity and heat. This approach makes it possible to determine the most efficient strategies for using biomass for energy, to make optimum use of the limited arable land available and thus to generate an optimum portfolio of energy services from one hectare of land. Regarding biofuels in transport Ajanovic et al. [11] analysed the economic challenges for their future relevance of biofuels in transport in EU countries. Gustavsson et al [12] discuss the use of biomass for climate change mitigation and oil use reduction.

Ajanovic et al. [13] (2014) projects a best-case scenario of 4650 PJ of additional biomass-based energy by 2050. This would correspond to approx. 7% of the total energy consumption of the EU-15 countries in 2010. A dynamic consideration of renewable energy sources from an economic, energetic and ecological point of view until 2050 shows that all analysed alternative energy sources would have lower CO_2 emissions than conventional diesel, but that economic competitiveness can only be guaranteed by a) cost reduction through technological learning, b) targeted measures (e.g. CO_2 taxes) and c) intensified research and development. Other studies focusing on the Renewable energy policy framework and bioenergy contribution in the European union are Scarlat et al [14], Potrč et al [15] and Frank et al [16)].

Regarding Austria, Haas et al [17] provided the first comprehensive analysis on the role of biomass feedstocks for energetic uses. Ajanovic et al [18] introduced an approach to quantify under which circumstances, to which extent and within which timeframe alternative energy carriers would become economically feasible in Austria, in comparison to their conventional alternatives, see also [19]. Methods to assess gross and net energetic potentials, costs, environmental aspects and cumulative life-cycle energy balances, as well as technological learning represented the focus points of this study. While this study covers wooden and agricultural biomass sources for the conversion to synthetic natural gas (SNG), bioethanol and Fischer-Tropsch-diesel other studies focus solely on agricultural biomass sources. Kalt et al. [20] describes transformation scenarios towards a low-carbon bioeconomy in Austria. Anca-Couce et al [21] analyse bioenergy technologies, uses, market and future trends with Austria as a case study and Kraussler et al [22] conducted a techno-economic assessment of biomass-based natural gas substitutes against the background of the EU 2018 renewable energy directive while Schmidt et al [23] discussed aspects of regional energy autarky – their potentials, costs and consequences. The Current potential of more sustainable biomass production using eco-efficient farming practices in Austria is analysed by Maier et al 2017 [24]. Stürmer et al [25] investigates the implications of agricultural bioenergy crop production in a land constrained economy for the example of Austria. The economic impacts of biomass use in Austria are analyzed in Fuhrmann et al, [26], Kristöfel, et al [27] and Kristöfel, et al [28].What new technologies may contribute to future biomass use is analyzed in another category of papers. Dokl et al [29] discusses the possible optimization of the biomass supply chain for power generation with the steam rankine cycle. Schmidt et al [30] analyse the cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass with a comparison of conversion technologies. The most recent contribution is by Sameti [31] (2026) on the options of machine learning-enhanced biomass forecasting for spatial bioenergy planning.

However, the major gap in the literature is that so far no comprehensive multi-disciplinary work exists. The major new contribution and research gap closed in this paper is that a holistic multidisciplinary approach is applied, considering economic, carbon life-cycle aspects and aspects of sustainability of potentials as well as analysing the optimal allocation of different feedstocks to various end uses and products simultaneously. To ensure availability of sustainable biomass in the long run, the use of different existing and additional available biomass feedstocks must be revisited in terms of minimizing carbon emissions and costs. The environmental and economic benefits of bioenergy strongly depend on the specific conversion routes and end-use sectors in which biomass is deployed. This highlights the need for a differentiated and systematic analysis of optimized bioenergy utilization pathways over time.

While numerous studies have analyzed individual bioenergy conversion pathways, comparatively few have assessed the long-term economic competitiveness and carbon performance of multiple biomass utilization options across different end-use sectors within an integrated framework. In particular, there is still limited evidence on how the relative cost competitiveness of bioenergy supply chains may evolve over time and how different CO_2 price trajectories could influence optimal biomass allocation.

Against this background, the primary objective this paper is to identify economically optimal biomass utilization pathways for Austria up to 2050 by developing scenarios based on dynamic modelling.* The analysis evaluates the cost structures, future cost developments, and

* This work has been conducted within the project BIOSTRAT, see acknowledgements.

carbon balances of selected bioenergy conversion chains derived from biomass and compares them with conventional alternatives.

To address this objective, the paper investigates the following research questions:

- What are the current overall production costs of selected energy carriers derived from biomass across different conversion technologies and end-use applications, and how are these costs distributed among capital expenditures, energy inputs, operation and maintenance (O&M), and CO_2 costs?
- How are the overall production costs of different bioenergy supply chains expected to evolve up to 2050, and how do they compare with those of conventional fossil-based alternatives?
- How do alternative CO_2 price trajectories (low vs. high) influence the economic competitiveness of bioenergy pathways and the resulting allocation of biomass resources?

Hence, different forest energy sources (firewood, forest wood chips, bark …) in various conversion chains for different end uses (heat, electricity) and products (Synthetic Natural Gas (SNG), Fischer-Tropsch (FT)-products) are investigated from economic point of view in comparison to their fossil competitors.

BACKGROUND: SOME HISTORICAL DEVELOPMENTS

In this chapter the major historical developments regarding the quantities of different biomass energy sources and carriers used in Austria are discussed. Fig. 1 depicts the history of gross biomass energy consumption by biomass energy carrier 1970 -2022. Note, that in 2005 a new more detailed statistic system was introduced splitting biomass in more specific sources.

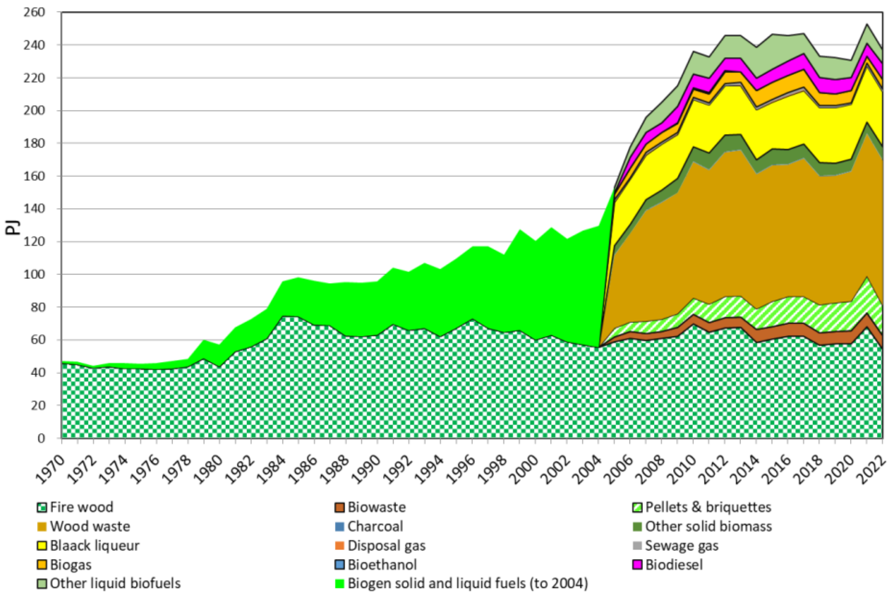


Figure 1. Gross biomass energy consumption in Austria by biomass energy carrier 1970 -2022 (Own figure based on Statistics Austria [32])

Historically, bioenergy deployment in Austria has been dominated by individual heating systems and district heating networks. Figure 2 illustrates the development of biomass utilization across different end-use sectors in Austria between 2010 and 2022. The overall biomass demand remains relatively stable throughout the period, with only moderate fluctuations driven primarily by shifts in the electricity and heat generation sectors. The input increased in heating plants, while a slight decline in the power industry could be observed. Residential space and water heating consistently represent the largest share of biomass consumption, highlighting the continued relevance of bioenergy in the building sector.

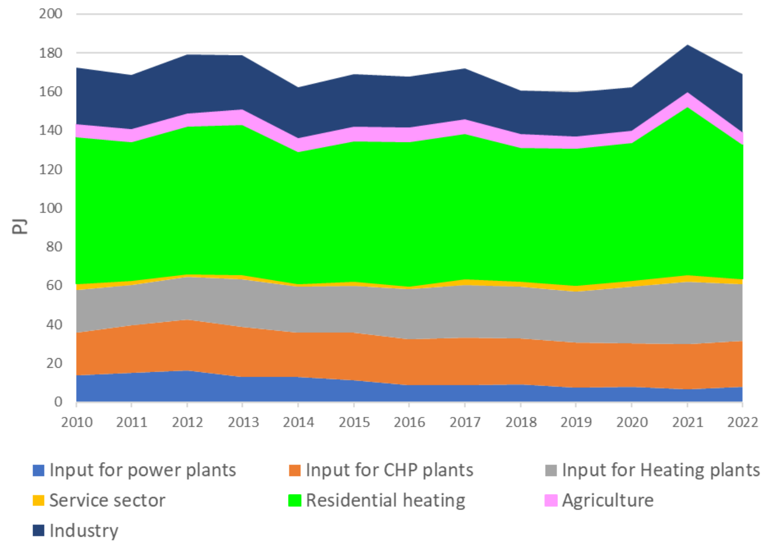


Figure 2. Development of biomass utilization across different end-use sectors (CHP refers to Combined heat and power) in Austria between 2010 and 2022 (Data source: Statistics Austria [32])

The real prices of biomass-based energy carriers (as of 2020) in Austria by biomass energy carrier 2010 -2024 are documented in Figure 3. The major finding of this figure is, that biomass energy prices have been and are quite stable over time except the years of the over-all energy crises 2021 to 2023.

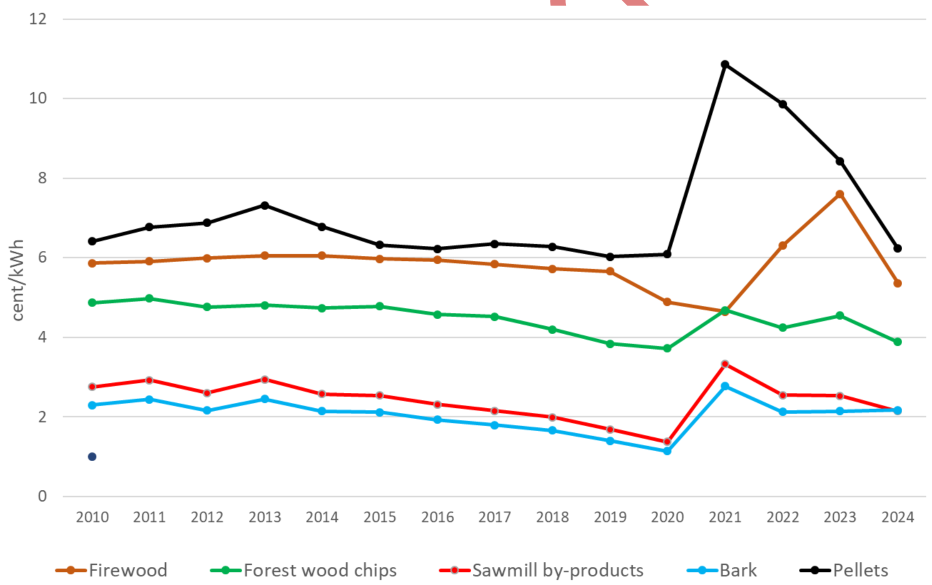


Figure 3. Real prices (as of 2020) of biomass-based energy carriers in Austria 2010 -2024 (based on own investigations)

METHODOLOGY

The method of approach applied is based on dynamic modelling on a yearly basis up to 2050.

Cost analyses

For the economic evaluation the overall costs of the specific biomass chains are compared with conventional energy carriers. The calculation of the CO_2 emissions was based on the life-cycle analyses (LCA) of the selected bioenergy pathways conducted within the BIOSTRAT project. The functional unit (unit to which all input and output flows as well as environmental impacts are related) was defined as 1 kWh (heat, power or fuel). Calculated impact category is the Global Warming Potential (GWP) given as CO_2-equivalent. Not all biomass feedstocks are suitable for all conversion pathways. Only the common combinations are included in the present study. Figure 4 shows the results in kg CO_2-eq/kWh of all chosen biomass conversion pathways including all upstream processes.

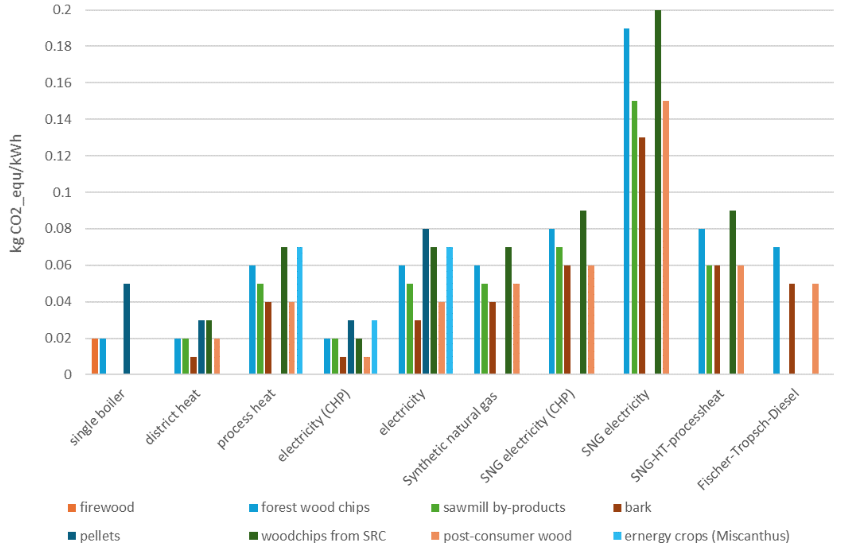


Figure 4. Specific CO_2 factors of different conversion chains for biomass-based energy carriers (kg CO_2-eq/kWh final energy) analyzed in Fuhrmann et al [33]

For the following dynamic economic analysis two CO_2 price scenarios until 2050 were assumed: a low CO_2 price scenario up to 200 €/ton CO_2 by 2050 and a high CO_2 price scenario reaching 400 €/ton CO_2 until 2050, see Figure 5.

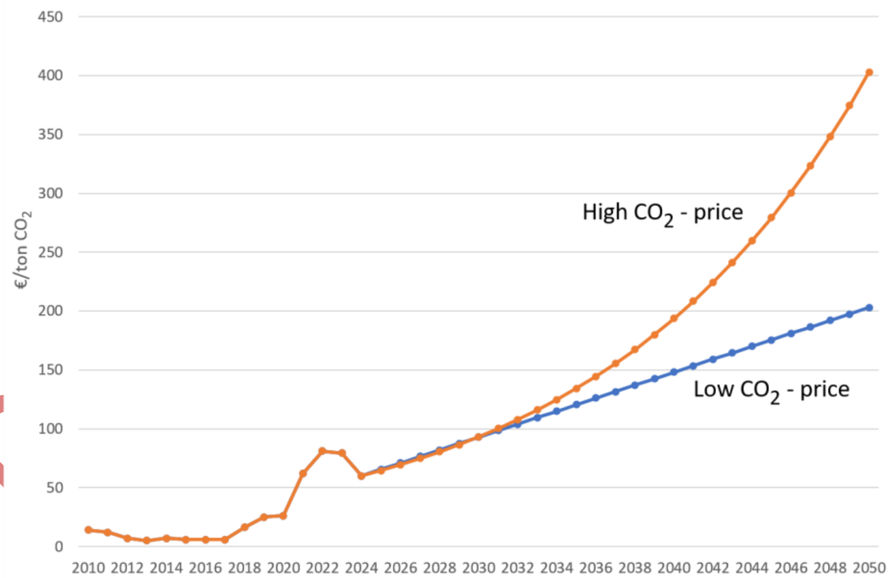


Figure 5. Low price vs. high price scenario of the development of the CO_2 price up to 2050 (Reference historical data: [34])

The calculation of the total production costs of the selected biomass-to-energy carrier chains takes into consideration capital costs, feedstock and energy costs as well as the operation & maintenance and CO_2 costs. Furthermore, it examines how the production costs of various bioenergy chains are projected to evolve up to 2050 in comparison with conventional alternatives, while also evaluating the influence of different CO_2 price levels, ranging from low to high following Fig. 5. Where applicable also the revenue of side products is considered.

The capital costs per kWh C_{Cap} for any energy carrier – conventional as well as biomass – are calculated as:

$$C_{Cap} = \frac{IC.\alpha}{T} \qquad [€/kWh] \qquad (1)$$

where IC refers to investment costs [€/kW], α refers to the capital recovery factor; while T denotes the full load hours [h/a].

The energy costs per kWh C_E are calculated as:

$$C_E = \frac{p_{FS}}{EC\ .\ \eta_{Con}} \qquad [€/kWh] \qquad (2)$$

where EC refers to energy content [kWh/ton feedstock], p_{FS} refers to the feedstock price [€/ton FS]; while η_{Con} denotes the efficiency of conversion technology.

The specific CO_2 costs C_{CO2} for any energy carrier – conventional as well as biomass – are calculated as:

$$C_{CO2} = p_{CO2} * f_{CO2} / \eta_{Con} \qquad [€/kWh] \qquad (3)$$

where C_{CO2} denotes the costs of CO_2 [€/kWh], p_{CO2} refers to the price of CO_2 [€/Tonne CO_2]; while f_{CO2}…denotes the CO_2-factor of an energy carrier [kg CO_2/kWh].

The sum of the sub-costs represents the yearly total production costs C_{Tot} for a specific energy carrier from a selected biomass fraction:

$$C_{Tot} = C_{Cap} + C_E + \frac{C_{O\&M}}{T} + C_{CO2} + R_{SP} \qquad [€/kWh] \qquad (4)$$

where $C_{O\&M}$ denotes the operation & maintenance costs for feedstock transport, electricity, heat, labour costs [€/kW] and R_{SP} denotes the revenue of side products.

Allocation Analysis

In the project BIOSTRAT sustainable dynamic biomass potentials of various biomass feedstocks have been investigated up to 2050 in Austria, see [35]. In a next step, the goal was to allocate these biomass potentials (Figure 6) to the various sectors and get a picture of how these sectors could be covered and where there still are gaps between supply and demand.
As shown, in Austria energy from biomass contributes significantly especially to heat supply and so it does in the scenarios of the Austrian Environmental Energy Agency (UBA [36]) up to 2050. This is documented in detail in Annex B. Due to phasing out of fossil energy, biomass remains a major renewable energy source source for heating of buildings but it is also important for electricity generation and in the industry sector. Based on the calculated costs and the projected demand derived from the WEM scenario of [36], biomass was systematically allocated across different energy sectors. The WEM ("with existing measures") scenario provides a baseline projection of energy consumption up to 2050 under currently implemented climate and energy policies.

Using this framework, the methodology first determined which energy sectors required biomass supply and evaluated the costs of different biomass types. The technical and economic suitability of each biomass source for the respective sectors was then assessed. After fulfilling the demand of high-priority sectors, any remaining biomass was allocated to lower-priority sectors, ensuring the most efficient use of available resources across the energy system.

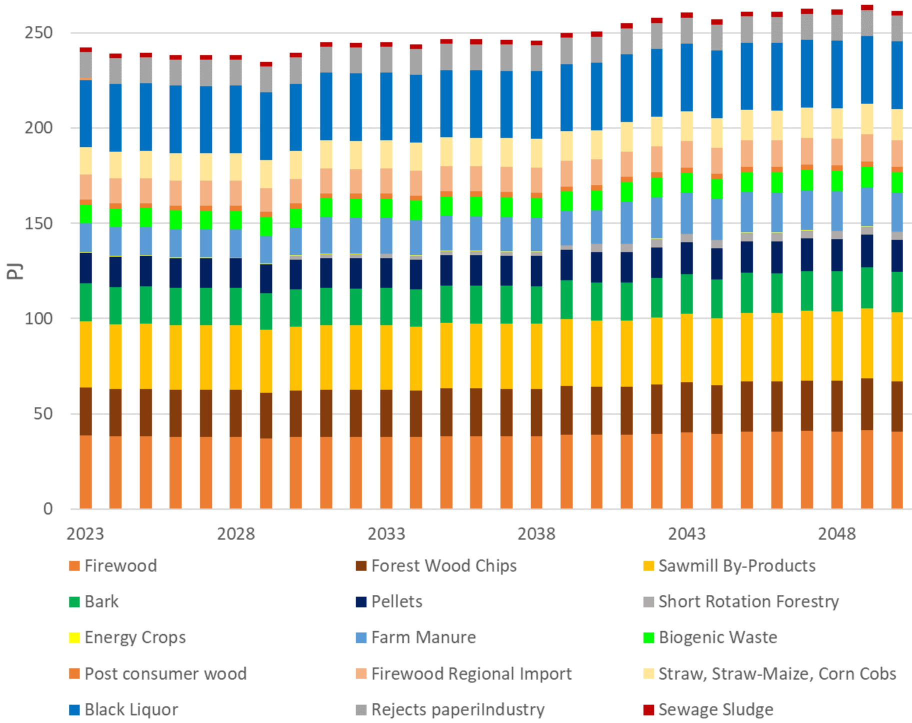


Figure 6. Sustainable dynamic biomass potentials investigated up to 2050 in Austria (own illustration based on [35])

Based on that, the prioritization order was the following:

1. High Temperature (HT) Industry
2. Electricity Generation

With same priority:

3. District Heat
4. Low Temperature (LT) Industry
5. Residential Heat/Buildings
6. Transport

With HT Industry making up 28% of the whole primary energy demand of the industry sector and LT Industry consisting of the remaining 72% [37]. Following this, the available biomasses were ranked by cost factors to determine which biomass energy sources are to be used first. The reference value was Forest Wood Chips (FWC) and the ranking can be seen in Figure 7. Biogenic Waste as well as Sewage Sludge and Black Liquor are among the cheapest biomasses while Firewood and Pellets make up the two most expensive biomass energy sources relative to FWC. Negative factors translate to receiving payment for the disposal of a substance.

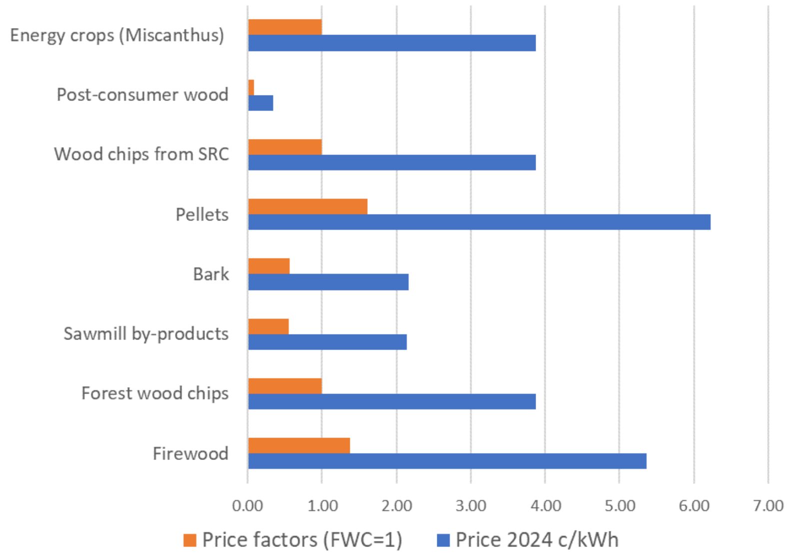


Figure 7. Biomass energy sources ranked by their cost factors (FWC refers to forest wood chips)

With this data, the allocation of biomasses to the sectors is started. This was done by looking at the sectors in the prioritization order and checking how much final energy was needed in a sector. Afterward, the cheapest biomass energy source that could be used in the sector was picked and multiplied with the corresponding conversion efficiency η for the use and the resulting final energy was allocated to the sector. This process was repeated either until the final energy demand of the sector was met or no more biomasses were available for use.

Depending on the application of biomass, up to two conversion efficiencies needed to be considered. Biomass could either be directly converted into power — for example, in a combined heat and power plant — or first transformed into SNG or Biomethane, in which case the efficiency of gas conversion also had to be considered. Equations 5, 6 and 7 show the formulas used. Equation 5 describes how the final energy for the use of SNG HT Process Heat $FE_{SNG\ HT\_PH}$ is calculated:

$$FE_{SNG\ HT\ PH} = PE \cdot \eta_{SNG_{Con}} \cdot \eta_{PH} \tag{5}$$

where PE denotes primary energy input [kWh/yr], $\eta_{SNG_{Con}}$ denotes the efficiency of the SNG conversion technology; while η_{PH_Con} denotes the efficiency of the process heat conversion technology.

Equation 6 and equation 7 illustrate the calculation of electricity FE_{Ele_CHP} and heat FE_{Heat_CHP} converted from a biomass energy source in a combined heat and power plant (CHP):

$$FE_{Ele\_CHP} = PE \cdot \eta_{Power} \tag{6}$$

$$FE_{Heat\_CHP} = PE \cdot \eta_{Heat} \tag{7}$$

Where η_{Power} denotes the efficiency of the electricity conversion and η_{Heat} refers to the efficiency of the heat conversion process.

The total efficiency of the CHP η_{Tot} is:

$$\eta_{Tot} = \eta_{Power} + \eta_{Heat} \tag{8}$$

Table 1 documents the conversion efficiencies that were used in the calculations. During the allocation process, it was preferred to make direct use of a biomass over converting it into a gas and then using it.

Table 1. Conversion efficiencies of the processes analyzed 2021 – 2050 ([38], [39], own analyses)

Process	**2021**	**2030**	**2040**	**2050**
SNG Production	60%	61%	63%	65%
Electricity from CHP	28%	29%	29%	30%
Heat from CHP	57%	57%	57%	57%
Total from CHP	85%	86%	86%	87%
FT Diesel	51%	52%	53%	54%

RESULTS OF THE COST COMPARISON

Comparison of costs for 2024

The final energy costs of the different end uses (applications) produced from forest wood chips (heat from boilers, district heat, process heat, electricity from CHP, electricity, SNG, SNG for electricity, SNG for CHP, SNG for high temperature (HT) process heat, FT-Diesel) are shown in Figure 8. The figure depicts a breakdown of the total production costs into capital, energy, operation and maintenance, as well as CO_2 costs for the year 2024. With the exception of electricity from CHP, SNG- electricity and SNG-CHP, energy costs represent the largest share of costs and that the use of biomass for energy production is cheapest for applications in the heating sector.

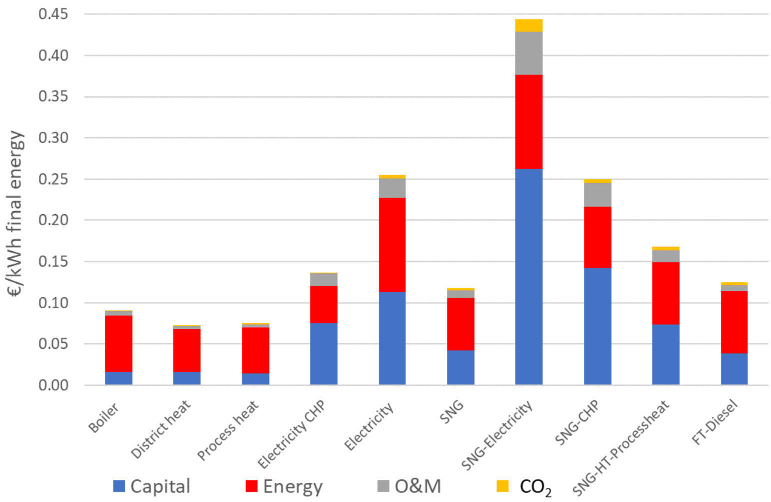


Figure 8. Comparison of final energy production costs by category (capital-, energy-, O&M (operation and maintenance) and CO_2-costs) of different uses and products from forest wood chips (for boilers biomass from fuel wood) in 2024

Figure 9 shows a comparison of the production costs of the usage of wood chips (fuel wood for boilers) and their conventional alternatives produced from diesel or natural gas. Among the three heat fractions (heat from boilers, district heat & process heat), wood chips or fuel wood are already economically competitive with their fossil-based alternatives. For electricity (with CHP and without), it is evident that the generation costs of fossil-based natural gas are considerably lower, mainly due to superior conversion efficiencies of natural gas power plants. While for FT-Diesel the conventional alternative currently is more economically competitive, the largest difference between wood chip-based and conventional energy carrier can be observed for SNG, where the conventional alternative is currently cheaper by at least the factor three.

Figure 9. Comparison of the total energy production costs of different end uses from wood chips and the fossil alternatives in 2024

Figure 10 shows the production costs of SNG from different biomass sources in 2024. As seen the cheapest biomass options would be to produce SNG from post-consumer wood, sawmill by-products and bark. But even in these cases, it would not be economically viable given the wholesale market prices of 2024.

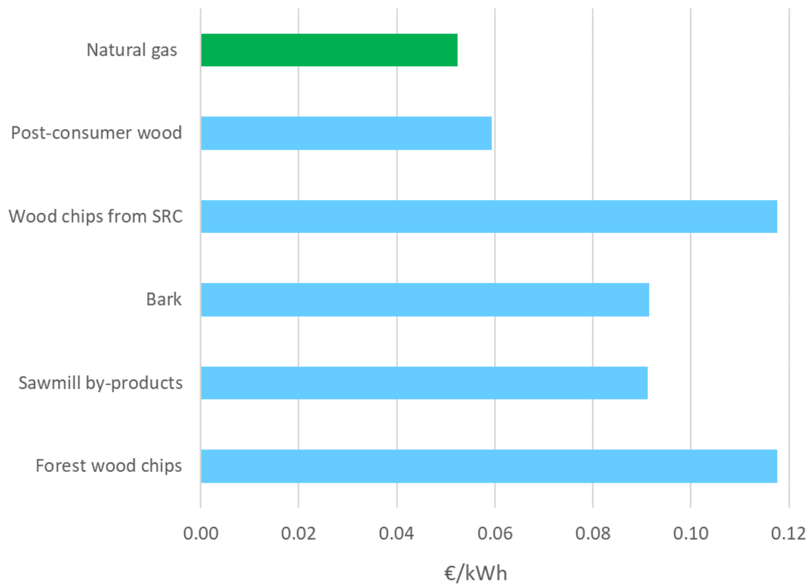


Figure 10. Comparison of the total production costs of synthetic natural gas (SNG) from different biomass feedstocks compared to natural gas (wholesale price) in 2024

Corresponding to the comparison of the costs for SNG production in Fig. 10 the next Fig. 11 shows a comparison of the total generation costs of electricity from biomass products in

CHP in 2024 compared to electricity from CHP from Natural Gas. Note, that the calculation for the natural gas costs is based on its wholesale market price.

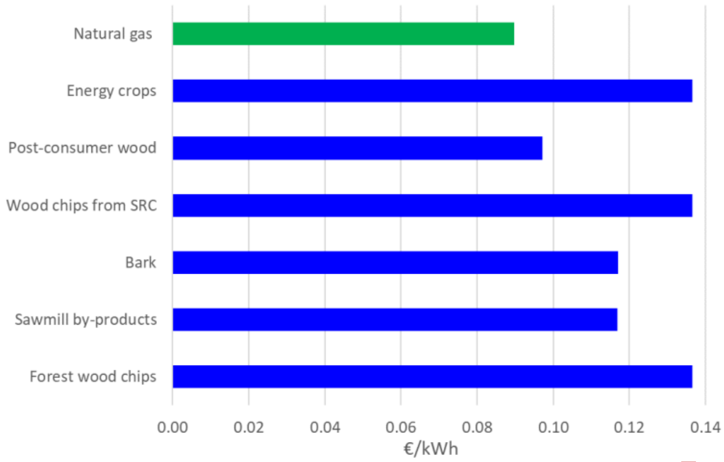


Figure 11. Comparison of the total generation costs of electricity in combined heat & power plants (CHP) in 2024 compared to electricity from Natural Gas in CHP (wholesale price)

Comparison of costs for 2050

Figure 12 shows the breakdown of the production costs into capital, energy, O&M, as well as CO_2 costs for the different energy carriers and their applications produced out of forest wood chips, for the year 2050. Energy costs constitute the major share of total production costs for each biomass-to-energy carrier chain.

It is evident that in the long run developments of the CO_2 price and the price of natural gas have the most significant effects on the economic feasibility of biomass as energy carrier, when analysed from a dynamic perspective until 2050. In the low CO_2 price scenario all energy carriers and their heat applications are economically feasible. In a comparison for the year 2050 based on the low CO_2 price scenario it can be seen that – with exception of SNG and its uses – the biomass-based energy carriers and their applications can compete economically with their conventional alternatives. In case of the three heat fractions under study (boiler, district heat, process heat), the biomass-based version is expected to have even lower production costs as their conventional alternatives by 2050, which can be largely attributed to the influence of the CO_2 price. Relatively longer biomass-to-energy carrier chains have been proven to be less efficient in terms of higher CO_2 factors, reduced conversion efficiencies and higher investment costs.

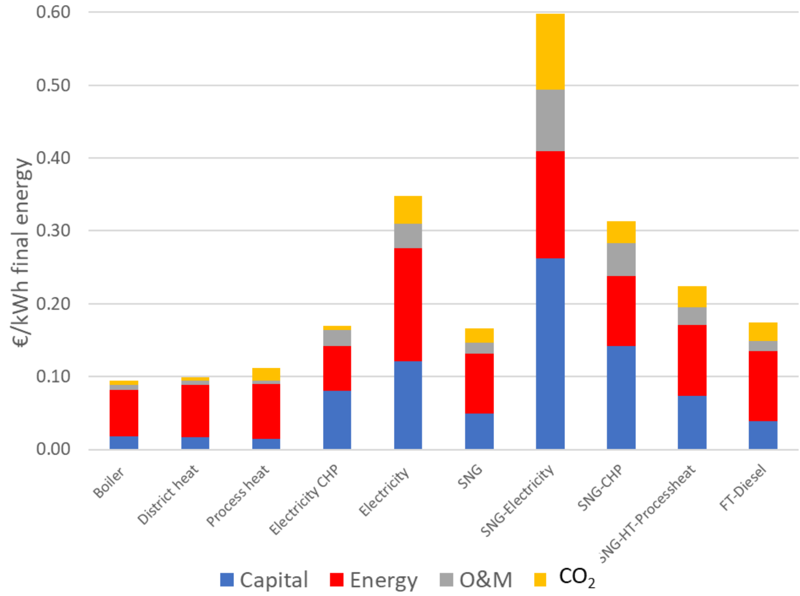


Figure 12. Comparison of final energy production costs by category (capital-, energy-, O&M (operation and maintenance) and CO_2-costs) of different uses and products from forest wood chips (for boilers biomass from fuel wood) in 2050

Figure 13 compares the costs of the different energy carriers and their applications produced out of wood chips for the year 2050, based on the low CO_2 price scenario. It is evident that – with exception of electricity generation with and without heat use and the production of SNG and its uses – all applications based on wood chips are economically competitive and all heat fractions (heat from boilers, district heat & process heat) were cheaper than their conventional alternatives. This is essentially due to the influence of natural gas price increasing steeper than wood chips prices.

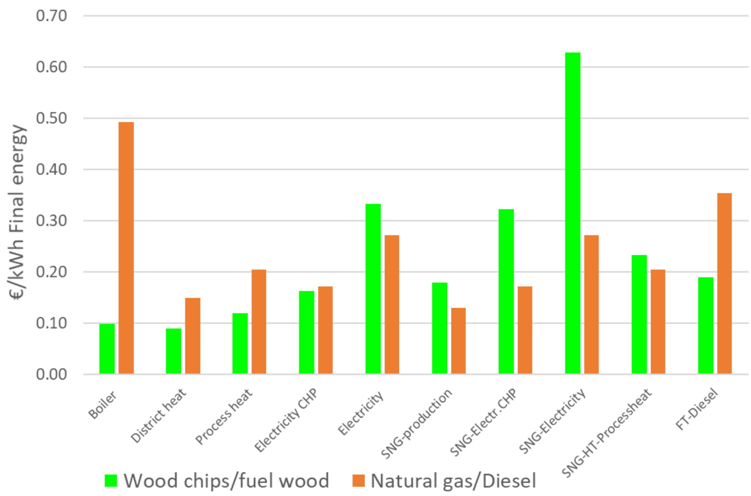


Figure 13. Comparison of total energy production costs of different end uses from wood chips and the fossil alternatives in 2050 in the low CO_2 price scenario

If the comparison is made in the high CO_2 price scenario by 2050 the prospects for wood chips are better especially for electricity generation with and without heat use and for SNG production, see Fig. 14. This is essentially due to the influence of the higher CO_2 price.

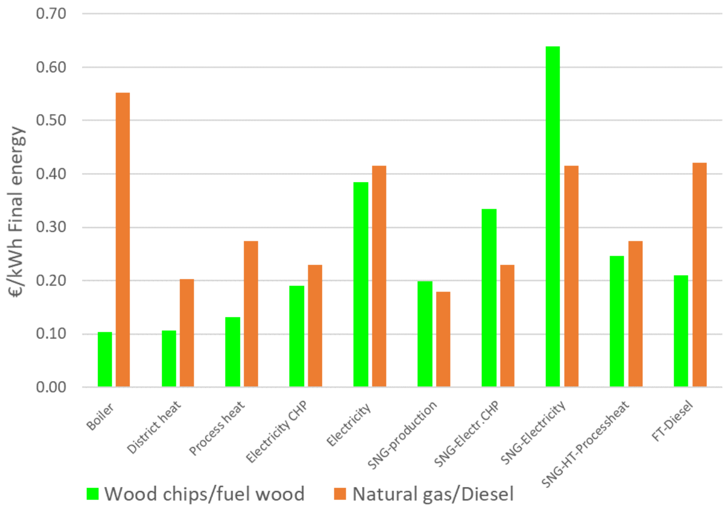


Figure 14. Comparison of total energy production costs of different end uses from wood chips and the fossil alternatives 2050 in the high CO_2 price scenario

Figure 15 depicts a comparison of the production costs of SNG from different biomass sources in 2050 and from natural gas (in the low CO_2 price scenario). As seen the cheapest options would be to produce SNG from post-consumer wood, bark and sawmill by-products . In these cases, it would finally be economically viable with the prices of 2050.

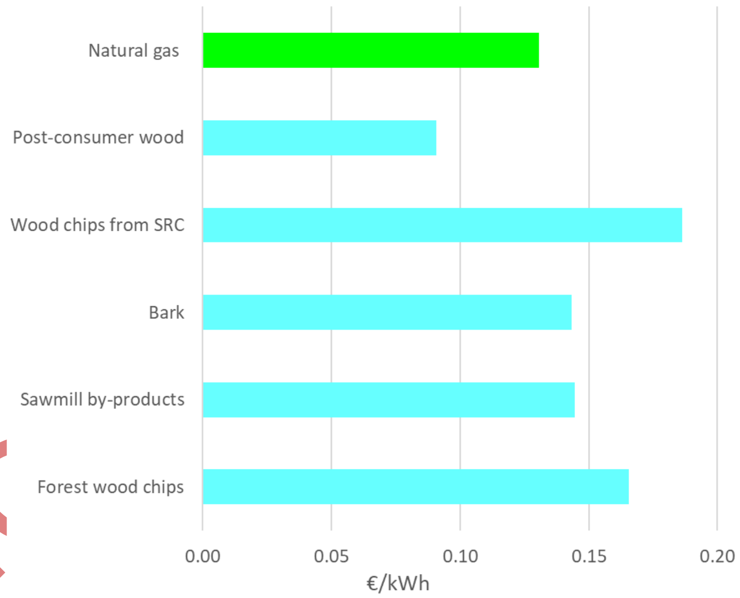


Figure 15. Comparison of the total production costs of Synthetic Natural Gas (SNG) from different biomass feedstocks in 2050 compared to Natural Gas (wholesale price)

Corresponding to the comparison of the costs for SNG production in Fig. 15 the following Fig. 16 shows a comparison of the total generation costs of electricity in CHP in 2050 compared to electricity from CHP from Natural Gas. Note, that the calculation for the natural gas costs is based on its wholesale market price. As seen, the final electricity costs from biomass products and natural gas are rather similar including CO_2 costs in the low CO_2-price scenario. For bark, SBP and post-consumer wood the costs are even lower than from natural gas. Of course, in the high CO_2-price scenario the economics is even more favourable for the use of biomass.

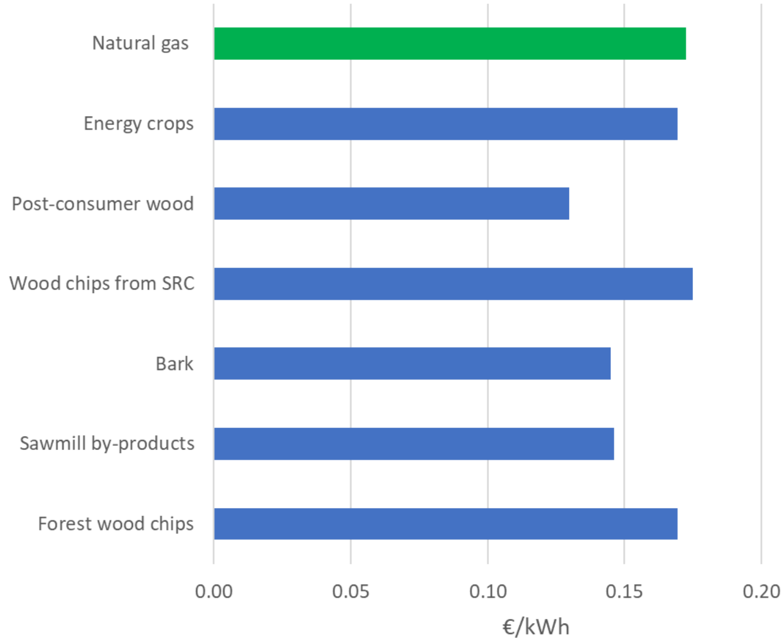


Figure 16. Comparison of the total generation costs of electricity in CHP in 2050 compared to electricity from CHP from Natural Gas (wholesale price)

Scenarios for electricity generation in combined heat and power plants (CHP)

Figures 17 and 18 depict scenarios for the costs of electricity generation in CHP from forest wood chips between 2010 and 2040 in comparison to scenarios for electricity production in CHP via natural gas, for both the low and high CO_2 price scenario until 2040. For the price scenarios of biomass energy carriers an increase of 0.5 % per year in the low price scenario, 1.5 % in the medium price scenario and 3% per year in the high price scenario are assumed. For natural gas the corresponding assumptions are: increases of 1.5 % per year in the low price scenario, 3 % in the medium price scenario and 5% per year in the high price scenario. The major reason for this difference in the assumptions is that historically biomass prices have been much more stable than the natural gas prices. In the Figures 17 and 18 it can be seen how these increases effect the economics of biomass vs natural gas for electricity generation from CHP for low and high CO_2 prices.

As seen in Figure 17 in case of the low CO_2 price scenario until 2040 – with a high natural gas price and low wood chip prices– the biomass-based production costs are almost equal to the conventional alternative and thus economically feasible. Figure 18 shows that in the high CO_2 price scenario until 2050, the wood chips-based production of the energy carriers under study would become economically feasible for all price scenarios of natural gas. Among the main reason for the low economic feasibility of biomass-CHP are the significantly higher investment costs (about double, see Annex A).

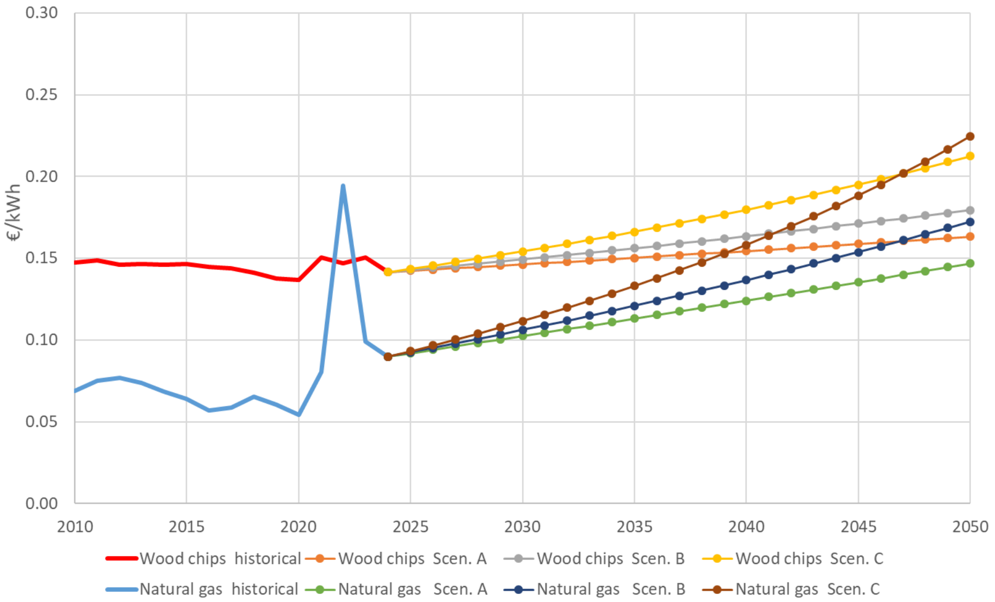


Figure 17. Scenarios for electricity generation costs in combined heat and power plants from wood chips and from natural gas up to 2050 – low CO_2-price scenario.

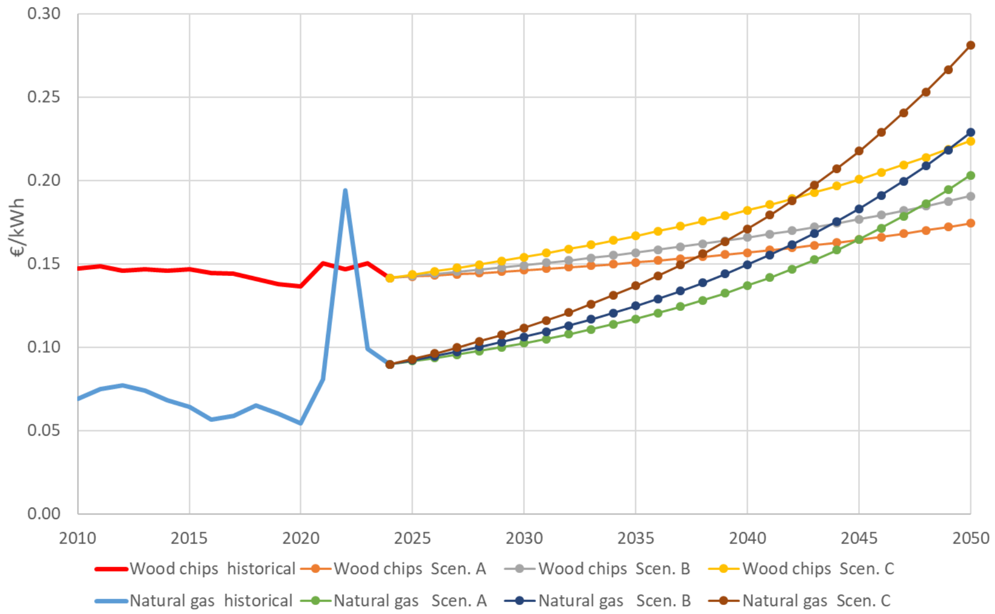


Figure 18. Scenarios for electricity generation costs in combined heat and power plants from wood chips and from natural gas up to 2050 – high CO_2-price scenario.

RESULTS OF THE ALLOCATION ANALYSIS

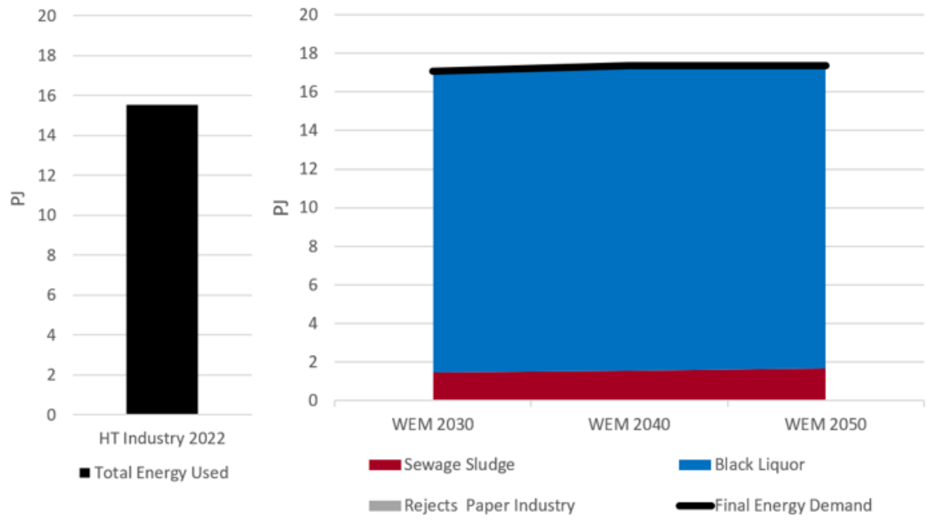
In the following the results of the allocation will be portrayed and briefly discussed. In the following Figures on the left-hand side, the status quo of the primary energy coverage of each sector can be seen while the right-hand side shows the possible coverage for the years 2030-2050 resulting from this analysis.

At this point it is important to mention that the status quo is portrayed in primary energy and the future projection is portrayed in final energy demand coverage which is why the scales of the two graphs might not match exactly. Also, the lower a biomass is set in a graph on the right-hand side, the cheaper it is and the price increases upwards.

High Temperature Industry

The sector of the highest priority was the high temperature (HT) industry Sector. About 16 PJ of total energy were put up by biomass energy sources in 2023 [34]. The analysis projected a final energy (FE) demand of 18 to 23 PJ from 2030 to 2050 which can be covered through SNG HT PH with Sewage Sludge and Black Liquor (Figure 19).

Note, that with respect to high temperature heat we have taken the recent share (from 2022) of 28% for heat with temperatures higher than 400°C [34]. However, for substitutable energy carriers up to 1000°C it might be possible that there are other possible alternative low carbon energy carriers, e.g. by industrial heat pumps or other electricity-based processes.

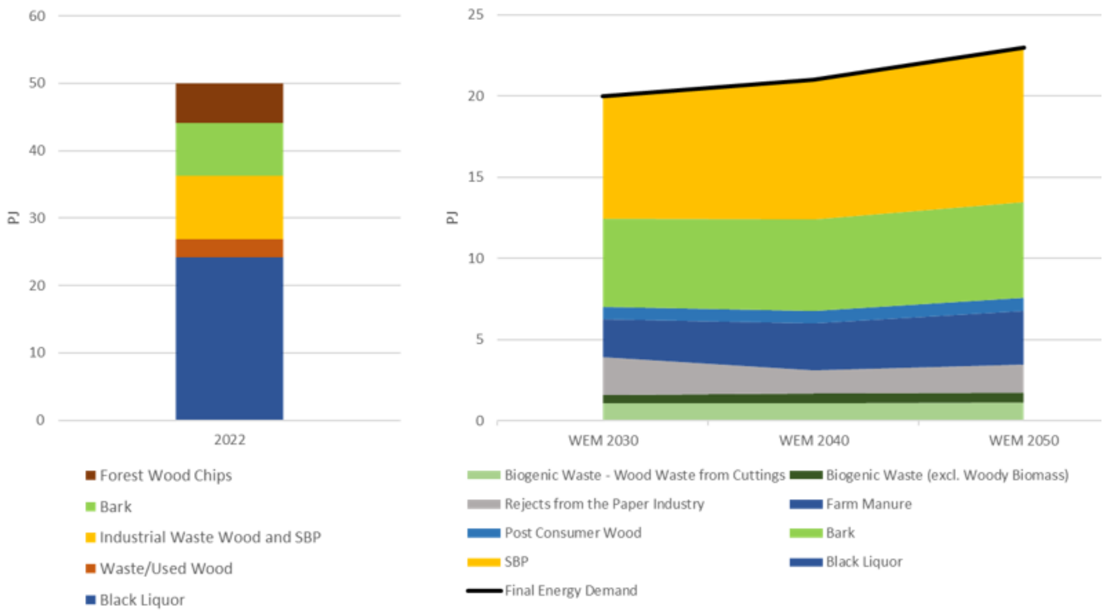


(a) (b)

Figure 19. Primary energy demand coverage (Figure 19a) and projected final energy demand coverage (Figure 19b) for the high temperature industry sector

Electricity Generation

For the electricity generation sector, data broken down into different biomasses was available for the status quo. In 2022 this sector was covered by forest wood chips, bark, industrial waste wood and sawmill by-products (SBP) as well as waste wood and black liquor, (Figure 20a). In Figure 20b the coverage up to 2050 can be seen, consisting to large parts of SBP, bark, black liqueur and farm manure. Some minor quantities are provided by biogenic waste. Note, that up to 2050 all electricity is generated in CHP plants.

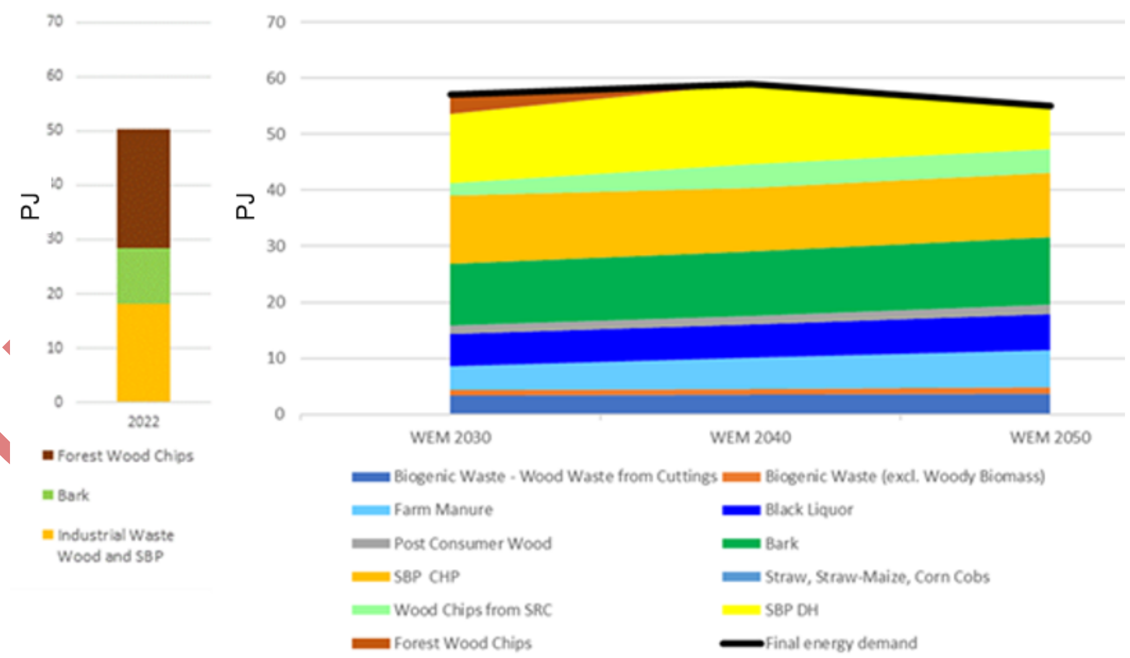


(a) (b)

Figure 20. Primary energy demand coverage in 2022 (Figure 20a) and projected electricity generation up to 2050 (Figure 20b)

District heating

Currently the district heat sector is covered by forest wood chips, bark, industrial waste wood and SBP. Our analysis concludes that in future it can be covered using the useful heat from the CHP plants used for electricity generation as well as SBP, wood chips from SRC and forest Wood Chips (Figure 21).

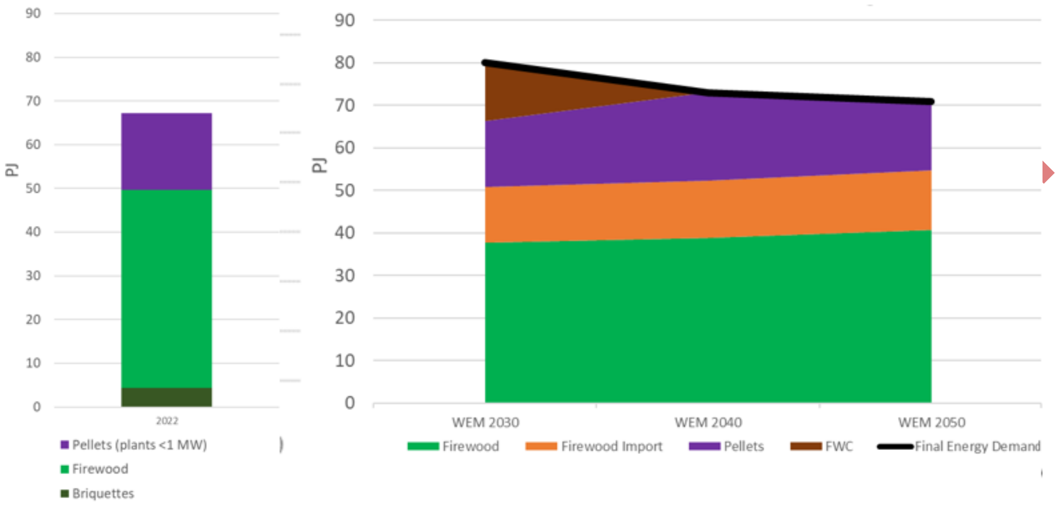


(a) (b)

Figure 21. Coverage of final energy demand by biomass 2022 (Figure 21a) and projected biomass demand for the district heat sector (Figure 21b)

Buildings

The residential heat in the buildings sector is currently covered by briquettes, pellets as well as firewood. In the analysis, this sector is made up of the sectors residential, services and agriculture. While it cannot be covered in 2030 and 2040, it comes very close to full coverage in 2050 using firewood, regional firewood imports, pellets and FWC (Figure 22). The data for firewood considers a scenario with increasing material use of firewood which is the reason for its decline in the graph.

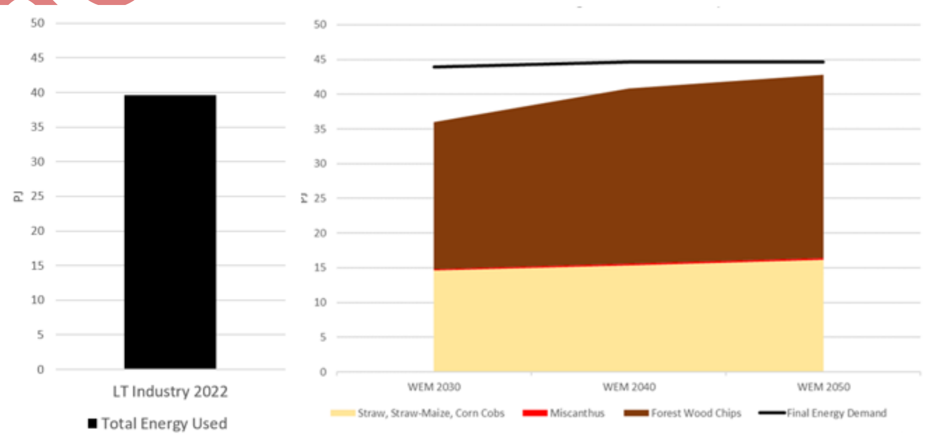


(a) (b)

Figure 21. Building sector: Final biomass energy demand Coverage in 2022 (Figure 21a) and projected energy demand coverage up to 2050 (Figure 21b)

Low Temperature Industry

For the Low Temperature (LT) industry, no broken down status quo data was available either [34]. This is the other sector where the analysis concluded that there is not enough biomass available to fully cover the projected demand. Yet, it has to be stated that by 2050 supply from biomass comes quite close to demand. Biomass energy demand in the LT industry is mainly covered by Straw, Straw-Maize, Corn Cobs, Forest Wood Chips and a very small share of Miscanthus (Figure 18). However, other alternative renewable energy sources could cover the rest of this area (e.g. solar thermal energy, heat pumps).



(a) (b)

Figure 22. Low temperature industry sector: Final biomass energy demand coverage in 2022 (Figure 22a) and projected FE demand coverage up to 2050 (Figure 22b)

Transport

Regarding the use of biomass in the transport sector, the demand for biofuels decreases from 20 PJ in 2021 to 10 PJ in 2050. Because the first generation biofuels currently used in road transport are expected to be phasing out (mainly due to EU policies) until 2050 the reminder will have to be covered largely by FT-Diesel (and maybe some quantities of other sustainable aviation fuels (SAF) fuels for use in airplanes). From our analysis it is concluded that it will not be possible to fully cover this quantity from the biomass sources considered in this analysis. However, how the future of SAF will look like cannot be appraised seriously today.

Total Energy Demand and Total Supply Potential

The final results of this analysis are documented in Fig. 23. This figure compares the Total primary and final biomass energy demand and total biomass supply potential in scenarios by 2030 and 2050. As seen from this Figure by 2030 for final energy supply from biomass is remarkable lower than the predicted demand. A major quantitative finding is that up to 2050 a total quantity of about 250 PJ of sustainable primary bioenergy sources will available while the expected demand in the chosen scenario will be about 255 PJ. Because of the assumed improvements in energy conversion efficiency and slightly increasing potentials (in total from 239 PJ by 2030 to 251 PJ in 2050) the final differences in 2050 are much smaller. Only around 3% to 4% biomass energy less than demanded can be provided by supply in Austria. The rest would have to be covered by imports or substituted by other renewable energy carriers.

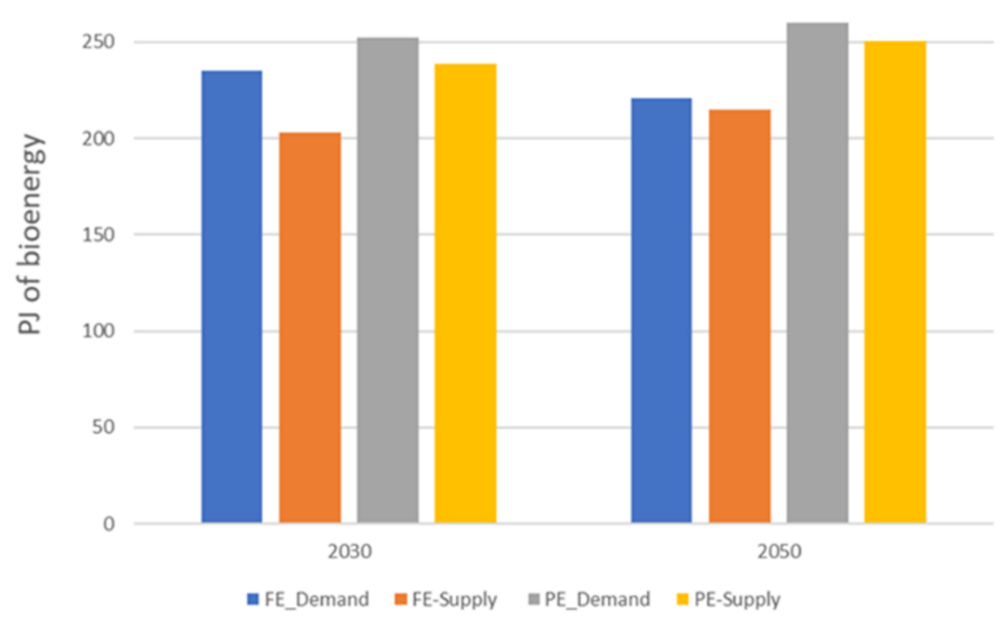


Figure 23. Total primary and final biomass energy demand as well as total sustainable biomass supply potential in scenarios by 2030 and up to 2050

CONCLUSIONS AND OUTLOOK

The major conclusions of these analyses are:

Under current and projected conditions up to 2050, biomass use for energy supply remains most cost-effective in individual heating systems and district heating networks. Heat applications continue to dominate economically due to relatively low production costs, while electricity generation, synthetic natural gas (SNG), and Fischer–Tropsch (FT) fuels remain more expensive, with longer conversion chains requiring high investment and energy input costs. Post-consumer wood, sawmill by-products, and bark are the most cost-efficient feedstocks for advanced applications, although broader economic viability depends on CO_2 pricing and fossil fuel cost trajectories. From a bottom-up perspective, heating applications are expected to remain the most widely deployed uses of biomass, with forest wood chips continuing to dominate district heating. Remaining biomass resources will be competitively allocated to sectors where use is already economically feasible, including new district heating networks, residential boilers, and low-temperature industrial processes. Societal considerations favor directing biomass to high-temperature industrial processes and other sectors with limited alternatives, maximizing its contribution to carbon neutrality and overall sustainability.

In electricity generation, combined heat and power systems using wood chips remain competitive, particularly during winter months, and are essential for achieving a 100% renewable electricity supply. Electricity generation without simultaneous heat utilization should be minimized and reserved for exceptional circumstances. In the transport sector, first-generation biofuels decline in relevance by 2040, emphasizing the need for second-generation biofuels and alternative renewable fuels.

High investment costs remain a barrier for innovative biomass pathways such as BioSNG and FT products, which will likely rely on low-cost residues rather than conventional wood chips. Overcoming these economic challenges is critical to enable broader deployment and fully exploit the potential of advanced biomass applications, particularly under high CO_2 price scenarios that enhance competitiveness relative to fossil alternatives.

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REFERENCES

1. Kraxner, F., Nordström, E.M., Havlík, P., M. Gusti,A. Mosnier,S. Frank, H. Valin,S. Fritz, S. Fuss, G. Kindermann, I. McCallum, N. Khabarov, H. Böttcher, L. See, K Aoki, Schmid E., Máthé L., Obersteiner M., Global bioenergy scenarios – Future forest development, land-use implications, and trade-offs. *Biomass & Bioenergy,* 57, 86-96, 2013. DOI: 10.1016/j.biombioe.2013.02.003
2. Havlík P., A.U. Schneider, E. Schmid, H. Böttcher, St. Fritz, R. Skalský, K. Aoki, St. de Cara, G. Kindermann, F. Kraxner, S. Leduc, I. McCallum, A. Mosnier, T. Sauer, and M. Obersteiner M., Global land-use implications of first and second generation biofuel targets. *Energy Policy,* 39(10), 5690-5702, 2011. DOI: 10.1016/j.enpol.2010.03.030
3. Bentsen, N.S., Jack, M.W., Felby, C., Thorsen, B.J., Allocation of biomass resources for minimising energy system greenhouse gas emissions, Energy, 69, 2014. https://doi.org/10.1016/j.energy.2014.03.045.
4. European Environmental Agency: How much bioenergy can Europe use without harming the environment, EEA-Report 7/2006.

5. Millinger, M., Hedenus, F., Zeyen, E., Neumann, F., Reichenberg, F., Berndes G., Diversity of biomass usage pathways to achieve emissions targets in the European energy system. Nature Energy 10, 226–242, 2025. https://doi.org/10.1038/s41560-024-01693-6
6. Kalt G., Kranzl, L., Haas R., Long-term strategies for an efficient use of domestic biomass resources in Austria. *Biomass and bioenergy,* 34, 449 – 466, 2010.
7. McCormick Kes, Kaberger Tomas: Key barriers for bioenergy in Europe: Economic conditions, know-how and institutional capacity, and supply chain coordination, *Biomass and bioenergy* , 31, 443-452, 2007.
8. Lim, C. H., Lam, H. L., "Biomass supply chain optimisation via novel Biomass Element Life Cycle Analysis (BELCA)," *Applied Energy,* Vol. 161(C), 733-745, 2016.
9. Pimentel, J., Eder, M., Maier, St., Bertok, B., Filep, B., Narodoslawsky, M., Optimization-based decision workflow for designing regional renewable energy systems, *Energy,* Elsevier, Vol. 358(C), 2026.
10. Knapek, J., Kralik, T., Valentova, M., Vorisek, T., Effectiveness of biomass for energy purposes: a fuel cycle approach. *WIREs Energy and Environment,* 4(6), 575-586, 2015. https://doi.org/10.1002/wene.164.
11. Ajanovic, A., Haas, R., Economic challenges for the future relevance of biofuels in transport in EU countries. *Energy*, (35), 3340–3348. 2010.
12. Gustavsson, L., Holmberg, J., Dornburg, V., Sathre, R., Eggers, T., Mahapatram, K.,, Marland, G., (2007). Using biomass for climate change mitigation and oil use reduction. *Energy Policy.* 35. 5671-5691, 2007. 10.1016/j.enpol.2007.05.023.
13. Ajanovic, A., Haas, R., Economic prospects of advanced biomass-based energy carriers in EU-15 up to 2050. *Int. J. of Environment and Sustainable Development*, 13, 93 – 108, 2014. 10.1504/IJESD.2014.056414.
14. Scarlat, N., Dallemand J. F., Monforti-Ferrario, F., Banja, M., Motola V., Renewable energy policy framework and bioenergy contribution in the European union – an overview from national renewable energy action plans and progress reports. *Renewable and Sustainable Energy Reviews Renewable and Sustainable Energy Reviews,* 51, 969–85, 2015.
15. Potrč, S., Čuček, L., Martin, Z Kravanja : Sustainable renewable energy supply networks optimization–The gradual transition to a renewable energy system within the European Union by 2050, *Renewable and Sustainable Energy Reviews,* 146, 111186, 2021.
16. Frank, S., H. Böttcher, P. Havlík, H. Valin, A. Mosnier, M. Obersteiner, E. Schmid, and B. Elbersen, B., How effective are the sustainability criteria accompanying the EU 2020 biofuel targets? *Global Change Biology - Bioenergy,* 5(3), 306-314, 2013. DOI: 10.1111/j.1757-1707.2012.01188.x
17. Haas, R., Kranzl L.: Bioenergie und Gesamtwirtschaft Analyse der volkswirt-schaftlichen Bedeutung der energetischen Nutzung von Biomasse für Heizzwecke und Entwicklung von effizienten Förderstrategien für Österreich, Wien. BMVIT 2003.
18. Ajanovic, A. , Haas R., CO_2-reduction potentials and costs of biomass-based alternative energy carriers in Austria, *Energy,* Volume 69, 120–131, 2014.
19. Ajanovic, A., Haas R., Beermann, M., Jungmeier, G., Zeiss, Ch., Perspectives for Alternative Energy Carriers in Austria up to 2050, Vienna 2012.
20. Kalt, G., Baumann M., Lauk Ch., Kastner T., Kranz L., Schipfer F., Lexer M., Rammer, W., Schaumberger A., Schriefl E., Transformation scenarios towards a low-carbon bioeconomy in Austria, *Energy Strategy Reviews,* Volumes 13–14, November 2016, Pages 125-133
21. Anca-Couce A., C. Hochenauer, R. Scharler: Bioenergy technologies, uses, market and future trends with Austria as a case study, *Renewable and Sustainable Energy Reviews* 135 (2021); https://doi.org/10.1016/j.rser.2020.110237
22. Kraussler, M., Pontzen, F., Müller-Hagedorn, M., Nenning, L., Luisser, M., Hofbauer, H., Techno-economic assessment of biomass-based natural gas substitutes against the background of the EU 2018 renewable energy directive. *Biomass Conversion and Biorefinery* 8: 935–944, (2018).

23. Schmidt, J, Schönhart, M., Biberacher, M., Guggenberger, T., Hausl, S., Kalt, G., Leduc, S., Schardinger, I., Schmid, E., Regional energy autarky: Potentials, costs and consequences for an Austrian region, *Energy Policy, 47*, 211-221, 2012.
24. Maier, St., Szerencsits M., Narodoslawsky M., Ismail I. M. I., Shahzad K., Current potential of more sustainable biomass production using eco-efficient farming practices in Austria. *Journal of Cleaner Production,* Vol. 155, 23-27, 2017.
25. Stürmer, B., J. Schmidt, E. Schmid, and F. Sinabell Implications of agricultural bioenergy crop production in a land constrained economy – the example of Austria. *Land Use Policy,* 30, 570-581. DOI: 10.1016/j.landusepol.2012.04.020, (2013).
26. Fuhrmann, M., C. Dißauer, C. Strasser, and Schmid, E., An econometric analysis of the sawmill by-product market to explore bioeconomy options in Austria, *Biomass and Bioenergy,* 180, 2024. 107007. DOI: 10.1016/j.biombioe.2023.107007.
27. Kristöfel, C., Strasser, C., Schmid E., Morawetz, U. B., The wood pellet market in Austria: A structural market model analysis. *Energy Policy,* 88, 402-412, 2016. DOI: 10.1016/j.enpol.2015.10.039
28. Kristöfel, C., Strasser C., Morawetz, U.B., Schmidt, J., Schmid, E., Analysis of woody biomass commodity price volatility in Austria. *Biomass and Bioenergy,* 65, 112-124, 2014. DOI: 10.1016/j.biombioe.2014.03.010
29. Dokl, M., Kravanja, Z., Čuček, L., Optimization of the Biomass Supply Chain for Power Generation with the Steam Rankine Cycle, *Computer Aided Chemical Engineering,* Vol. 52, 979-984, 2023.
30. Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E., Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies, *Applied Energy,* 87, 2128-2141, 2010.
31. Sameti, M., Dominguez, C G., Panduru, K., Gaffey, J., Machine learning-enhanced biomass forecasting for spatial bioenergy planning under uncertainty, *Energy Conversion and Management*, Vol. 31, 2026, https://doi.org/10.1016 /j.ecmx.2026.102034
32. Statistics Austria, Gesamtenergiebilanz Österreich 2024 (Wien 2025)
33. Fuhrmann, M., Dißauer Ch., Strasser Ch., CO_2-factors of different biomass conversion chains for various biomass resources (Mimeo) 2025.
34. EEX: EU ETS Spot, Futures & Options, 2026, https://www.eex.com/en/markets/environmental-markets/eu-ets-spot-futures-options.
35. Jandl, R., Hager, H., Kraxner F., Ledermann T, Weiss P., Carbon dioxide neutrality of sustainably managed forests of Austria, *Ecological Engineering,* Volume 209, 107417, 2024, https://doi.org/10.1016/j.ecoleng.2024.107417.
36. UBA: Energie- und Treibhausgas-Szenarien, Wien 2023.
37. Statistics Austria, Nutzenergieanalyse (NEA) 2022, Wien 2023.
38. Hofbauer H., Reallabor zur Herstellung von Holzdiesel und Holzgas aus Biomasse und biogenen Reststoffen für die Land- und Forstwirtschaft, TU Wien, Wien 2020.
39. Schmid J., C., Florian Benedikt F., Fuchs J., Mauerhofer A., M., Stefan Müller St., Hofbauer H., Syngas for biorefineries from thermochemical gasification of lignocellulosic fuels and residues—5 years' experience with an advanced dual fluidized bed gasifier design, *Biomass Conversion and Biorefinery*, 11, pages 2405–2442 (2021)

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ANNEX A: Input parameter for the energy cost calculations

Table A-1. Input parameter for the total cost calculation of biomass end uses and products

	Efficiency η	Fullload-hours (h/yr)	Investment costs (€/kW)	O&M costs (€/(kW.yr))
Heat boiler	80%	3000	700	15
District heat	88%	3500	800	11
Process heat	87%	5000	1000	14
Electricity	34%	4500	4800	54
Electricity CHP	85%	2000	3200	46
SNG-production	60%	7000	4200	61
SNG --> Electricity	34%	4500	7400	105
SNG --> Electricity CHP	51%	2000	9000	95
SNG --> Process heat	51%	5000	5200	70
FT-Diesel production	51%	7500	4100	67

Table A-2. Input parameter for the calculation of the total costs of end uses from natural gas

	Efficiency η	Fullload-hours (h/yr)	Investment costs (€/kW)	O&M costs (€/(kW.yr))
Heat boiler	82%	3000	630	4
District heat	89%	3500	720	8
Process heat	89%	5000	900	14
Electricity	55%	4500	1900	23
Electricity CHP	87%	2000	1600	27

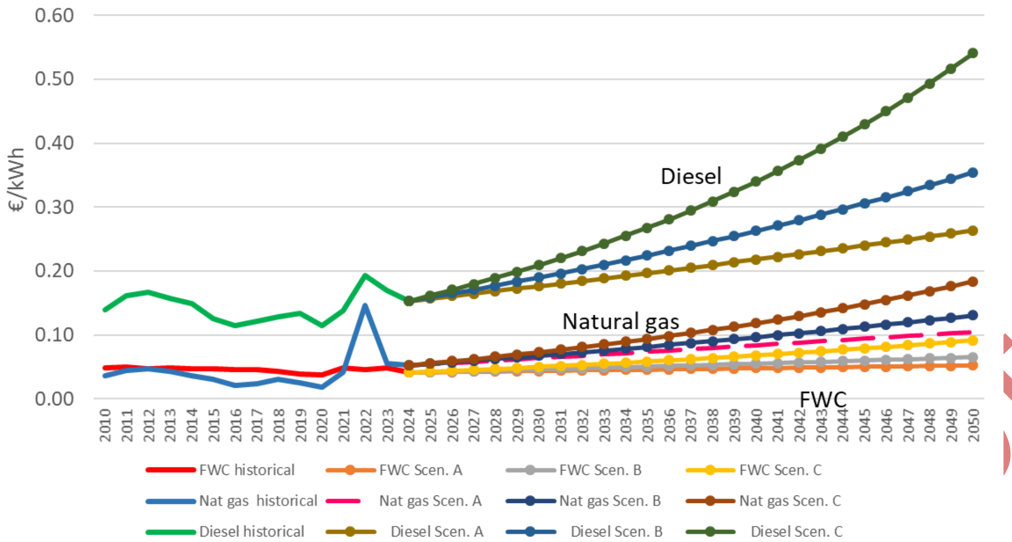

Figure A-1. Historical prices and scenarios of price development for forest wood chips (FWC), Natural gas and Diesel (Scenario **low** CO_2 price) up to 20250 (low, medium and high price scenarios) including taxes *)

*) Note, that for diesel the Austrian excise tax is also included

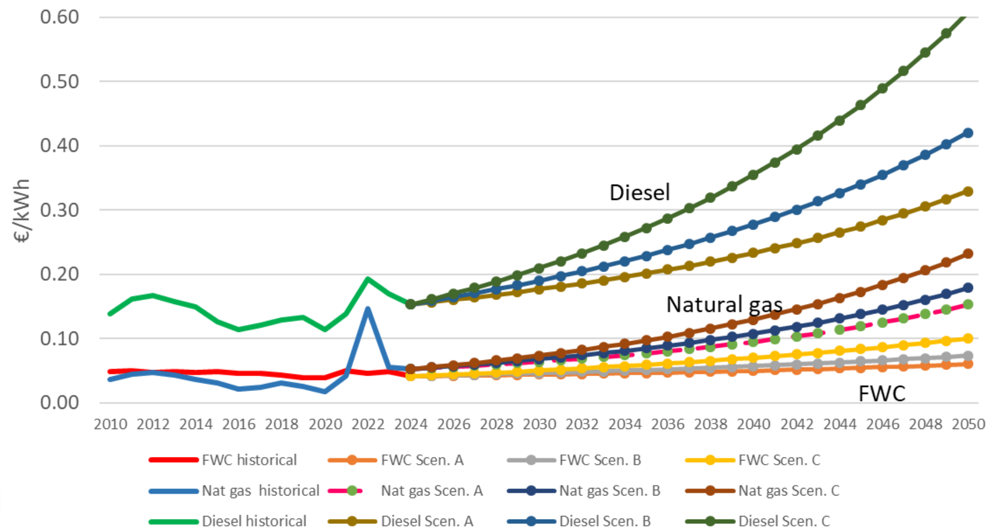

Figure A-2. Historical prices and scenarios of price development for forest wood chips (FWC), Natural gas and Diesel (Scenario **high** CO_2 price) up to 2050 (low, medium and high price scenarios) including taxes *)

*) Note, that for diesel the Austrian excise tax is also included

ANNEX B: Major historical and scenario data for final energy demand from the WEM – scenario (UBA 2023 [36])

Table B-1. Final energy demand Austria: Historical and future data from the WEM – scenario by sector up to 2050 (UBA 2023 [36])

Sector	Historical 2021	WEM 2030	WEM 2040	WEM 2050
Buildings	84	72	67	63
Electricity generation	16	20	21	23
Industry	51	61	62	62
Agriculture	7	7	7	8
Transport	20	17	12	10
District heat	48	57	59	55
Total biomass	**226**	**234**	**228**	**221**
Total final energy	**1123**	**1134**	**1079**	**1065**

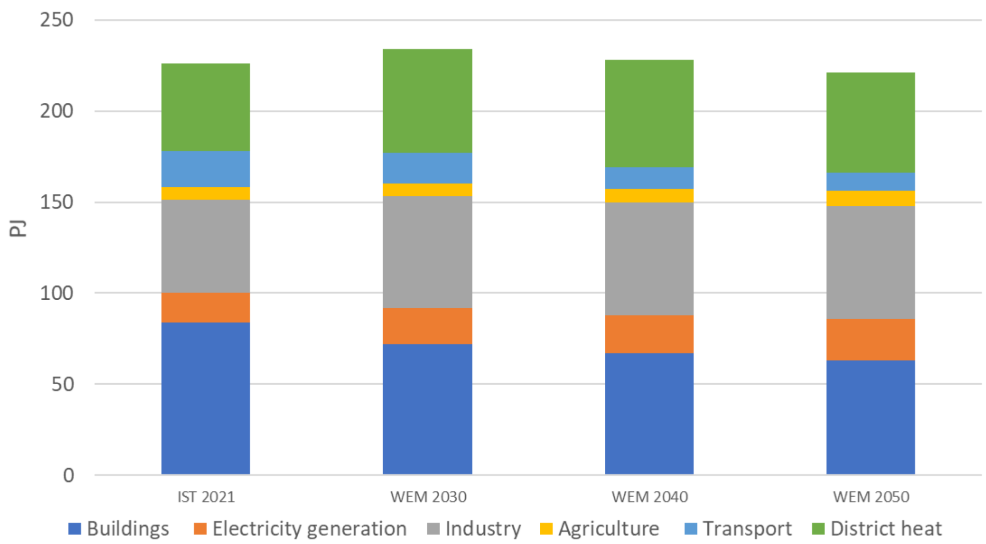

Figure B-1. Historical and scenario data from the WEM – scenario by sector up to 2050 (UBA 2023 [36])