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ENERGY UTILIZATION OF AGGLOMERATED LOGGING RESIDUES

Kraków 2026

Project supported by
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Contents

FROM THE AUTHORS

Both globally and regionally, forestry faces key challenges: the energy crisis and climate change. The rational use of wood raw materials addresses both of these issues. High-quality wood should be marketed as a long-lived resource due to its CO_2 storage properties. Wood of lower quality can be a valuable addition to the energy mix.

Forest woody biomass intended for energy comes primarily from logging residues, i.e., branches, treetops, stumps, and other woody debris. These raw materials are used to produce woodchips, pellets, and briquettes. The volume of logging residue harvested is, for obvious reasons, correlated with the overall level of timber harvesting, which is gradually increasing in all European countries. Timber harvesting depends on current forest management needs. Still, it also stems from the need to address damage to stands resulting from abiotic and biotic factors, wind impacts, harmful insect infestations, disruptions to water conditions, air pollution, and weather anomalies. These factors tend to increase, so the volume of logging residue harvested can periodically increase significantly. Removing excess logging residue facilitates soil preparation for planting using technical means at the machine level and reduces fire risk. Complete removal of woody residues and organic matter from the forest is not always desirable. Some wood is deliberately left in the forest ecosystem for ecological reasons, as it plays a vital role in soil processes.

The direct use of logging residues for producing energy carriers is associated with many limitations and difficulties, which can be eliminated through torrefaction. The main reasons for considering this process are: (1) increased calorific value and energy density; torrefaction removes moisture and volatile substances, thereby increasing the carbon concentration in the final product; (2) improved physical properties; torrefaction-treated biomass is less fibrous, which facilitates further fragmentation; (3) increased hydrophobicity; torrefied residues do not absorb moisture from the air, which solves the problem of their storage and prevents rotting, mold, and decomposition; (4) easier transport and storage; due to higher energy density and water resistance, more energy can be transported in the same volume; (5) reduced emissions; reduction of sulfur dioxide, nitrogen oxides, and other pollutants; (6) reduced fire risk; Torrefaction removes volatile substances that are more easily ignited, making the finished product safer to store and use.

In the V4 countries (Visegrad Group – Poland, Czech Republic, Slovakia, Hungary), energy production is conducted on similar principles, primarily using hard coal, and European Union requirements require a gradual reduction in its use. We are committed to seeking alternative energy sources. Forest biomass can undoubtedly be a significant supplement to the overall balance of energy obtained from renewable sources.

Logging residues are a byproduct of the timber harvesting process. In addition to pure wood, they contain a significant amount of bark, pine needles, forest litter, mineral impurities, and other contaminants. In contrast, post-disaster wood consists primarily of trees broken by wind and wood infested by secondary pests that do not meet quality and dimensional standards. It is also important to note that logging residues are a product that must be managed appropriately and should not be left entirely on forest surfaces. Currently, their use is limited.

In the future, biomass products obtained from forest logging residue will likely become more critical. Using logging residues and post-disaster wood, their torrefaction and pressure agglomeration of torrefied material may contribute to the development and broader use of renewable energy sources in the V4 region.

This monograph is the result of collaboration between international research teams from the Warsaw University of Life Sciences (Poland), the University of Agriculture in Krakow (Poland), the Czech University of Life Sciences Prague (Czech Republic), the Technical University in Zvolen (Slovakia), and the University of Sopron (Hungary). It was developed as part of the project "Logging Residue Torrefaction and Pressure Agglomeration as a Method to Conserve Fossil Fuels," conducted from October 1, 2024, to March 31, 2026. The project is co-financed by the Governments of the Czech Republic, Hungary, Poland, and Slovakia through Visegrad Grants from the International Visegrad Fund. The fund's mission is to advance ideas for sustainable regional cooperation in Central Europe. The overarching theme of the monograph is renewable energy sources, encompassing the use of plant biomass, including forest logging residues for solid fuels production. This biomass was analyzed for its potential for torrefaction and subsequent pressure agglomeration into pellets.

The monograph is intended for academics, producers of solid fuels in the form of pellets or briquettes, representatives of state and private forests, and employees of public administration bodies involved in environmental protection and use of renewable energy sources. The monograph can also serve as inspiration for manufacturers of biomass combustion plants and practitioners in the ever-expanding renewable energy industry.

Authors

INTRODUCTIONS

In December 2015, the European Commission published the communication „Closing the loop - An EU action plan for the Circular Economy” (European Commission, 2015), which proposes actions in EU countries aimed at changing the economic development model..

These actions are focused on several priority areas, including plastics, food waste, critical raw materials, demolition and construction waste, biomass and biomass-based products. The communication emphasizes the role of innovation and transformation towards Circular Economy (CE).

CE is associated with the management of renewable resources throughout their entire life cycle, in this case, biomass management. It includes processing, production of goods, their sale, use of goods, and bio-waste management. This is consistent with the assumptions of the „A zero waste for Europe” program (European Commission, 2014), which emphasizes that the EU will „*…encourage the cascading principle in the sustainable use of biomass, taking into account all biomass using sectors so that biomass can be utilised in a most resource efficient way…*”.

The obligation to support the development of renewable energy sources also stems from EU directives, including Directive 2001/77/EC (European Commission, 2009; European Union, 2001) on the promotion of electricity from renewable energy sources in the internal electricity market. Pursuant to the Directive, Member States are required to take appropriate measures to increase the consumption of electricity and heat from renewable energy sources in line with national indicative targets.

The bioeconomy supports agriculture, forestry and fisheries, as well as many other sectors of the economy, including the forestry and timber industry, pulp and paper, furniture, construction, and organic recycling.

One of the primary sources of biomass is agricultural production, which is primarily used for food, then industrial and finally energy purposes. Another major source of biomass is forestry, which includes timber production but also serves to natural and recreational functions, contributes to air, water and soil protection, and provides biomass for energy use.

The chemical composition, quantity and properties of biomass make it suitable for use in biochemical, chemical, and thermochemical processes, for the creation of bioproducts and biomaterials, and for direct conversion into biofuels through gasification and pyrolysis processes, pressure agglomeration, and solid fuel production. This enables the creation of local value chains in industry and energy sector.

Adopted by the European Parliament and the European Council „Going climate-neutral by 2050” (European Commission, 2019) is consistent with the goals „Paris Agreement on climate change” (UNFCCC, 2016) and covers almost all areas of EU policy (Werle, 2021). These documents assume the maximum use of renewable energy sources (RES). There will be a need to increase the use of biomass in zero-emission economies, provided that its production comes from sustainable sources. This serves to ensure that forests and other ecosystems in the European Union that absorb emissions are not going to be degraded.

In countries V4, in the Energy and Climate Plans for 2021-2030, it was assumed that the share of energy from renewable sources in the power sector will be 31% in Poland (PL), 31.5% in the Czech Republic (CR), 32% in Slovakia (SK) and 29% in Hungary (HU). The share of solid biomass in the given amounts will be 11.5% (PL), 66.1% (CZ), 61% (SK) and 43% (HU), respectively (Bufka et al., 2022; European Commission, 2025; MKiŚ, 2019; MPO ČR, 2024; Roder, 2012; Scarlat et al., 2015).

The European Environment Agency (Scarlat et al., 2013) estimates that the available biomass potential in the European Union countries in 2020 (excluding Bulgaria and Romania) was 9,839 PJ (forest biomass), 4,007 PJ (biomass of agricultural origin) and 4,181 PJ (other waste biomass). Slightly different estimates were given by Ruiz et al. (Ruiz et al., 2019), stating that the biomass potential to meet the stringent requirements of the Paris Agreement is 8,344 PJ. In other hand, other works have estimated (Elbersen et al., 2012), that this potential is much higher and amounts rise to total of 15,686 PJ, of which 7,006 PJ is forest biomass, 6,604 PJ is agricultural biomass, and 2,076 PJ is other waste biomass. Of course, we have to not forget about the sources of biomass that reach Europe from outside the EU (Hoefnagels et al., 2014). For example, in 2010, wood pellets were shipped to Europe from Canada, the southeastern region of the USA and northwestern Russia (Goh et al., 2013). Although demand from Asian countries such as South Korea and Japan is growing, countries currently focused on biomass exports to Europe are expected to continue this trend (Roder, 2012; Scarlat et al., 2013). In addition, there is large influence of exports from South American countries (Brazil and Uruguay) and Africa (mainly Mozambique), where large cellulose plantations operate (Schut et al., 2010; Valenzuela, 2015).

One of the potential treatments of woody biomass that improves its usability in energy production is torrefaction – i.e. controlled carbonization in the temperature range from 200 to 350°C in non-oxidizing atmosphere (van der Stelt et al., 2011). This process reduces the moisture content of the biomass, sterilizes it and increases its energy density (Chen et al., 2015). Wood is transformed into a product with parameters comparable to coal, which leads to improved ability to replace solid fossil fuels (Jha et al., 2022; Kambo and Dutta, 2015; Phanphanich and Mani, 2011; Tumuluru et al., 2011; Weber and Quicker, 2018). To enable the use of energy biomass, there is necessity to minimize the need to invest in the conversion of existing combustion plants and also enable the financing of necessary investments through savings in carbon credits set in the European Union's emissions trading system (Schipfer and Kranzl, 2019; Starfelt et al., 2015).

1. FOREST BIOMASS AND ITS USE IN THE V4 COUNTRIES

1.1. Forest biomass

1.1.1. Slovakia

Within the framework of the forestry economy (FE) of the Slovak Republic (SR), financial and economic data and achieved results of the entire FE SR sector were processed (Table 1.1.), i.e. for forest managers and business sector operating in the Forest Management Agency of the Slovak Republic. Sales and revenues reached 1,287.9 million €. Compared to 2022, there was increase by 8.3%. Taxes in the amount of 93.35 million € were paid to state and municipal budgets (€12.7 million less year-on-year).

Social and health contributions amounted to 96.97 million € in 2023 (€11.53 million more year-on-year). Costs reached €1,162.05 million. The economic result of the Forest Management Agency of the Slovak Republic was €68.15 million, which was €27.25 million less year-on-year (Moravčík, 2024).

Table 1.1. Summary of the most important Forestry indicators for the years 2010 – 2023 (NFC, 2025)

Indicator	Unit of measurement	Year					
		2010	2015	2017	2020	2022	2023
Economic result	Thousand €	22 100	51 630	48 800	25 510	95 400	68 150
Support from public sources		40 136	55 413	51 546	39 442	21 959	24 166
Direct costs of cultivation activities		43 898	56 484	57 728	41 936	53 483	54 669
Wood harvesting, in Total	Thousand m^3	9 860	9 142	9 393	7 510	7 687	7 514
Wood supplies, in Total		9 599	8 995	9 361	7 448	7 436	7 101
Average timber monetization	$€ \cdot m^{-3}$	39.40	47.03	47.09	44.68	74.23	74.57
Forest area	Thousand ha	2 011	2 015	2 019	2 025	2 028	2 028

According to the Summary Information on the State of Forests (SISF), the area of forest land in the Slovak Republic in 2023 reached 2.028 million ha, of which 1.955 million ha was forest land (forest stands). Forest cover calculated from the area of forest land is 41.4% of the total area of the Slovak Republic.

Since 1990 it has increased by 51.7 thousand ha, i.e. by 2.6%, or by 1.57 thousand ha on average per year. The area of forest land (forest land with forest stands) has also been increasing in long term period, which in 2023 according to SISF data reached 1,955,522 ha.

Since 1990 the area of forest stands has increased (mainly by changing type of land) by 33.8 thousand ha, i.e. by 1.76%, i.e. by 1,024 thousand ha on average per year.

The area of forest stands usable for timber production was 1,795.9 thousand ha. This group of forest stands does not include forests in protected areas with the 5th level of protection, in protective zones of water resources of the 1st level, in protective forests in extremely unfavorable locations and in stands with predominant presence of dwarf pine.

Forest cover, as a percentage of the area of forest land in the total area of the Slovak Republic (4.903 million ha including water areas), was 41.4% in 2023. It has increased by 1.1 percentage points since 1990 and by 2.3 percentage points since 1970. On fig. 1.1 is possible to observe constant increase in both forest cover and area of forest land and forest stands until 2023.

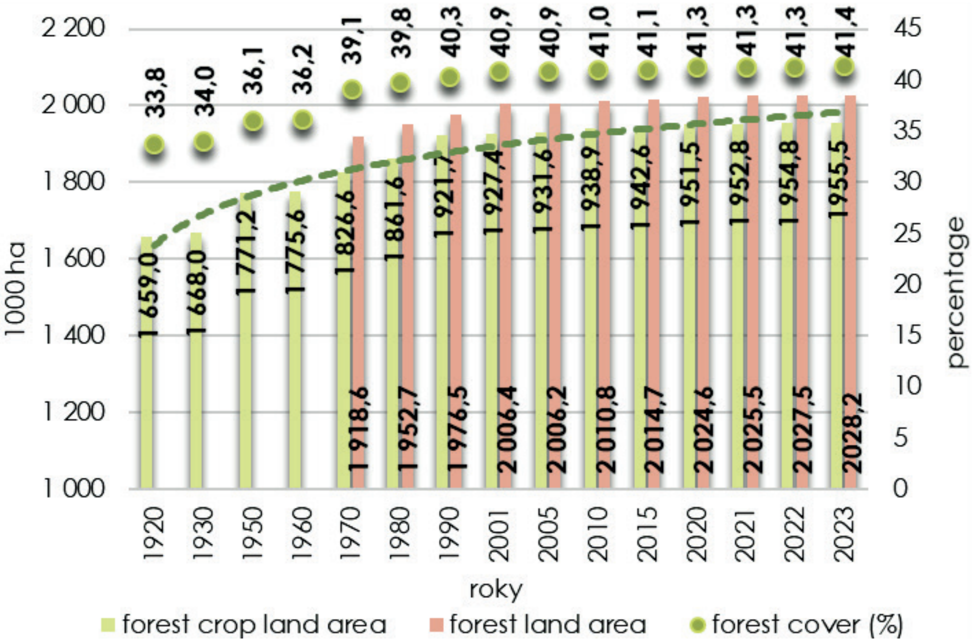


Figure 1.1. Forest land, area of forest stands (1,000 ha) and forest cover (%) (MARD, 2021)

In forest stands, deciduous trees predominate with representation of 64.8%. The representation of coniferous trees (35.2%) is decreasing due to the influence of harmful factors in forests, mainly on spruce. The highest representation among trees is beech (35.4%), spruce (21.1%), holm oak and sessile oak (10.3%) and pine (6.4%).

The current tree species composition of the forests of the Slovak Republic has been partially changed compared to the original tree species representation. The changes occurred during several centuries of forests human use, primarily in favor of more productive and economically desirable tree species (spruce, pine, larch), as well as the natural spread of some tree species (e.g. hornbeam, cer, acacia). The representation of tree species in restored forest stands is prescribed by the forest management program regarding specific site conditions and social requirements in accordance with the concept of functionally integrated forest management (FIFM).

The following tree species had the highest representation in the forests of the Slovak Republic in 2023: forest beech (35.4%), Norway spruce (21.1%) and summer and winter oaks (10.3%). The representation of coniferous trees (35.2%) has been decreasing for a long time due to the influence of harmful factors in forests (especially wind and bark beetles). Since 1980, when the representation of coniferous trees was the highest, it has decreased by 7.3 percentage points. The largest decrease was recorded by spruce, whose representation decreased by 5.1 percentage points. The representation of fir has decreased by 2.2 percentage points since 1970, with the largest decrease occurring in the years 1970–1990 mainly due to the harmful effects of immissions. Only the presence of larch has increased since 1980 in the coniferous species part. Among the deciduous species, the presence of European beech has increased the most since 1980, by 5.6 percentage points. The presence of oak has decreased by 1.3 percentage points.

In addition to the representation of individual tree species, the important indicator of forest species diversity and stability are also the representation of forest types and the number of tree species in forest stands. From this point of view, more stable deciduous (46.4%), predominantly deciduous (8.6%) and mixed forests (20.0%) prevail in the Slovak Republic, the total representation of which is 75.0% and is increasing annually. The representation of coniferous and predominantly coniferous forests is 25.0%. Since 2015, the representation of coniferous forests has decreased by 3.1 percentage points. According to the number of tree species, forest stands with three tree species (24.8%) are the most represented in the forests of the Slovak Republic, followed by two tree species (20.2%) and four tree species (19.6%). The trend of development of this indicator is favorable; Since 2015, the representation of forest stands with the number of tree species of 4 or more has increased by 2.6 percentage points. On fig. 1.2 is possible to see the representation of individual tree species in Slovakia in 2023.

According to SISF data from 2023, the total volume of wood stock on forest land in the Slovak Republic was 487.1 million m^3 of rough wood without bark (rough wood). Compared to 2022, it increased by 4.3 million m^3 (by 0.9%), almost to the level of 2021. The stock of deciduous wood increased to 295.1 million m^3, i.e. by 3.7 million m^3 compared to the previous year. The stock of coniferous wood reached 192.0 million m^3. The ratio of coniferous and deciduous wood stocks was 39.4% to 60.6%. The average stock of wood per hectare was 250 m^3 rough wood. For coniferous trees, it was 280 m^3 and for deciduous trees, 234 m^3.

The current culmination of the wood reserves volume (around 485 million m^3), which is currently observed, is manifestation of gradual change in the unbalanced age structure of forest stands in the Slovak Republic, associated with the shift of age stages that are above normal in terms of area and volume to the age at which their gradual renewal is carried out. The cause of the emergence of such unbalanced age structure was high timber harvesting and large area of logged forest in the first half of the last century, i.e. during the period of war conflicts and socio-economic crises. Forest stands were subsequently renewed on the logged areas, which are currently approximately 80 to 130 years old. They are located in age stages 9 to 13 that are above normal in terms of area, which are in other hands also the source of the current increased possibilities for timber harvesting. The development of such unbalanced age structure is associated with cyclical changes in the development of production-ecological indicators, including wood reserves. The cyclical development trend is confirmed by the long-term overview of the annual change in the volume of wood stocks in forest stands in the Slovak Republic according to the SISF shown in the figure 1.2.

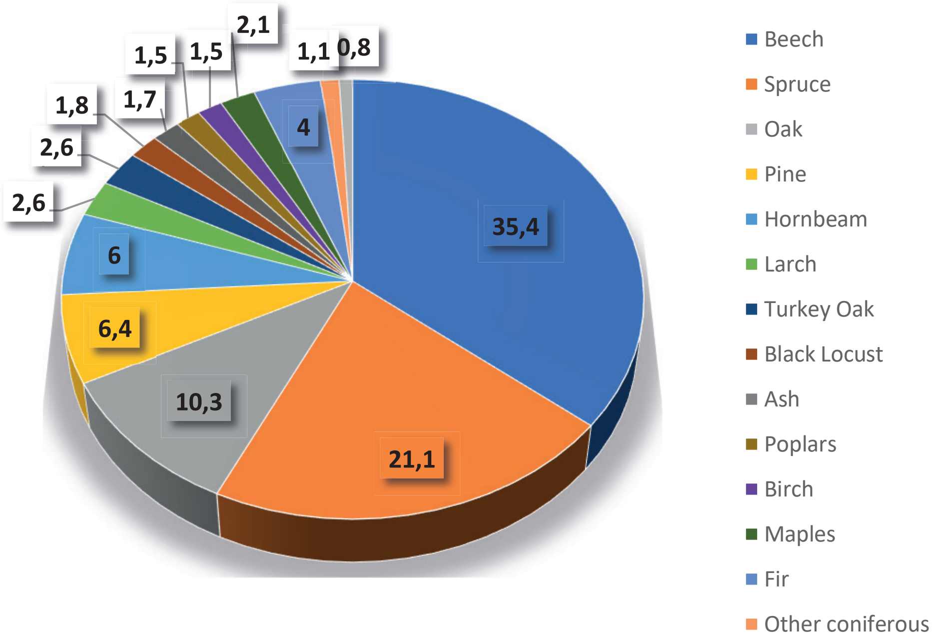


Figure 1.2. Percentage of conifers and broadleaves in forest stands of the SR in 2023 (%) (MARD, 2021)

According to LHE (Lesná hospodárska evidencia / Forest management records) data, there was carried out forest restoration on area of 10,059 ha in 2023, which was 1,178 ha, or 10.5% less than in 2022, but up to 36.7% less than in 2015. The decrease is mainly related to the continuing trend of reducing timber harvesting in the years 2020 to 2023. At the end of 2022, area of 1,935 ha remained for forest restoration, which arose mainly from timber harvesting, unsuccessful restoration and after natural disasters.

In forest restoration, artificial regeneration prevailed (6,307 ha) with share of 62.7%. Natural regeneration was recorded on area of 3,752 ha, or 37.3%, which corresponds to the trend observed over the past 15 to 20 years. The share of natural regeneration was higher in forests managed by state organizations (39.3%). In non-state forests it was 35.6%, of which the highest share was in private (55.7%), municipal forests (37.5%) and community forests (34.3%).

The increase in the share of natural forest regeneration results mainly from the orientation of the Slovak Forestry Administration towards close-to-nature management. Natural regeneration provides the potential for the composition and structure of forest stands to take into account the impacts of climate change and the provision of FIFM in the future. To restore ecological stability and due to changes in habitat conditions related to climate change, there will be necessary greater extent forest stand reconstructions. In connection with adjustment of the tree species composition, these reconstructions will largely rely on artificial forest regeneration and the quality of forest reproductive material used.

The preparation of soil and forest stands together for natural regeneration was carried out in 2023 on area of 6,328 ha, which was 1,154 ha less than in 2022. The volume of these activities was the lowest for the monitored period since 2012. According to the results of NIML 2, there is more natural regeneration in the forests of the Slovak Republic than results from the LHE data. This underestimation in records is related to the fact that natural regeneration occurs wherever there are suitable conditions for its occurrence, regardless of whether it is pre-log forest stands or stands ripe for forest regeneration. Sometimes it also occurs after artificial afforestation of logged areas. In the tree species composition of forest regeneration according to NIML 2, beech, hornbeam and valuable broadleaves prevail, and from conifers spruce, fir, pine and other conifers have consistently low representation. The above findings also correspond to the assessment of forest regeneration in the 1st age stage according to SISF, where we also observe the highest representation of beech (38.1%) and spruce (30.0%).

Logging is necessary to ensure supply of forest biomass (wood) for community/society needs, which is carried out either according to the PSL economic measures plan, as intentional logging, or when eliminating consequences of harmful factors in forests, as accidental logging. When removing forest land or deforestation of land for the purpose of building and facilities construction necessary for LH (Lesné hospodárstvo / Forests management), logging is recorded as extraordinary. When determining the amount and method of logging there is necessary to tako into account the provisions of generally legal regulations on professional forest management, on the principles of logging and on forest categorization.

Wood is an important raw material, an ecological, renewable, recyclable and strategic material of the future. Its rational use and processing supports industry and increases employment. In addition, by saving carbon in forests, in products from harvested wood and by using wood as a substitute for non-renewable raw materials and energy sources, the forestry and timber sector contributes significantly to mitigating climate change. Revenues from the sale of harvested wood are used to ensure comprehensive forest care, for their restoration, cultivation and protection, as well as for the construction, maintenance and reconstruction of the forest transport network, investments in mechanical and technological equipment and more.

7.223 million m^3 of wood was harvested in the Slovak Republic in 2023, which was 0.464 million m^3 less than last year. The actual timber harvest was 2.31 million m^3 lower than the planned harvest, determined on the basis of current harvesting possibilities and the urgency of forest regeneration. 53.3% of coniferous and 46.7% of deciduous wood was harvested. Of the total timber harvest, state forest organizations harvested 54.2% and non-state forest entities the remaining 45.8%. Of the above-mentioned timber harvest, 3.507 million m^3 (48.6%) was harvested in the process of eliminating the consequences of harmful factors in forests, of which 85.0% was coniferous and 15.0% was deciduous wood.

The state owned 793.0 thousand ha of forest land in 2023 according to the SISF, which represents 40.8% of the total area of forest land. State forest management organizations managed 989.3 thousand ha of forest land in this period. The remaining area of forest land was managed by non-state forest management entities. In the systems of protected areas (national, European and other international protected areas), there are forest lands with area of 1.16 million ha, which is 59.5% of the total area of forest land in the Slovak Republic.

Forests in the Slovak Republic are divided into three categories according to their predominant use: economic, protective and special purpose.

The most represented category is commercial forests (CFs). Its area in 2023 was 1,422.7 thousand ha, i.e. 72.8%. CFs are intended mainly for the production of wood and other forest products while ensuring the non-production functions of forests. Forestry measures are applied in them within the framework of the so-called functionally integrated forest management. The representation of CFs was higher in non-state forests 76.1%; in state forests it was 69.5%.

The area of protective forests (PFs) in 2023 reached 341.4 thousand ha, i.e. 17.5% of the area of forest stands in the Slovak Republic. The representation of PF in state forests was 17.2%, in non-state forests 17.7%. The functional focus of PF results from the given natural conditions. The main objective of management in PF is to ensure their protective functions, in particular the protection of soil, water and infrastructure. The area of PF is gradually increasing slightly, mainly due to the refinement of the identification of relevant habitats; since 2000 it has increased by 1.5%.

Special purpose forests (SPFs) are declared to meet the specific needs of society, legal entities or individuals. They apply special (functionally differentiated) management regime with the deliberate strengthening of one or more selected functions (services): nature protection, national defense, hunting, recreation, educational and research, protection of genetic resources, water protection, spa and medical treatment, etc., unless these requirements could be met by normal management. Currently, SPFs cover area of 191.4 thousand ha, which represents 9.8% of the forest stands area in the Slovak Republic. Their area decreased by 149.6 thousand ha, i.e. by 43.9%, compared to 2000 (341 thousand ha), mainly due to the deletion of the subcategory "forests affected by emissions" from the SPF category. The representation of SPFs in state forests was 13.3%, while in non-state forests it was lower (6.2%).

The total supplies of fuel wood biomass from LH were 1.3 million tons in 2023, and increased by 5 thousand tons compared to 2022. The trend of the decrease here continued approximately since 2015, when the volume of fuel wood biomass supplies was the highest (1.45 million tons). Supplies of fuel chips from LH are provided by private companies that have technological equipment for their production and transportation, or trading companies. Currently, approximately 48% of the usable potential of fuel wood biomass on forest lands is not used. This is wood unsuitable for mechanical and chemical processing, the occurrence of which is related to the high extent and frequency of disaster situations and subsequent accidental logging, mainly in coniferous (spruce) stands. This situation can increase the potential of deciduous wood (due to the postponement of its logging), the assortment structure of which includes higher share of fuel dendromass.

The above mentioned situation is not in line with the Integrated National Energy and Climate Plan for 2021-2030, which set the goal of increasing the share of renewable energy sources (RES) to 19.2% in 2030 compared to 16.9% in 2019. However, for the favorable condition of forest habitats, the preservation or increase of biodiversity, and for the purposes of mitigating the consequences of climate change, the presence of adequate volume of dead wood and hollow trees is desirable.

The production of sawn timber in the Slovak Republic in 2023 was approximately 1.37 million m^3 (softwood sawn timber 1.12 million m^3 and hardwood sawn timber less than 0.25 million m^3). Up to 63% from this number was exported from Slovakia, which is negative phenomenon, since it is production with lower added value and its processing into production with higher added value is carried out abroad. The largest processors of softwood sawn logs are: Rettenmeier Tatra Timber s.r.o.; PRP, s.r.o.; Amico Drevo, s.r.o.; Píla Rosík, s.r.o. Several medium-sized and small sawmills specialize in sawing lower-quality softwood sawn logs and the production of wooden pallets and packaging, e.g. DREVOPAL s.r.o; TURWOOD, s.r.o.

The largest processors of hardwood sawn logs are: Kronospan s.r.o.; Beky a.s.; LESAGRO s.r.o.; Arifex, spol. s.r.o. Characteristic feature of hardwood sawmills is their relatively narrow specialization in the production of specific products with varying degrees of added value depending on the wood species processed (oak barrel blanks, beech railway sleepers, poplar lumber, ash stumps, etc.).

There are several companies operating in the Slovak Republic that are focused on the production of glued composite and structural materials and the production of subsequently processed lumber with higher added value. The most important companies include: DOKA DREVO s.r.o.; MYWOOD Polomka Timber, s.r.o.; Rettenmeier Tatra Timber s.r.o.; Amico Drevo, s.r.o.; Slovlepex, a.s.; DREVOMAX s.r.o.

Veneer production in the Slovak Republic is approximately 21.2 thousand m^3 per year, and hardwood veneers predominate in production. 60 to 70% of veneer production is exported, but despite this, the trade balance is negative. This means that veneer imports are higher than veneer exports produced in the Slovak Republic. Together with the available raw material resources, this provides room for their higher production in the Slovak Republic. Plywood production in the Slovak Republic reached 100 thousand m^3 in 2023. Even after taking into account foreign trade, the majority of plywood production is processed in Slovakia. The largest veneer producers are: Dyha Tirola s.r.o.; Slovincom s.r.o.; Fibra spol. s.r.o.; DYHATECH s.r.o.; LESAGRO s.r.o.

Particleboard (DTD) was produced in the Slovak Republic in 2023 in volume of 741.5 thousand m^3. 538 thousand m^3 were exported in 2023. There is no production of OSB boards in the Slovak Republic. The trade balance, despite the import of the entire consumption of OSB boards, is highly surplus. The largest producers of DTD in the Slovak Republic are: IKEA INDUSTRY SLOVAKIA, s.r.o., o.z. Malacky Boards; Kronospan, s.r.o.

1.1.2. Poland

The Visegrad countries harvest average of 21 million m^3 of timber annually, which is similar to the average level of timber harvested in European Union countries (20 million m^3) (Forest Information System). Timber harvesting in Poland is lower compared to the Scandinavian countries (average 67.24 million m^3) or Germany (78.67 million m^3). It is arguably comparable to France (47.39 million m^3) or the Czech Republic (33,350 m^3) and significantly higher than in Slovakia (7.51 million m^3) and Hungary (6.67 million m^3).

Poland is leading European country in terms of forest area. Forests cover 9.294 million hectares, which is approximately 31% of the country's land area. Forest cover is 29.6% (DGLP, 2024; Główny Urząd Statystyczny, 2024). Forest area is growing every year, and it is expected that by 2050, forest cover will increase to 33%. The majority of stands are managed by the State Forests National Forest Holding (77%). Individuals own approximately 18.1% of stands, with the remaining 4.9% being national parks, municipal forests and others. The State Forests are therefore the primary timber producer in the Polish timber market. (DGLP, 2024).

The species structure is dominated by coniferous forests (68.7%), with pine, spruce, fir and larch. Foresters are moving away from monocultures and introducing an increasing number of deciduous species. Deciduous stands occupy 31.3% of the area. Oaks, ash, maple, sycamore, and elm are increasingly common, as are birches, beeches, alders, poplars, hornbeams, aspens, lindens and willows.

In the State Forests, over the last decade, the total timber harvest has averaged approximately 42 million m^3 per year, of which round timber accounts for approximately 40 million m^3 on average (Table 1.2). The volume of harvested nett merchantable timber per hectare of forest area increased over the last decade from 4.16 m$^3\cdot$ha^{-1} in 2015 to 4.60 m$^3\cdot$ha^{-1} in 2022 and 4.28 m$^3\cdot$ha^{-1} in 2023. The average value of this indicator during this period was 4.32 m$^3\cdot$ha^{-1}. The timber harvest in Poland amounted in 2023 to 41.66 million m^3, of which merchantable timber harvested amounted to 39.85 million m^3 (Główny Urząd Statystyczny, 2024). The volume of timber harvested is not only planned, but also incidental, resulting from the need to process damaged stands caused by abiotic and biotic factors, including wind, harmful insect infestations, water disturbances, air pollution and weather anomalies. The volume of timber harvested as part of forest health maintenance in 2023, resulting from the harvest of deadwood, broken trees and fallen trees, resulting from natural processes and impact of the factors mentioned above, amounted to 7.48 million m^3, which constituted approximately 19% of the total harvested merchantable timber (DGLP, 2024).

The most common species in Polish forests is Scots pine (*Pinus sylvestris* L.), accounting for 58.9%. It occurs most frequently on the poorest soils, which is reflected in the forest habitat type distribution. Among the broadleaf species, the most numerous are oaks (*Quercus sp.*) at 8%, common beech (*Fagus sylvatica* L.) at 6.4% and silver birch (*Betula pendula* Roth) at 6.7% (Główny Urząd Statystyczny, 2024).

The forest age structure is dominated by stands in age classes III (40-60 years) and IV (60-80 years), covering 20 and 22.8% of the area, respectively. Stands over 100 years old constitute 15.7% of the State Forests National Forest Holding and 5.3% of the private forests.

The average forest yield in Poland in the State Forests National Forest Holding is 291 m$^3\cdot$ha^{-1}, while in private forests it is 273 m$^3\cdot$ha^{-1}. Gross standing timber resources in 2023 amounted to 2,696 million m^3 of merchantable timber, of which 2,073 million m^3 are in the State Forests and 497 million m^3 are in private forests. Almost half (48.3%) of the timber resources are in age classes III and IV.

Table 1.2. Timber harvesting and forest area in 2015-2023 (DGLP, 2024; Główny Urząd Statystyczny, 2024)

Year	Total million m^3	Rubble million m^3	Rubble m^3·ha^{-1}	Forest area million ha
2015	40.25	38.33	4.16	9.21
2019	42.37	40.64	4.38	9.26
2020	39.67	38.06	4.11	9.26
2021	42.24	40.69	4.39	9.26
2022	44.65	42.70	4.60	9.27
2023	41.66	39.85	4.28	9.29

The most interesting parts of trees for energy reasons are the tops and branches less than 7 cm in diameter, as well as stumps. These fragments, according to Hakkil (Hakkila, 1991, 1989), constitute significant portion of the tree biomass, which in the case of pine is 24% and spruce 43%. In Poland, the share of logging residues in the total mass of harvested wood varies in the range of about 7 to 17% – on average, it is over 11%, and depends largely on the forest site type (Gałęzia, 2016). This share increases with habitat fertility. In LMśw (fresh mixed broadleved forest), it averages 13.3%, and in BMśw (fresh mixed coniferus forest), it averages 10.5%. The lowest values were found for Bśw (fresh coniferus forest) – approximately 7.9%. It can be assumed that the share of woody biomass, which forms logging residues, in the total woody biomass exceeds 15% (Gendek et al., 2018c). For the recently recorded harvest in Poland of approximately 42 million m^3, the volume of post-felling residue should be approximately 6.3 million m^3. The harvest of post-felling residue changes with the age of the stands, increasing especially in late thinning stands (60-70 years old) and in felling stands (Vares et al., 2005). In practice, the recovery of post-clearing residues is limited, mainly for ecological reasons. According to Zajączkowski's forecasts (Zajączkowski, 2013) harvest of this raw material will amount to approximately 2.04 million m^3 in the State Forests and 0.3 million m^3 in private forests in 2031. Based on the data contained in Table 1.2, based on the difference between total harvest and the harvest of merchantable timber, it can be estimated that the harvested amount of small-sized timber, including logging residue, is less than 2 million m^3 annually.

Estimating the amount of post-logging residue can be subject to significant error. The average error in estimating the volume of post-logging residue in forest plots is, according to Gendek et al. (Gendek et al., 2018c) is 6.1%, which means that forest administration employees underestimate the amount of post-felling residue by relatively small amount, but large scatter in the obtained results should be expected (up to approximately -33%). The estimation error is not affected by the size of the area where felling work was carried out, but it is greater in stands growing in more fertile habitats. The boundary values of errors for estimating the share of post-felling residue adopted by the State Forests (40%) are sufficient.

The quality structure of harvested wood is influenced by natural disasters (e.g. windfalls occurring with varying frequency). Wood raw material harvested from stands as part of planned felling differs in structure from post-disaster wood. For example, a shift of raw material from higher to lower quality classes is noted (Nagadowski, 2008). The quality of wood raw material on post-disaster areas may change in short time, which is related to the action of atmospheric factors and the type of damage to the wood (Jankowiak et al., 2021; Porter, 1995; Szewczyk et al., 2020). The share of small-sized and unclassified wood in post-hurricane areas is usually higher than that obtained in standard areas, which is mainly due to the damage that occurred.

1.1.3. Hungary

The amount of 7.3 million hectares of agricultural land are under cultivation, of which nearly 2 million hectares are forests in Hungary (Oak 21%, Turkey oak 12%, Beech 6%, Hornbeam 5%, Acacia 25%, Other hardwoods 7%, Poplars 10%, Willows 1%, Softwoods 4%, Pine trees 9%) (Agrárminisztérium, 2025). The renewable biomass (dendro- and phytomass) occurring in forestry and agriculture is on average 55-58 million tons of dry matter per year (Szilágyi, 2022). Greater utilization of the 25-26 million tons of by-product potential generated annually in agriculture and 1-2 million tons in forestry is subject to numerous ecological, economic and technological conditions (Bíró, 2011). Up to 6-8 million tons could be utilized for energy purposes, with an energy content of 17-23 TWh. In the energy balance, firewood has an energy content of 3.5-5.8 TWh, and other biomass has an energy content of nearly 1.2 TWh. In this analysis is examined only a part of the energy potential, so-called dendromass utilization possibilities based on woody raw materials, which is area that is becoming increasingly important considering due to depletion of fossil energy sources. In Hungary is the trend to focus more on renewables and utilize them as much as possible. So in many cases, the so-called farming and production residues can form the basis of an alternative form of energy generation, despite the fact that this section of biomass is considered economically wasteful and have no economic role.

Significant quantities of wood pulp that can be used for energy production can come from four main sources, but we should not forget about other areas of the agricultural sector:

- traditional forestry (from the public and private sectors) from the range of firewood, which can be called residential firewood, export firewood, power plant firewood, long firewood, energy wood, etc.;
- waste generated during wood using, cutting site by-products, thin material, twigs, stumps, etc.;
- by-products formed during the processing of wood (e.g. bark, "bark", or used wood products called "altholz" (e.g. furniture, building demolition wood);
- wood from energy plantations, which is mostly utilized in the form of chips.

Among the woody biomass raw materials, we can also mention wood chips and cuttings formed in orchards and vineyards during the care of vineyards, which can be utilized for energy purposes.

Numerous statistical data, domestic and foreign test results were reviewed during the research, synthesizing the data and thus revealing the possible dendromass potential, energy content values, and the realistically exploitable quantities.

According to the statistical data of the Forestry Department of the National Geographic Center, based on data from recent years, the average and approximate living tree stock of Hungarian forests is 400 million gross m^3, and the current growth is about 13 million gross $m^3 \cdot year^{-1}$, Timber extraction totals 7 million gross $m^3 \cdot year^{-1}$.

The living timber stock of the forest is continuously increasing, which is clearly evident from the rate of timber harvesting and mortality, which does not exceed the rate of current growth. The wood energy potential of Hungarian forests depends on the expected amount of firewood and the possibility of utilizing logging residues.

The total volume of industrial wood in 2022 was 2,900,991 nett m^3, and the volume of firewood assortment was 4,442,665 nett m^3, which is significant in terms of assortment distribution, 60.5%. The outstanding value compared to the previous year (52.8%) and years before was due to the national firewood program. Examining multi-year average data, the firewood potential is realistically expected to be between 3-4 million nett $m^3 \cdot year^{-1}$. The total firewood quantity includes forest chips for energy purposes, thick firewood and thin firewood (Agrárminisztérium, 2024).

Significant amount of so-called logging by-products or waste is generated during logging (Pappné Vancsó, 2010), where the amount, depending on the interventions, tree species and production work system, can represent up to 15-20% of the gross wood volume. Cutting waste can be specified as all twigs, bark and other waste materials resulting from logging, e.g. fallen branches, which cannot be used for industrial purposes, but are suitable for energy purposes.

While the produced firewood can be fully utilized for energy production, only a small part of the significant amount of expected waste can be transported from the forest to the energy production site/plant. The reasons for this are as follows:

- The majority of bark residues appear in the timber industry, as they are transported there together with forest waste.
- The usable part must be counted together with other wood industry waste.
- The small amount of bark that is broken into small fractions and ends up on the forest floor covered with vegetation during field debarking cannot be collected economically.

Only fraction of the production waste generated during logging can be utilized (wood, broken wood, knock-outs), because significant part of it is also sent to the timber industry (due to oversizes, roundings in the accounting), or in the form of uncollectible material (sawdust, small chips, etc.).

The collection of thin wood, branches, twigs, crown parts with a diameter of less than 5 cm can significantly increase the amount of wood that can be transferred for energy production. Only the thin wood part of the end uses, mainly carried out in the form of clear cuts, can be collected productively and efficiently. There is counted of about 2/3 of all amount of this wood part and this can be transferred for utilization, e.g. in the form of forest chips.

The stump could still be used for energy purposes. After logging, due to the technology of felling operations, the stump or rootstock, the part of the tree below the cutting blade remains in the cutting area. Depending on the tree species it is usually account for 10-20% of the above-ground tree volume, but can even be 25%.

The collection of stumps and rooted stumps can only be economically solved in a few cases, where ecological aspects must also be taken into account. It is costly operation, therefore it is only justified where the growing site or the target stock were planted, requirements for complete soil preparation, rotation and thorough deep loosening. Stump removal is carried out on 3−5 thousand ha of land in the country every year, but the utilization of the removed stumps has not been solved. Difficulties for easy utilization is made by the fact that the stumps may contain a lot of dirt, soil and sand grains, which can lead to the destruction of equipment and boilers during energy utilization. The tree species of the areas affected by stump removal in Hungary are mostly acacia, poplar and pine. If we estimate the amount of stumps that can be removed in the case of these three tree species, we could potentially talk about up to 300 thousand m^3. Only a fraction of this can be currently utilized in Hungary due to difficulties mentioned above. Larger quantities of stumps can only be technically collected in areas where clear-cutting has been carried out within the end use. However for the listed tree species, stumping and subsequent rotary soil preparation can only be carried out on flat or slightly undulating surfaces and only on some genetic soil types, e.g. sandy soil. Based on all these facts, nearly 160 thousand tons of stumps could be produced, the energy content of which would be nearly 1.8 PJ (Szalay, 2018). In comparison, the extracted quantity based on the 2022 data was a fraction of this amount, 2.2 tons.

The amount of logging residues that can be used for energy purposes according to Szalay study (Szalay, 2018) currently accounts for nearly 12% of the gross wood volume. If the wood is not produced in concentrated manner, collecting the residue is uneconomical.

Generally the wood produced as by-product is only partially collected, with approximately 4.5% of the thin wood part where the felling site residues being utilized (Agrárminisztérium, 2024), which is most often sold to power plants or to lesser extent to heating plants, boilers, or pellet and briquette factories. It can be stated that nearly 1 million tons of sewage sludge are generated nationwide annually, calculated in fresh wet state, from which, taking into account technical and ecological aspects, about 700 thousand tons can be collected, from which about 7.7 PJ of energy can be obtained.

One possible way to use and recycle wood processing by-products and used wood products (altholz) is to produce energy. According to research conducted by Alpár and his colleagues, surveys and investigations have been conducted for a long time regarding the generation, type and quantity of wood waste (table 1.3). The rate of by-products generated can be calculated based on data from companies using wood (e.g. sawmill companies, wooden house manufacturers, furniture companies, parquet producers, manufacturers of construction wood raw materials). It is estimated that 0.5-0.7 million m^3 of by-products may be generated during wood processing.

The amount of used wood products is slowly increasing, on average it can be calculated at 0.6-0.8 million m^3, but surface-treated products cannot be used for energy purposes. Therefore, a total potential of approximately 1.5 million m^3 can be calculated, which is nearly 0.65 million tons. According to estimates, about 150 thousand tons of wood-based packaging waste are also generated annually, so we can talk about a total energy potential of 800 thousand tons, which means 8.6 PJ of energy.

Table 1.3. Yield and by-product ratios in major wood industry sectors (Alpár et al., 2011)

Woodworking Industries	Product (%)	By-product (%)
Sawmill Industry	50-70	30-50
Wooden House Manufacturers	45-55	45-55
Furniture Industry	20-45	55-80
Parquet Manufacturers	30-35	65-70
Construction Industry: Door and Window Manufacturing	30-45	55-70
Plywood Manufacturing	35-45	55-65
Particle Board Manufacturing	~95	~5

There are nearly 4,000 ha of energy-related tree plantations in Hungary, but there may be large inaccuracies in the area size from year to year, due to lack of notification or the liquidation of the plantation. In terms of tree species, poplar stands occupy 80% of the area, and the proportion of willow and acacia is 7-7%. The yields can vary greatly for different tree species (Ranalli, 2007), harvestable volume of wood can also depend on the cutting cycle and the production technology, the growing location and the climate can also have great influence, so the determination of the dendromass potential can only be considered as an order of magnitude value (Rénes, 2008). The area data for Hungary, as well as the yield of approximately 10 $t\cdot ha^{-1}\cdot year^{-1}$ and calorific value of 18 $MJ\cdot kg^{-1}$ (Szalay, 2018) so theoretical energy potential values is nearly 0.7 PJ and this number can be derived from the harvest of energy plantations can be calculated.

Useful dendromass can be obtained from management practices in orchards and vineyards, primarily from pruning and renovation, but its economical collection is only possible in large-scale areas (Pinter et al., 2009). According to observed studies, 150-700 thousand tons of grapevine branches can be produced nationwide every year in Hungary. Taking into account the calorific value after pruning, 165 thousand tons of fruit tree prunings can be collected annually, which would provide 2.6 PJ of energy if utilized (Table 1.4). In the case of vineyards, 57 thousand tons of branches can realistically be collected. Taking into account the current utilization is energy content nearly 1 PJ.

Table 1.4. Dendromass energy potential opportunities (summarized according to previous ones) (Pinter et al., 2009)

Energy source	Mass potential ($t\cdot year^{-1}$)	Energy potential ($PJ\cdot year^{-1}$)
Firewood	2800 000	30.1
Logging (forestry) residues, by-products	700 000	7.7
Wood processing (timber industry) by-products	800 000	8.6
Energy tree plantation	40 000	0.7
Fruit tree cuttings	165 000	2.6
Grape vines	57 000	1.0
Total		50.7

Among the renewable resources that can be used for energy purposes in our country, some of the potential in the utilization of dendromass is still largely unexploited. This is mainly due to the technological and economic limitations of its use. Unfortunately, the time when fossil energy carriers will be exhausted is approaching dangerously, so we will be forced to rely on alternative solutions and, without disemboweling nature, to use as much of the by-products, used wood products or even grape pruning wood as possible.

The energetic potentials can be determined and calculated through the exploration of dendromass sources that can be used for energy purposes.

The power plants and heating plants using biomass raw materials in Hungary used 57.6% of wood chips (1,366 thousand tons) for their energy production in 2021. There was observed an increase of more than 25% compared to the amount used in the previous year. There was observed the total use of after chips (forest chips, sawdust, bark) as firewood accounted for 9.1%, sunflower husks for 5%, cereal straw and paper industry waste for 6.3 and 6.6%, respectively. Other raw materials accounted for 15.4%, which is 6% point decrease compared to the 2020 value. Other municipal waste is worth mentioning among the other raw materials, which contributed more than 5% to biomass-based energy production in 2021. According to data provided by the Hungarian Energy Agency, although their share is constantly increasing, renewables still account for a small percentage of thermal energy production in our country, with total share of 16.8% in 2022 (MEKH, 2022).

Based on what is stated in the National Forest Strategy, in the medium term nearly 4 million m^3 of firewood can be calculated as renewable dendromass in Hungary. The growing demand for energy wood could be met to some extent by the possible development of sediment utilization and the efficient use of wood industry by-products and wood waste.

1.1.4. Czech Republic

Forest management in the Czech Republic (CR) is gradually improving in the context of the negative impacts of climate change and the related extensive bark beetle calamities of recent years. 2024 has become the warmest year in recorded history since 1850 according to NOAA (National Oceanic and Atmospheric Administration, USA) (Moon et al., 2024). The average temperature surpassed the warmest year to date, 2016, by 0.15°C. The ten warmest years occurred in the last decade. Heat waves hit southern Europe in particular (record in Italy of 47.8°C) and North America. High temperatures contributed to the development of large-scale forest fires in Canada. 2024 was the warmest year since 1961 in the Czech Republic. The average temperature of 10.3°C was 0.5°C higher than the previous year, 2023, and higher than the long-term average of the climate normal (1991–2020). However, the higher temperatures were compensated by slightly higher precipitation of total 732 mm (107% of the annual climate normal) (Ministerstvo zemědělství, 2024).

The area of forest land in CR is currently constantly growing. This is partly due to the excess of the area of newly afforested, where originally non-forest land is over the area of land that is being removed from the forest for various reasons, and partly also due to the constantly improving data from the land registry (Ministerstvo zemědělství, 2024). The development of the total area of forest land (ha) is shown in Figure 1.3.

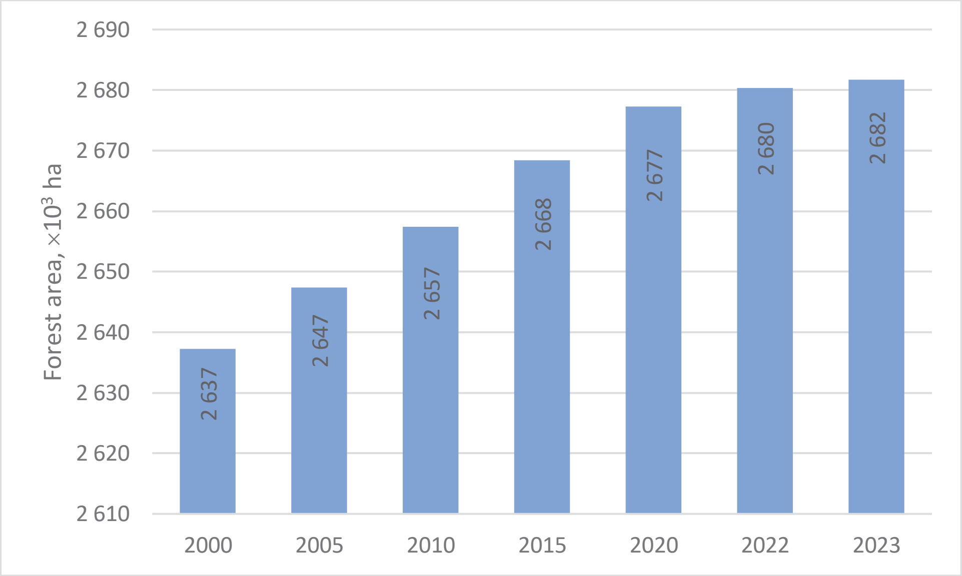


Figure 1.3. Development of the total area of forest land in the Czech Republic (ha) (Ministerstvo zemědělství, 2024, 2023, 2022, 2021, 2016, 2011)

The total area of coniferous trees in the Czech Republic continues to decrease. The share of deciduous trees is constantly, albeit slowly, increasing in contrast of the state mentioned above. In 2022 by 0.8% and in 2023 by 0.6%, spruce and pine are still declining due to the calamity in the Czech Republic, and beech, oak and maple are appearing more (Ministerstvo zemědělství, 2024). In addition to the total representation of individual tree species, the occurrence of stand mixtures within the spatial distribution units of forests is also an important indicator in terms of assessing the species biodiversity of the Czech Republic's forests (Leuschner and Ellenberg, 2017). The ratio of mixing of individual tree species within these units is constantly increasing in favor of mixed stands and stands with predominance of deciduous trees. This increasing trend was also recorded in 2023 (Ministerstvo zemědělství, 2024). It is the result of continuous efforts by foresters to achieve an optimal species composition of forests, which has been supported in the long term by targeted state subsidy policy (see Table 1.5).

Table 1.5. Species composition of forests in the Czech Republic from the total area of forest land (ha and %) (Ministerstvo zemědělství, 2024, 2023, 2022, 2021, 2016, 2011)

Wood type	Year					
	2000	2010	2015	2020	2022	2023
	Area of land ha / %					
Norway spruce	1 397 012	1 347 239	1 315 487	1 274 241	1 222 920	1 202 456
	54.1	51.9	50.6	48.8	46.8	46.0
Fir	23 138	25 869	28 699	31 429	33 119	33 939
	0.9	1.0	1.1	1.2	1.3	1.3
Pine	453 159	436 308	428 030	419 874	418 340	417 505
	17.6	16.8	16.5	16.1	16.0	16.0
Larch	97 170	100 761	100 283	100 632	102 518	103 194
	3.8	3.9	3.9	3.9	3.9	4.0
Other conifers	4 586	6 352	7846	10 252	11 192	11 695
	0.2	0.2	0.3	0.4	0.4	0.5
Conifers	1 975 065	1 916 529	1 880 344	1 836 427	1 788 089	1 768 789
	76.5	73.9	72.3	70.4	68.4	67.7
Oak	163 761	178 466	185 044	195 252	203 500	207 485
	6.3	6.9	7.1	7.5	7.8	7.9
Beech	154 791	189 998	211 835	235 755	251 663	257 083
	6.0	7.3	8.2	9.0	9.6	9.8
Birch	74 560	72 264	71 796	72 744	74 879	76 272
	2.9	2.8	2.8	2.8	2.9	2.9
Other deciduous	183 696	209 559	219 207	230 856	239 469	244 037
	7.1	8.1	8.4	8.9	9.2	9.3
Deciduous	576 808	650 287	687 882	734 606	769 511	784 877
	22.3	25.1	26.5	28.2	29.5	30.1
Totally free of bruschwood	2 551 873	2 566 816	2 568 227	2 571 033	2 557 600	2 553 665
	98.8	98.9	98.8	98.5	97.9	98.8

The natural species composition in the Czech Republic is reconstructed as the composition of natural forest communities that would have developed without human intervention under given natural conditions and the current climate. The recommended tree species composition for the forest management of the Czech Republic (see Figure 1.4) represents an economically, ecologically and functionally optimized representation of tree species, which guarantees a balanced fulfillment of the production and non-production functions of the forest. Coniferous tree species make up a total of 54.4% compared to 45.6% of deciduous tree species (Ministerstvo zemědělství, 2024).

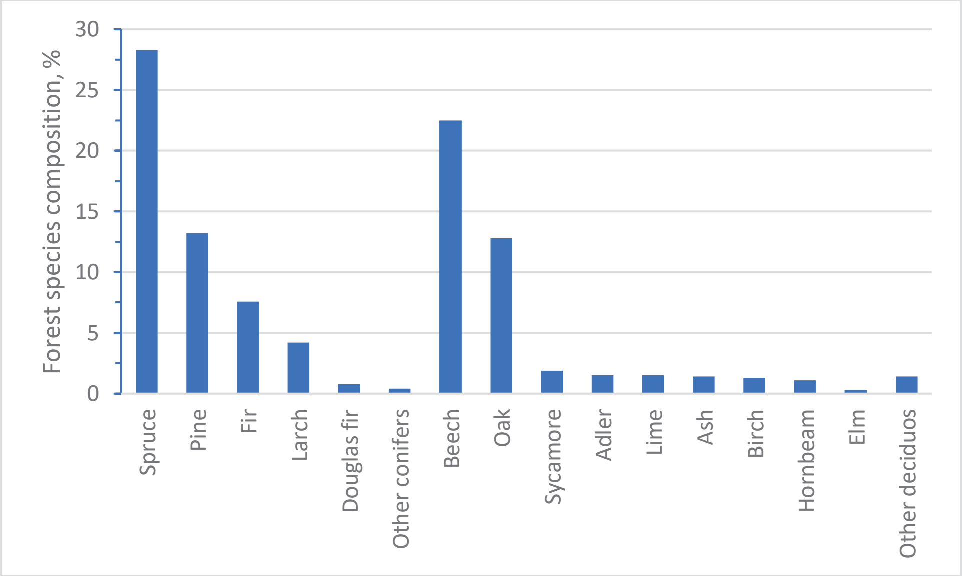


Figure 1.4. Recommended tree species composition of forests in the Czech Republic (%) (Ministerstvo zemědělství, 2024)

Natural forest regeneration in the Czech Republic increased by 2,881 ha to 12,447 ha (+30.1%). Conifers slightly predominated (52.4%), with spruce being the most widely used tree species (40.2%). The most extensive natural forest regeneration took place in the Vysočina Region (2,265 ha, i.e. 18.2% of the total natural forest regeneration in the Czech Republic) (ČSÚ, 2025a, 2025b). The forest land occupied an area of 2,683,138 ha at the end of 2024, which represented 34.0% of the whole area of the Czech Republic. State-owned forests accounted for 54% of all forests (ČSÚ, 2025a, 2025b).

The total of 18.49 million m^3 of raw wood was harvested in the forests of the Czech Republic in 2023, which is decrease of 6.62 million m^3 compared to the previous year. This volume was largely contributed by the processing of random wood logging, 11.03 million m^3. The share of random logging was 59.7%, and the unfavorable initial conditions for planned forest management continue, see Figure 1.5 (Ministerstvo zemědělství, 2024).

In terms of the logging composition by species, the volume of coniferous logging decreased by 6.45 million m^3 compared to 2022 to a total of 16.60 million m^3. The share of coniferous logging in total logging was approximately 90% (see Table 1.6). The proportion of deciduous and coniferous logging is mainly determined by the processing of random logging, especially so-called bark wood (Ministerstvo zemědělství, 2024).

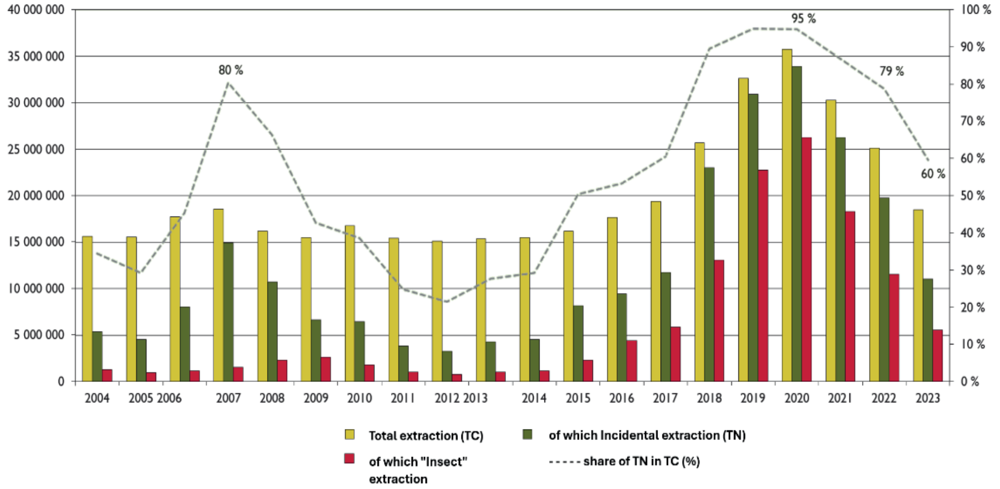


Figure 1.5. Development of total and incidental timber in the Czech Republic (m^3, %) (Ministerstvo zemědělství, 2024, 2023, 2022, 2021, 2016, 2011)

Table 1.6. Timber harvesting in the Czech Republic (mil. m^3, m^3) (Ministerstvo zemědělství, 2024)

Timber harvesting	i.e.	2000	2010	2015	2020	2022	2023	2024
Conifers	mil. m^3	12.85	15.07	14.38	34.49	23.05	16.6	15.67
Deciduous		1.59	1.67	1.78	1.26	2.06	1.89	2.13
Totally		14.44	16.74	16.16	35.75	25.11	18.49	17.8
Totally per 1 inhabitant	m^3	1.41	1.59	1.53	3.34	2.38	1.71	1.61
On 1 ha forest land		5.48	6.3	6.06	13.35	9.37	6.89	6.5

The timber harvesting decreased by 0.7 million m^3 (-3.7%) in 2024 compared to the previous year. A smaller part of the harvested timber (45%) came from random harvesting of 8.0 million m^3. Random harvesting decreased by 3.0 million m^3 year-on-year. The disaster in the forests in the Czech Republic was therefore on the decline (ČSÚ, 2025a).

The main share of timber was made up of coniferous species (88.0%, 15.7 million m^3), while deciduous species take place of about 2.1 million m^3. The individual species, spruce (68.5%) prevailed, followed by pine (13.9%), beech (4.7%) and larch (4.4%). From a territorial point of view, the most timber was harvested in the South Bohemian Region (2.7 million m^3, i.e. 14.9% of total timber in the Czech Republic) (ČSÚ, 2025a).

The total amount of timber harvested in the Czech Republic in 2023 was 18,493 thousand m³, of which 16,600 thousand m³ of coniferous and 1,893 thousand m³ of deciduous. The total amount of timber harvested is therefore already reaching normal level for balanced forest management after previous over-harvesting (caused primarily by the elimination of the extensive bark beetle calamity on the dominant spruce tree species, which gradually affected spruce stands throughout the Czech Republic between 2015 and 2022) (Ministerstvo zemědělství, 2024). Domestic consumption of forest products (i.e. coniferous and deciduous logs, fiber and fuel) decreased by 2,415 thousand m³ year-on-year, while production (wood harvesting) decreased by 6,617 thousand m³ year-on-year, imports increased by 185 thousand m³ and exports decreased by 4,017 thousand m³. Domestic consumption of forest products for 2023, amounting to 14,920 thousand m³, fully ensured the domestic demand of wood processing companies and the population in the Czech Republic for basic forest products (Ministerstvo zemědělství, 2024).

The total amount of timber harvesting and subsequent deliveries of raw wood were continuously influenced by the obligation of forest owners for priority and quickly process random and decreasing calamity bark beetle wood. This was due to more favorable, colder and wetter weather in the first half of 2023, together with a significant decrease in the area of attractive spruce stands for bark beetles. The delivered assortments from domestic production are listed in Table 1.7.

Table 1.7. Timber supplies (i.e. timber sold including forest owners' own consumption in thousands m³)

Delivered assortments from the factory (without imports)		2021	2022	2023	2024
Log wood x)		17 739	14 635	10 333	9 502
from that	coniferous	17 301	14 019	9 723	8 822
	deciduous	438	616	610	680
Pulp and other industrial wood xx)		7 407	6 070	5 186	5 056
from that	coniferous	6 950	5 421	4 533	4 321
	deciduous	457	649	653	735
Fuel		5 110	4 405	2 974	3 249
from that	coniferous	4 463	3 610	2 344	2 531
	deciduous	647	795	630	718
Total wood deliveries		30 256	25 110	18 493	17 807
from that	coniferous	28 714	23 050	16 600	15 674
	deciduous	1 542	2 060	1 893	2 133

Note:
x) including roundwood and quarry.
xx) including wood for the production of wood pulp.
Total deliveries do not include mining residues and forest chips in the volume of approximately 2.9 million m³ in 2021 and 2022 and 2.5 million m³ in 2023 (qualified estimate).
(ČSÚ, 2025a)

After a significant decrease in 2008–2009, average prices for all types of raw softwood in the Czech Republic continued to increase from 2010 until the end of 2014 and reached their highest values in the 1st quarter of 2015. From the 2nd quarter of 2015 until the end of the 4th quarter of 2020, average prices for softwood continued to decrease (the largest decrease was during 2020) (Ministerstvo zemědělství, 2022). Development of average prices thus reflected a significant excess of supply (from forest owners and entrepreneurs) over demand (from processors) for raw wood on the domestic market for all types of coniferous wood (in connection with a significant increase in coniferous wood harvesting in the processing of mainly disaster wood - bark beetle wood). The turnaround occurred from the 1st quarter of 2021, when in 2021-2022 there was a significant increase in average prices for all coniferous wood varieties up to historically high values - i.e. after the Covid period with a revival of production in the entire wood processing industry and at the same time with a significant decrease in the amount of coniferous wood harvesting (in connection with a decrease in bark beetle infestation of spruce stands) and rising inflation due to the energy crisis and the resulting of war in Ukraine. However, since Q2 2023, there has been a significant decrease in average prices for all coniferous assortments, with the exception of firewood and larch logs (Ministerstvo zemědělství, 2024).

There was opposit situation for hardwood where a partial increase inaverage prices happened from the second quarter of 2015 to the end of 2021 for almost all hardwood roundwood cuts in the monitored wood species oak and beech; hardwood fuel was also still in demand, while for fiber wood of the 5th quality class there was a significant decrease in average prices during 2020 with a subsequent increase in 2021. Also during 2022–2023, there was a significant year-on-year increase in average prices for all hardwood assortments in the monitored wood species oak and beech and the price index for hardwoods in total. This price trend was mainly related to a partial decrease in hardwood logging in previous years and growing domestic demand (Ministerstvo zemědělství, 2024).

There was a significant year-on-year decrease in average prices for all coniferous assortments, with the exception of firewood and larch logs, in 2023 compared to 2022, when average prices were at their highest level to date and exceeded prices from 2015 (i.e. before the bark beetle disaster). On the contrary, in 2023, there was a further increase in average prices for all deciduous assortments compared to 2022. The average price for coniferous fuel also increased by 11.5% year-on-year to 1,151 $CZK \cdot m^{-3}$, and for deciduous fuel there was an increase of 15.6% and the average price reached 1,761 $CZK \cdot m^{-3}$.

There has been a significant increase in the capacities of sawmills in the country over the past eight years, This situation happened through the construction of new sawmills or the reconstruction of existing operations, especially among foreign owners. This situation started significantly increased amount of harvested wood (especially in the range of spruce logs, fiber and fuel) as a result of processing the historically highest bark beetle disaster in the Czech Republic. This has resulted in a significant predominance of the supply of raw wood at favorable prices for both domestic and foreign processors (see Table 1.8). The amount of wood harvested has significantly decreased to approximately 18.5 million m^3 after a significant decrease in the bark beetle disaster in 2023, which is already at a sustainable level of balanced forest management (i.e. practically at the level of the total average annual increase) (Ministerstvo zemědělství, 2024).

Table 1.8. Wood products market (thousand m³)(Ministerstvo zemědělství, 2024)

Product	Year	Production	Import	Export	Consumption
Softwood lumber	2021	5 015	526	2 291	3 250
	2022	4 720	583	2 338	2 965
	2023	4 201	448	1 677	2 972
Hardwood lumber	2021	145	338	67	416
	2022	222	136	34	324
	2023	220	50	10	260
Veneers	2021	30	42	53	19
	2022	28	58	58	28
	2023	27	17	18	26
Plywood, blockboards	2021	260	186	245	201
	2022	240	230	277	193
	2023	230	217	299	148
Particleboard	2021	1 710	705	1 321	1 094
	2022	1 651	656	1 134	1 173
	2023	1 640	404	1 035	1 009
Fiberboard	2021	45	574	156	463
	2022	41	438	150	329
	2023	40	145	69	116
Wood pellets and other agglomerated products	2021	634	85	475	244
	2022	709	69	431	347
	2023	603	275	359	519
Wood chips	2021	1 036	181	19	1 198
	2022	1 009	246	366	889
	2023	867	106	199	774
Wood waste	2021	697	22	238	481
	2022	690	210	480	420
	2023	593	77	440	230

There is a noticeable decrease in the production of domestic wood pellets for energy purposes in the Czech Republic in 2023 from approximately 40 pellet plants to 470 thousand tons (compared to 538 thousand tons in 2022) (Ministerstvo zemědělství, 2024). The reason was decrease in sawn logs, because sawmills produce pellets as a by-product of pressing sawdust. This is another significant type of ecological fuel, which is currently the cheapest after heating with firewood. At the same time, 94.5% of the pellets produced had the international certification of the highest quality EN plus A1. The Czech Republic exported 322 thousand tons of domestic pellet production (mainly to Italy, Austria and Germany), imported 29 thousand tons of pellets from abroad and 177 thousand tons of pellets were consumed in the Czech Republic. The largest annual production of pellets comes from sawmills-pellet factories Pfeifer in Chanovice in the Pilsen region, Mayr-Melnhof Holz Paskov in Staříč and in Scandinavian concern Stora Enso in Ždírec nad Doubravou (total of 279 thousand tons). The pellet market (or sales of pellets) exceeded CZK 3.5 billion in 2023. Austrian woodworkers in particular responded to the bark beetle disaster by increasing the processing capacity in their companies (e.g. expanding the capacity for cutting coniferous logs in 2022 to 780 thousand m³ at the Pfeifer Holz sawmill in Chanovice in the Pilsen region). Sawmill Javořice, joint-stock company had similar intention, which after reconstruction - replacing the belt technology at the sawmill with more modern technology from the German manufacturer Linck in combination with technology from Dřevostroj Čkyně - increased the sawmill's cutting output to 470 thousand m³ in 2022, increased the yield of lumber, energy savings and enabled better response to the bark beetle wood being processed. The new Labe Wood, s. r.o. sawmill was built in Štětí at cost of over CZK 2.5 billion and started operating in September 2020. This is plant with the most modern sawmill technologies and the sawmill's cutting capacity in 2022 was already 800 thousand m³ of coniferous logs with the production of joinery / carpentry and building materials. The neighboring paper mill Mondi Štětí, joint-stock company processes the by-products of production from the sawmill for the production of cellulose and paper; sawdust and bark are also processed here for energy production. These large sawmills noted partial decreases in the cutting of coniferous logs in 2023 based on the economic optimization of sawn timber production with its possible further processing into products with higher added value.

1.2. Pellet market

The European pellet market began in the mid-1980s. However, not all countries noted the same pace of market development. For example in Poland it began with a 15-year delay. As a result of this situtation some countries currently have developed their own internal markets, while others are just starting to establish their first production plants. Some countries have significant production, but due to a lack of domestic demand, they export almost all production. Other countries, on the other hand, import significant quantities of pellets because of the lack of sufficient raw material resources to meet their needs (Flizikowski and Mroziński, 2016). The European Union accounts for 44% of the world's pellet production. Biofuel consumption in EU countries is estimated at 50%. As a result, Europe remains the world's largest producer and consumer of pellets (Lenartowska, 2024). According to the EuroStat report (2023), the largest pellet producer in Europe in 2022 was Germany (3.57 million tons) (Figure 1.6). Other countries with large production include France (2.05 million tons), Poland (2 million tons), Sweden (1.81 million tons) and Latvia (1.77 million tons) (Więcek, 2024).

After steadily increasing between 2013 and 2021, wood pellet consumption in Europe reached 34.6 million tons in 2021. After this highest number consumption fell to 32.1 million tons in 2022 due to the energy crisis. This trend continued also in 2023 and consumption decreased to 30.1 million tons in Europe. The largest amounts of pellets are burned in the United Kingdom (over 6.8 million tons), followed by Germany (3.4 million tons) and France (3.1 million tons).

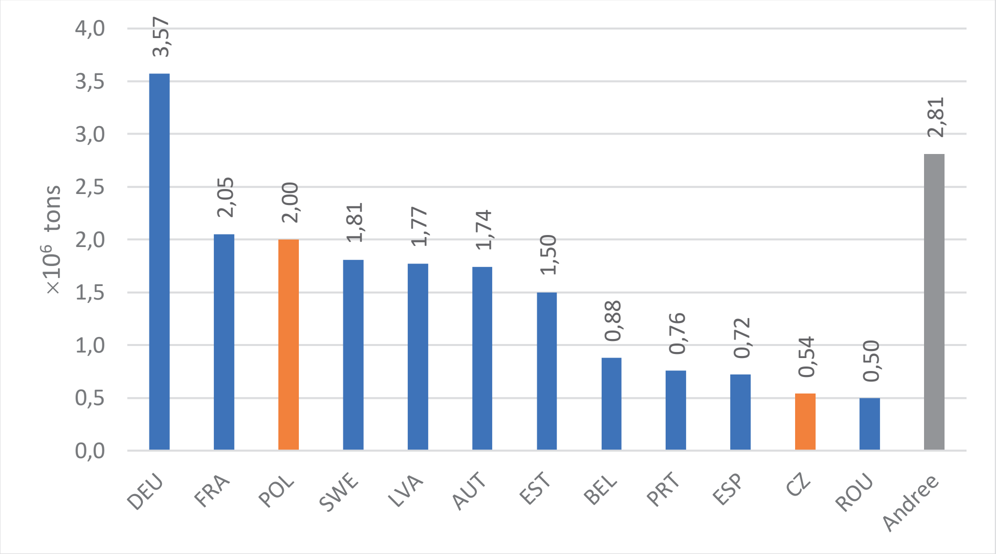


Figure 1.6. Ranking of pellet production in Europe in 2022 based on report data (Eurostat, 2025)

Pellets are burned up to 50 kW installations in various European countries. For comparison of the situation, there is necessary to mention that the consumption was in Germany 19%, in Italy 18.6%, in France 16.1% and in Poland 6.0% (Figure 1.7)

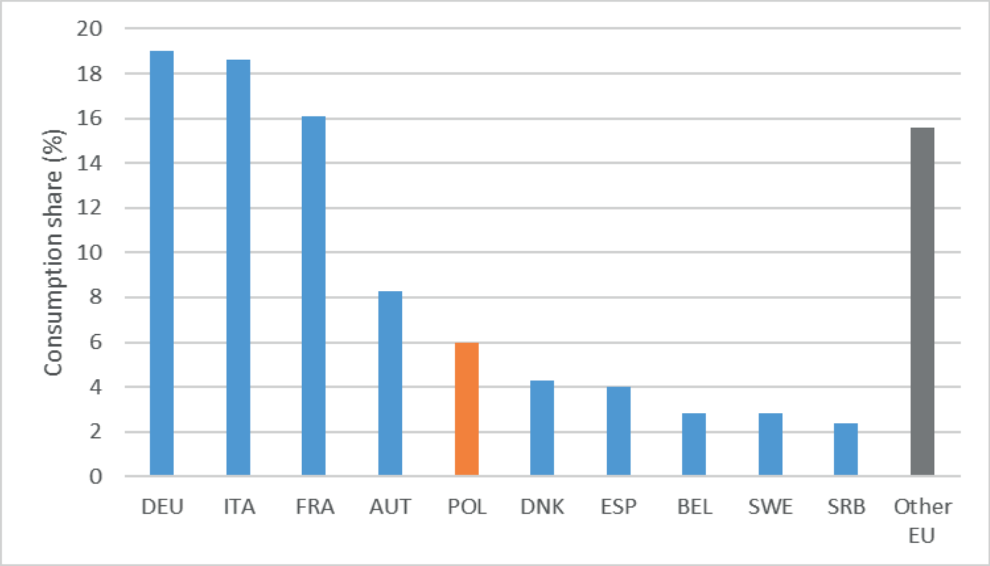


Figure 1.7. Wood pellet consumption in Europe in 2023 in individual installations with a power of up to 50 kW (Bioenergy Europe, 2025)

1.2.1. Slovakia

The wood biomass represents in Slovakia a significant renewable energy source, supported by EU (European Union) goals for emission reduction and sustainable energy. Processing wood biomass into chips, pellets and briquettes forms is vital part of the energy infrastructure, especially in rural areas where it provides heat and power. This research outlines the amount of processed biomass, key processing companies and the benefits of these products for Slovakian energy.

Slovakia's abundant forest resources offer a high potential (Table 1.9 – 1.11) for biomass energy. However, the share of biomass in Slovakia's total energy consumption remains below 1%, less than in neighboring Austria and Sweden, where biomass accounts for up to 15% of the energy mix (Hudák, 2022). The state forests manage an estimated 1.6 million cubic meters of wood suitable for chipping, including wood from storm-damaged areas (Tolnayová, 2004).

In Slovakia, the production of wood pellets, briquettes, and wood chips has grown as part of the renewable energy sector, but specific quantities vary by year and product type. In 2022, Slovakia's production of wood pellets was estimated at around 700,000 metric tons, driven by both domestic consumption and exports, particularly to countries within the European Union where demand is high due to initiatives supporting bioenergy. This production volume indicates a rise in the use of solid biofuels, aligning with trends across Europe (IndexBox, 2024). Wood briquettes, while not as extensively reported as pellets, are also a part of Slovakia's biofuel production portfolio, mainly catering to local demand. Wood chips, commonly used in combined heat and power (CHP) plants, are another significant output, though detailed data for recent years is sparse. However, wood chips remain an integral part of biomass energy production within Slovakia, contributing to the country's efforts in sustainable energy production and reduced reliance on fossil fuels (Flach and Bolla, 2022). Overall, Slovakia's biofuel market reflects a steady integration of renewable resources, with wood pellets leading in both production and export. The use of wood biomass in Slovakia has increased in recent years, primarily driven by the demand for renewable energy sources like wood chips, pellets, and briquettes. The production of these biomass products has become more popular due to supportive policies and subsidies intended to encourage sustainable energy, particularly in rural and forested areas.

Table 1.9. The potential of wood biomass in Forestry for energy use in Slovakia. Modified by (Oravec and Slamka, 2014)

Year	In the past 2015	Current 2025	Vision 2050
Indicator	Thousand ton		
Firewood from registered logging	380	370	286
Manipulation wastes from registered logging	445	406	346
Waste after mechanical processing of wood in forestry	160	200	240
Stumps and roots	40	40	40
Waste after pruning	60	80	110
Thin unutilized roughness after logging	1587	1715	2083
Total forest fuel biomass	2672	2851	3105

Table 1.10. The potential of wood biomass in Wood Processing Industry for energy use in Slovakia. Modified by (Oravec and Slamka, 2014)

Year	In the past 2015	Current 2025	Vision 2050
Indicator	Thousand ton		
Waste after mechanical processing	1416	1540	1710
Liquid waste	485	520	560
Total	1900	2060	2260

Wood chips, often sourced directly from logging residues and wood-processing industry byproducts, are typically used in large-scale heating applications. In Slovakia, the annual consumption of wood chips for energy purposes has reached about 4 million cubic meters. However, environmental advocates have raised concerns, stating that this level of consumption exceeds sustainable forestry capacities, potentially impacting forest biodiversity and health (Šupa, 2020).

Table 1.11. Energy (energy value) use of wood biomass produced on forest and non-forest land Modified by (Oravec and Slamka, 2014)

Year	In the past 2015	Current 2025	Vision 2050
Indicator	PJ		
Forest soil - firewood	7.0	7.1	6.7
Forest soil – fuel chips	7.6	19.1	21.4
Total	14.6	26.2	28.1
Non-forest land - white areas of linear planting - fuel wood	0.6	1.2	1.2
Non-forest land - white areas of linear planting - fuel chips	1.2	2.3	2.5
Non-forest land - white areas of linear planting - total	1.8	3.5	3.7
Intensive stands - fuel chips	0.2	4.3	12.4
Total firewood	7.6	8.3	7.9
Total fuel chips	9.0	25.7	36.3
Total Department of Agriculture	16.6	34.0	44.2
Total in Wood Processing Industry	22.8	24.7	27.1
Total	39.4	58.7	71.3

Major processors like Mondi SCP, Rettenmeier Tatra Timber, and Bukóza Holding process more than 4.2 million cubic meters of wood annually, generating about 800,000 tons of wood chips. Some of this output is directed to energy production, with companies producing pellets and briquettes or exporting chips (Oravec and Slamka, 2014).

1.2.2. Poland

In Poland, there is no mandatory registration of wood waste. Consequently, there is a lack of current and comprehensive data on its supply. It is difficult to provide an exact figure for the amount of woodchips produced in Poland, as it varies and depends on numerous factors related to forestry, the timber industry, the energy sector and horticulture. There are no official statistics on the amount of woodchips in circulation, but their production and use are significant.

Woodchips are a vital raw material for the energy sector, generating heat and electricity. Approximately 6.9 million tons of wood biomass, including woodchips, were consumed in Poland in 2022. It is estimated that 1 ton of woodchips has a volume of approximately 4 cubic meters (WJK Invest, 2014), which amounts to approximately 27.6 million cubic meters of woodchips per year. Currently, logging residues and woodchips produced from them are one of the renewable energy sources commonly used by the energy industry (Gendek and Nurek, 2016; Gendek and Więsik, 2015; Gendek and Zychowicz, 2015; Moskalik, 2013, 2004).

The volume of post-logging residue harvested is, for obvious reasons, correlated with the overall level of timber harvesting. In Poland, approximately 38 million cubic meters of round timber have been harvested in recent years. It is estimated that in forest areas, post-logging residues, such as branches, tree crowns and pieces of wood, constitute approximately 10-17% of the wood mass, which translates to 3.8-6.5 million cubic meters of residue that can be processed into chips.

The sawmill industry is the largest producer of wood waste, including wood chips. This industry accounts for over 63% of the total wood waste. Sawmill waste is dominated by lumpy waste including offcuts, edgings and root sap, which can be processed into chips along with sawdust and bark. Remaining part 37% of wood waste can be splitted into two parts, 14% comes from the furniture industry (waste from wood-based materials and solid wood components, wood dust, sawdust and shavings) and 13% from the wood-based panel industry (solid piece waste, wood-based materials, shavings, wood dust and bark). Waste from the pulp and paper industry accounts for over 8% of the total waste (primarily bark). The share of the joinery industry in the wood waste supply does not exceed 2%. The waste generated in this industry is mainly sawdust and shavings as well as solid waste pieces.

All of the wood waste presented above can be used to produce energy and heat, either unprocessed or processed into chips, pellets or briquettes.

The energy properties and ease of use make the pellets one of the most popular and effective ecological energy source. According to the EU report prepared by the European Court of Auditors (ECA, 2023), Poland ranked fifth place among European pellet producers., The pellet production has steadily increased since 2012 from approximately 0.6 million tons to 1.4 million tons in 2019 (IndexBox, 2025a). Production dropped to 1,070,000 tons in 2019 (Figure 1.8). Average annual pellet production in Poland during this period was approximately 0.9 million tons. Poland was the third-largest pellet producer in Europe in 2022 with production reaching 2.2 million tons.

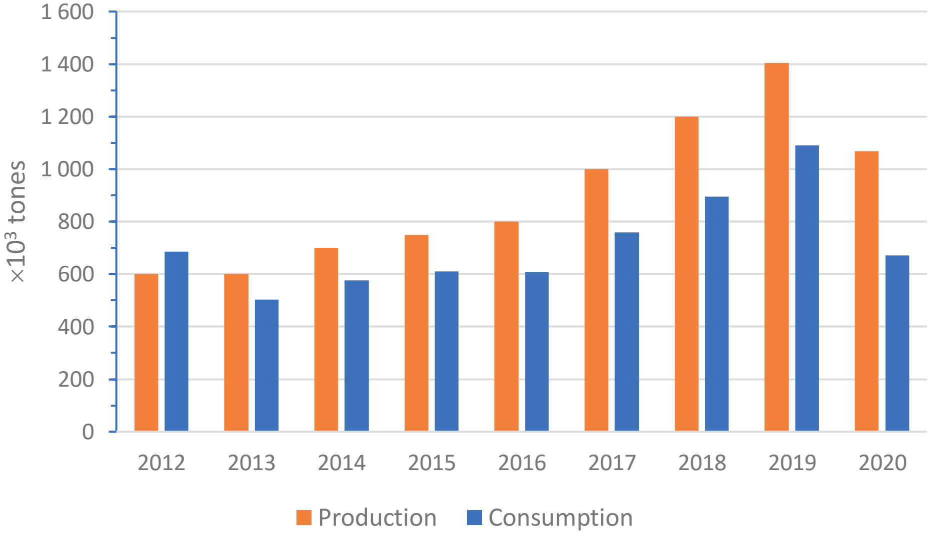


Figure 1.8. Pellet production and consumption in 2012-2020 (IndexBox, 2025a)

140 plants with a total production capacity of 2.7 million tons were operating in Poland in 2023. Domestic pellet production decreased slightly in 2024 by approximately 0.2 million tons, compared to the previous year.

The average price of pellets in Poland in 2022 increased from PLN 850 to approximately PLN 2,600-2,700 per tonne (Kędziora-Urbanowicz, 2025). This negative trend was primarily due to uncertainty in the fuel market. The price of 1 ton of pellets is stable in 2025, averaging PLN 1,250. Stabilizing pellet prices and growing public environmental awareness are contributing to increased interest in this heating source. The forecasts for the development of the pellet industry in Poland are optimistic, both for individual consumers using pellet boilers in households and for industrial customers in the commercial power sector. Industry experts point to challenges related to the availability of raw materials for pellet production, especially in the context of planned regulations limiting the burning of sawdust and wood chips for energy purposes. Additionally, pellet producers in Poland must compete with producers in the Baltic states and Ukraine (estimated at approximately 20,000 tons·month^{-1}), where production costs are significantly lower.

Poland recorded the highest pellet production in Europe between 2022 and 2024, at plants certified with ENplus® (confirming the repeatability of pellet parameters in quality class A1 or A2). Several new small- and medium-sized production units of up to 10,000 tons per year have been established in the last two years.

Poland maintained its leading position in Europe in 2024 in terms of the number of ENplus® certified wood pellet producers. According to data published by Magazyn Biomasa, Poland had 69 certified producers, the highest number in Europe. The production of certified pellets reached in 2023 13.6 million tons and in 2024 14.5 million tons. The largest production of certified pellets comes from German plants with over 3.5 million tons, Austria with

1.7 million tons, France and Spain with approximately 0.7 million tons each and Belgium with 0.6 million tons. Poland ranked sixth place in Europe with projected production of 0.56 million tons in 2024.

The introduction of changes to the law / regulation regarding the production and use of pellets and briquettes is intended to eliminate low-quality products from the market and reduce environmental emissions. The proposed changes will introduce certification requirements, meaning confirmation of the quality class of wood pellets by independent third party. This means that every type of wood pellet marketed and sold in Poland must meet specific quality standards for quality class A1, if used in heating appliances of classes 3, 4, and 5; and/or meeting ecodesign requirements or quality class A2 if used in heating appliances below emission class 3, as defined in the EN 305-5 standard (*EN 303-5*, 2022). Thanks to the introduced guidelines, users will be assured that the biofuel they purchase is of the highest quality, burns efficiently, and is safe for health and the environment.

Currently, there are approximately 100 pellet producers operating in Poland, many of them small and local manufacturers. Among the largest pellet producers are STELMET S.A., IKEA Industry Poland Sp. z o.o. (Wielbark Branch), Barlinek Inwestycje Sp. z o.o., and Sylva Sp. STELMET and Barlinek. These companies hold ENplus certificates confirming their quality. The SBS Group and Stelmet are among the leading pellet producers in Europe.

1.2.3. Hungary

The Hungarian pellet industry has a relatively short history. Production started in 2008, in the first years there were only 7–10 small and medium-sized plants operating, with a production capacity of around 5,000 t·year^{-1}. By 2011 this had expanded to 11 plants, with a capacity of 126,500 t·year^{-1}.

At that time, domestic consumption was still very low (in 2008, around 1,000 t·year^{-1}), while the majority of production was exported (80%) – primarily to Italy and Poland.

According to data of the IndexBox (IndexBox, 2025b), domestic pellet production reached its peak in 2017, when it was 22,000 t·year^{-1} (Figure 1.9). However, by 2022 it shows a significant decline: only 6,600 tons, which was 59.4% decrease compared to the previous year IndexBox.

This clearly shows that although the production capacity was previously around 100,000 t·year^{-1} (for example in the case of Pellet Hungary Kft), the actual production remained well below it and indicates a structural market decline.

According to IndexBox, domestic pellet consumption reached its maximum in 2017 about 29,000 t·year^{-1}, and then by 2022 it decreased to 7,400 tons, so there was 32.3% annual decline.

This is consistent with the production statistics and shows that the domestic pellet market could not show sustainable growth and domestic market demand also declined significantly.

Previously was exported 70–75% of production in 2009–2010, so domestic pellet exports dominated while domestic consumption was only 25%. The main target export lead to countries: Italy, Austria, Slovakia, Poland. Some imports came from Ukraine or Romania with the goal to meet domestic demand.

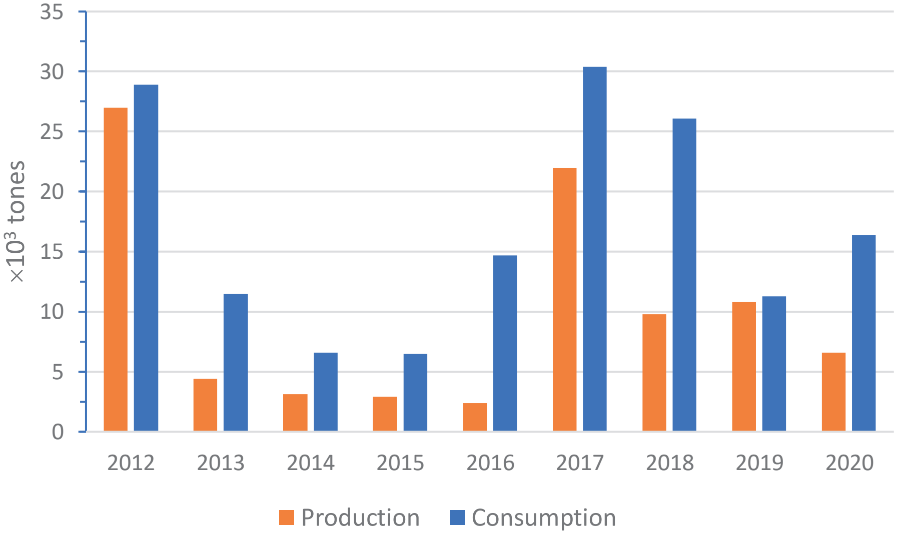


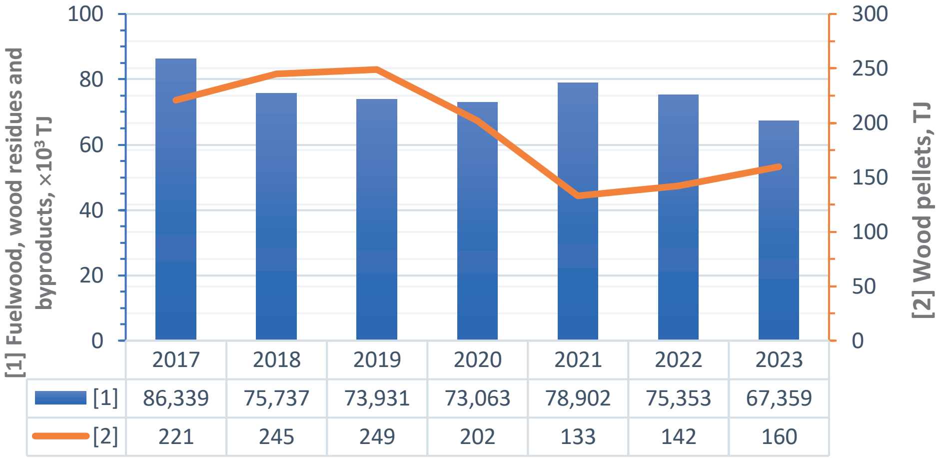
Figure 1.9. Pellet production and consumption in Hungary in 2012-2020 (IndexBox, 2025b)

In recent years, the size of exports has also decreased, but its proportions are not available in public sources, but it is believed that the decline was accompanied by contraction of the export market. Pellet production was previously supported by significant investment subsidies, with subsidy intensity of up to 50–70% (KMEC Engineering, 2024). However, these incentives later diminished as gas and electricity prices became uncertain.

In Europe, industrial pellet use is expected to decline in 2023 (e.g., large power plant consumption has declined), while residential use remains stable, especially despite adverse weather conditions (ARGUS, 2024). In Hungary even residential demand has fallen.

In Hungary's primary energy mix, biomass (which may also include wood pellets) accounted for more than 25% of renewables around 2021 (Wikipedia, 2025). The role of pellets has declined due to technological and infrastructural deficiencies and the rise of geothermal and solar energy.

According to Eurostat, Hungarian energy production and consumption between 2017 and 2023 ranged from approximately 86,000 TJ to 67,000 TJ, with minor fluctuations. The dynamics of energy production and consumption from various sources, including wood pellets, are presented in Figure 1.10. In Hungary, renewable energy sources primarily include firewood and other solid biomass, such as wood waste, municipal waste, and agricultural by-products (corn and sunflower husks and stalks, oilseed cake, etc.).



	2017	2018	2019	2020	2021	2022	2023
[1]	86,339	75,737	73,931	73,063	78,902	75,353	67,359
[2]	221	245	249	202	133	142	160

Figure 1.10. Production and consumption of energy from renewable sources in 2017-2023

However, the energy volume from wood pellet production and trade remains negligible compared to other biomass sources. The period up to 2019 is good example of the expansion phase of the wood pellet sector, followed by subsequent decline. It showed downward trend between 2019 and 2021. Following the outbreak of the war in Ukraine in 2022, there was slight increase, which is naturally related to the country's geopolitical situation.

Low share of energy production and consumption from wood pellets is primarily due to Hungary's reliance on other energy sources, such as nuclear power, natural gas, and renewable energy sources (RES) such as geothermal energy, solar energy, and wind power. Many EU member states, such as Denmark, Poland, and Croatia, often prefer locally sourced wood chips and residues to wood pellets for energy generation.

According to IndexBox forecasts, the production and consumption of pellets and the energy generated from them in Hungary is expected to stagnate or decline further in the coming years unless new incentives, subsidies, or consumer orientation (for example, by supporting net-zero emissions targets) are developed.

1.2.4. Czech Republic

For the purposes of energy statistics, the energy use of biomass means the combustion of wood and plant matter, including cellulose extracts, both separately and together with non-renewable fuels for the purpose of generating electricity or heat. Ministry of Industry and Trade of the Czech Republic (Bufka et al., 2024) uses simplified division of biomass into the following categories:

- fuel wood,
- wood waste, sawdust, bark, chips, residues from forest harvesting,
- plant materials,

- briquettes and pellets,
- cellulose extracts,
- liquid biofuels (for energy use),
- other biomass,
- charcoal (not statistically monitored).

Wood chips in the Czech Republic are produced as a residual product during wood processing or its targeted crushing (Krilek et al., 2024). Its origin can also be derived from regular tree trimming in orchards, maintenance of vegetation around roads, etc. Wood chips are classified as solid biofuels and are used to produce heat or electricity. Their characterization ranks them rather as a fuel for industrial combustion equipment and only marginally for heating small buildings. Wood chips require combustion equipment that is structurally adapted to the changing properties of the chips (Malaťák et al., 2024). These properties are mainly determined by the water content (% by weight). The water content of fresh wood chips reaches more than 55% by weight, in this state the wood chips are unsuitable for energy purposes (Malaťáková et al., 2021). Wood chips need to be dried to usable moisture content below 30% by weight, when their bulk density drops to approximately 250 kg·m^{-3} and their calorific value increases to over 10 MJ·kg^{-1}. The calorific value of wood chips is inversely proportional to the water content and ranges approximately from 10 to 16.5 MJ·kg^{-1} (Gendek et al., 2018b).

The total balance of solid biomass used for energy purposes in the Czech Republic is shown in Figure 1.11. The production of electricity and thermal energy from biomass by type in 2023 is shown in Tables 1.12 and 1.13. Wood chips and wood waste by their type of biomass have the largest share in the production of electricity and thermal energy in the Czech Republic.

Table 1.12. Electricity production from biomass by type in 2023 (Bufka et al., 2024)

Fuel	Gross electricity production (MWh)	Delivery to own business or facility including losses (MWh)	Electricity sales (MWh)	Fuel consumption (t)
Firewood	0	0	0	0
Wood chips, waste	1 332 803	324 925	1 007 878	1 348 955
Cellulose leachates	796 928	638 131	158 796	476 259
Biomass materials	96 169	8 387	87 782	99 679
Briquettes and pellets	212 610	48 302	164 308	129 409
Other biomass	0	0	0	0
Liquid biofuels	0,8	0,7	0,1	0,2
Total	2 438 510	1 019 745	1 418 765	2 054 301

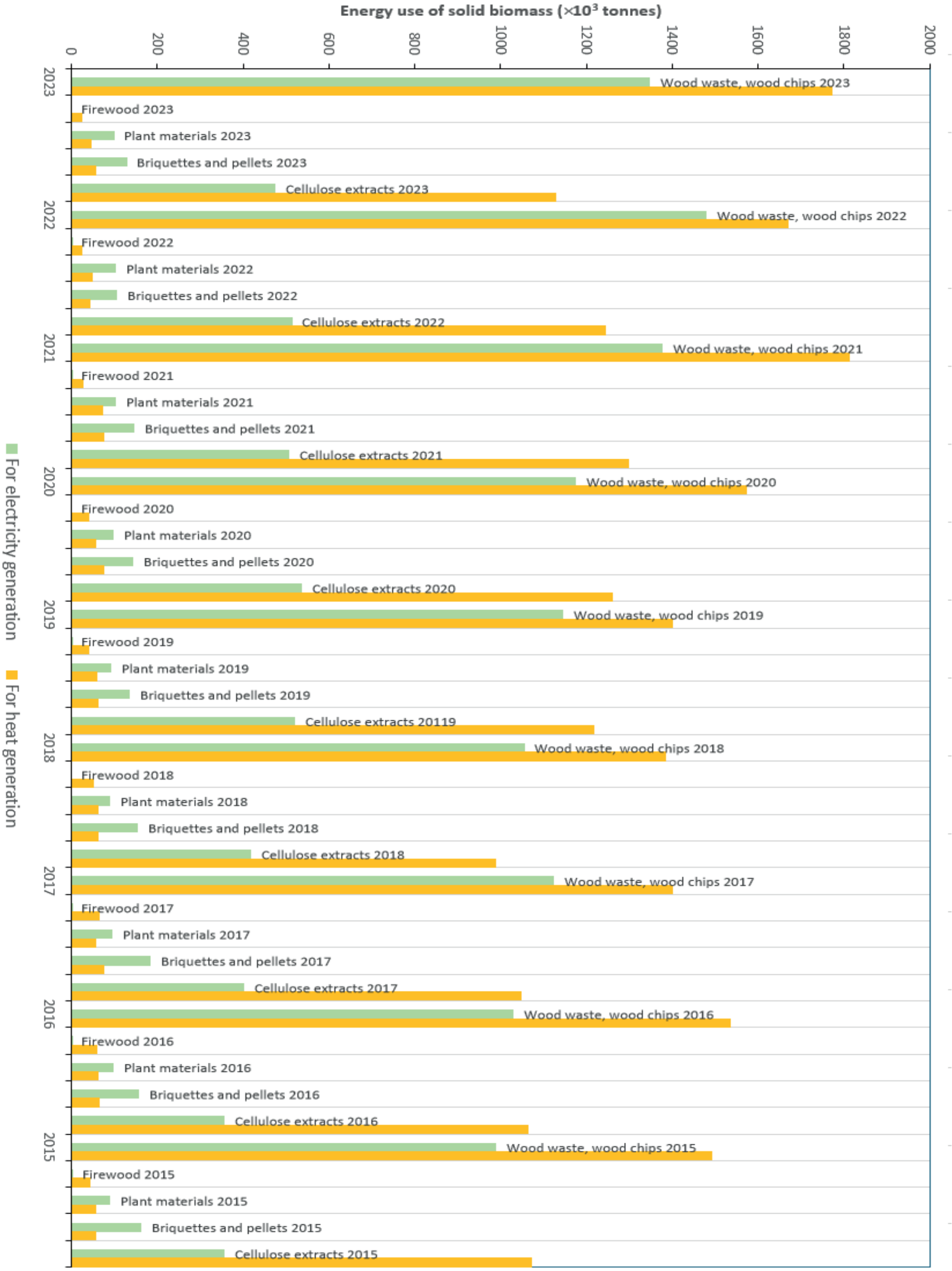


Figure 1.11. Energy use of solid biomass (tonnes) (Bufka et al., 2024)

Table 1.13. Thermal energy production from biomass by type in 2023 (Bufka et al., 2024)

Fuel	Gross heat production (GJ)	Delivery to own business or facility including losses (GJ)	Direct deliveries to third parties (GJ)	Fuel consumption (t)
Firewood	264 253	234 098	30 155	26 532
Wood chips, waste	14 462 488	8 172 018	6 290 470	1 774 073
Cellulose leachates	10 084 956	9 379 386	705 570	1 129 904
Biomass materials	485 483	139 879	345 604	46 881
Briquettes and pellets	841 146	269 307	571 839	58 657
Other biomass	0	0	0	0
Liquid biofuels	0	0	0	0
Total	26 138 325	18 194 687	7 943 638	3 036 047

The development of electricity production from 2010 to 2023 from biomass and wood chips (biomass) is shown in Tables 1.14 and 1.15. Electricity production from biomass is constantly growing, with current electricity production from wood chips having almost doubled since 2009.

Table 1.14. Development of total electricity production from biomass (Bufka et al., 2024)

	Gross electricity production (MWh)	Delivery to own business or facility including losses (MWh)	Direct deliveries to third parties (MWh)	Fuel consumption (t)
2010	1 492 239	647 011	845 227	1 253 224
2011	1 684 572	691 896	992 676	1 351 767
2012	1 817 337	748 384	1 068 954	1 458 831
2013	1 683 272	828 414	854 858	1 404 471
2014	1 992 217	872 214	1 120 003	1 504 733
2015	2 091 495	864 847	1 226 648	1 603 186
2016	2 067 745	835 414	1 232 331	1 643 865
2017	2 213 397	878 842	1 334 555	1 806 696
2018	2 120 883	856 702	1 264 181	1 720 830
2019	2 398 734	1 025 184	1 373 550	1 897 821
2020	2 498 965	1 066 564	1 432 401	1 956 385
2021	2 664 593	1 107 372	1 557 221	2 135 214
2022	2 659 449	1 115 976	1 543 473	2 204 776
2023	2 438 510	1 019 745	1 418 765	2 054 301

Table 1.15. Development of electricity production from wood chips, wood waste, etc. (biomass) (MPO 2024)

	Gross electricity production (MWh)	Delivery to own business or facility including losses (MWh)	Direct deliveries to third parties (MWh)	Fuel consumption (t)
2010	641 840	112 199	529 641	768 205
2011	820 001	141 455	678 546	845 218
2012	881 041	172 543	708 498	910 014
2013	787 970	183 115	604 855	868 035
2014	971 632	230 271	741 360	908 098
2015	1 064 771	249 451	815 320	990 706
2016	1 053 513	250 265	803 248	1 029 498
2017	1 133 382	258 236	875 146	1 123 599
2018	1 098 773	257 982	840 791	1 056 142
2019	1 229 830	279 635	950 195	1 146 021
2020	1 247 045	272 645	974 400	1 176 161
2021	1 430 219	324 135	1 106 084	1 377 328
2022	1 493 186	345 001	1 148 186	1 479 290
2023	1 332 803	324 925	1 007 878	1 348 955

The development of thermal energy production from biomass and wood chips (biomass) from 2010 to 2023 is shown in Tables 1.16 and 1.17. Thermal energy production from biomass is constantly growing, with the current production of thermal energy as well as electricity from wood chips having doubled since 2009.

Table 1.16. Development of total thermal energy production from biomass (Bufka et al., 2024)

	Gross heat production (GJ)	Delivery to own business or facility including losses (GJ)	Direct deliveries to third parties (GJ)	Fuel consumption (t)
2010	16 065 796	14 030 923	2 034 873	1 963 777
2011	16 132 625	13 615 828	2 516 798	1 936 961
2012	16 447 311	14 016 595	2 430 716	2 047 408
2013	20 053 936	16 118 151	3 935 785	2 436 130
2014	20 368 961	15 740 037	4 628 924	2 549 479
2015	22 214 848	16 740 913	5 473 934	2 726 226
2016	23 695 960	17 917 965	5 777 995	2 792 501
2017	21 940 177	15 648 881	6 291 297	2 650 008
2018	21 507 294	15 517 317	5 989 978	2 551 618
2019	24 154 160	17 398 171	6 755 989	2 785 587

	Gross heat production (GJ)	Delivery to own business or facility including losses (GJ)	Direct deliveries to third parties (GJ)	Fuel consumption (t)
2020	26 446 458	18 603 445	7 843 013	3 011 626
2021	28 486 112	19 529 868	8 956 245	3 292 391
2022	26 777 904	18 995 880	7 782 024	3 039 078
2023	26 138 325	18 194 687	7 943 638	3 036 047

The energy use of pellets in the Czech Republic is very dynamic with growing production and consumption. The Czech Republic is a significant producer of pellets and the number of households is growing, also thanks to subsidy programs for the replacement of old boilers. There has been a constant increase in pellet production in the Czech Republic since 2010, see Table 1.18. There is noticeable decrease in the production of wood pellets for energy purposes in the Czech Republic in 2023, see Table 1.18, to 470 thousand tons compared to 538 thousand tons in 2022.

Table 1.17. Development of thermal energy production from wood chips, wood waste, etc. (biomass) (Bufka et al., 2024)

	Gross heat production (GJ)	Delivery to own business or facility including losses (GJ)	Direct deliveries to third parties (GJ)	Fuel consumption (t)
2010	8 147 677	6 803 490	1 344 187	983 790
2011	8 415 717	6 613 994	1 801 723	1 005 722
2012	8 397 359	6 769 668	1 627 691	1 077 439
2013	10 012 747	7 199 441	2 813 306	1 252 275
2014	10 896 859	7 587 027	3 309 832	1 335 912
2015	12 313 628	8 417 844	3 895 784	1 492 231
2016	12 946 212	8 926 599,6	4 019 612	1 537 473
2017	11 464 006	7 039 886	4 424 120	1 401 504
2018	11 588 055	7 181 483	4 406 572	1 384 713
2019	11 903 110	6 944 152	4 958 958	1 401 818
2020	13 320 889	7 504 993	5 815 896	1 573 202
2021	15 083 677	8 205 731	6 877 946	1 812 845
2022	14 133 349	7 943 513	6 189 836	1 670 725
2023	14 462 488	8 172 018	6 290 470	1 774 073

Table 1.18. Basic balance of wood pellets (thousand tons) (Bufka et al., 2024)

	Production	Of which pellets certified ENplus	Import	Export	Change in stock	Delivery to the domestic market
2010	145	12	13	111	50	
2011	148	67	19	111	56	
2012	157	93	18	128	47	
2013	163	124	36	131	68	
2014	199	176	25	138	-26	199
2015	249	233	24	215	9	249
2016	330	311	24	277	15	330
2017	367	350	27	294	-1	367
2018	391	362	27	320	-1	391
2019	400	378	22	293	-13	400
2020	486	450	22	352	-3	486
2021	526	505	27	423	11	526
2022	538	504	22	374	-23	538
2023	470	444	18	318	-4	470

1.3. Legal framework for using solid biofuels

The development trends for renewable energy sources vary across European Union countries. These are largely influenced by natural resources of individual regions, historical and economic conditions in regions, and national legal frameworks. The European Union regulatory mechanisms allow certain degree of "freedom" for development of renewable energy sources, taking into account local potential and conditions, but the principles of sustainable economic and social development, as well as competitiveness, must be maintained. Directive 2009/28/EC of the European Parliament and of the Council, replaced by Directive 2018/2001 (European Union, 2018a) on the promotion of the use of energy from renewable sources assumes sustainable development through the development of renewable energy sources, including solid biofuels (or biomass). It also assumes the obligation to develop domestic biomass resources and implement measures to increase its availability, as well as to promote its use for energy purposes.

According to the Polish Ministry of Climate and Environment, Poland's energy transition will not rely on biomass. Estimates suggest that Poland's total biomass potential could reach approximately 280 PJ per year, which corresponds to 78% of projected demand in 2025. In practice, this translates into shortage that could impact investment decisions in the sector. Similar problems are occurring in other V4 countries. The biomass potential in the Czech Republic is 105-110 PJ·year^{-1}, in Slovakia 52 PJ·year^{-1}, and in Hungary 95-100 PJ·year^{-1}. This translates to projected demand in 2025 of cca 15% (CZ), 70% (SK), and 9-10% (HU), respectively. Biomass can be considered as renewable energy source only in the case where it meets certain sustainability criteria. This regulation limits „freedom” to source it, especially from abroad.

EU countries based on Regulation (EU) 2018/1999 of the European Parliament and of the Council from 11 December 2018 (*Regulation (EU)*, 2018) prepared and submitted documents regarding their National Energy and Climate Plans for 2021-2030. These plans envisage gradual reduction in the use of biomass in the energy sector. V4 countries lack sufficient sustainable woody biomass potential to implement biomass-based energy transition. Depending on the policies of individual countries, state support may be gradually phased out and funds redirected to other transition needs. Given the limited domestic resources of the V4 group affected by this issue, companies planning that the biomass-based transition will be forced to source imported biomass with Ukraine, North and South American countries as primary destinations.

The biomass and pellet trade offered both high-quality pellets and biomass that demonstrated average efficiency while also being low-priced. Quality requirements for pellets were not particularly stringent. These were generally limited to the operation of heating devices, not the quality of the biomass itself.

Boiler manufacturers themselves determined what type of pellets were suitable for their devices and owners should follow the recommendations provided.

The pellet certification was voluntary until June 2025. However, there were many producers who ensured their biomass met stringent standards, ENplus and DINplus certificates provided good measure of quality and producers or traders, who produced or sold biomass and meeting standardized production and quality requirements, could apply for these certificates. Some certified companies marketed their products primarily abroad and this resulted in significant supply of questionable quality pellets on the domestic markets.

The lack of uniform legal standards led to the sale of biomass that did not meet any quality requirements. With this situation developed unfair practices, i.e. trade in contaminated pellets with plastic fragments.

The new criteria have been introduced tightening quality standards for biomass (both imported and domestically produced) for protection of customers and standardization the law on pellet production and the requirements imposed on it. The goal is to eliminate solid fuels containing chemical additives from sale and allowing wood pellets and briquettes meet strict environmental requirements for heating purposes. Consequently, all lower-quality fuels will be withdrawn from sale.

Pellet quality regulations are being implemented across the V4 countries to varying degrees, depending on the geopolitical situation in each country. The new quality criteria for wood pellets intended for heating purposes were introduced in Poland from June 2025 by the Regulation of the Minister of Climate and Environment (Dz.U. 2025 poz. 618, 2025), which are consistent with the EN ISO 17225-2 standard (*ISO 17225-2*, 2021), valid in all European countries, including the V4 and EU countries. They introduce requirements:

- Pellet diameter ranging from 6 to 8 mm,
- Length ranging from 3.15 to 40 mm,
- Moisture content not exceeding 10% in the working state and 1.2% in the dry state,
- Minimum calorific value of 16.5 $MJ \cdot kg^{-1}$,
- Fines fraction not exceeding 1%,
- Bulk density ranging from 600 to 750 $kg \cdot m^{-3}$,
- Chemical additive content not exceeding 2% and maximum levels of selected elements: 0.3% nitrogen, 0.04% sulfur and 0.02% chlorine.

The introduction of stricter standards for wood pellets could disrupt the market and domestic distributors of this type of fuel could face significant challenges. The biggest problem could be a significant reduction in the availability of the raw material in domestic markets. Owners of biomass stoves will be forced for imported fuel, which will undoubtedly drive up pellet prices. Such changes will be felt most acutely by small producers, many of whom will be unable to adapt to the new market conditions.

There is also a significant risk for users of pellet boilers. The implementation of new regulations regarding this fuel type will cause the domestic market lack of pellets. Although the goal is to improve the quality of burned biomass and reduce pollutant emissions, such decisive action may make it difficult for many consumers to purchase sufficient fuel to heat their homes. The introduction of new, more stringent requirements for pellets will also result in an increase in the price of this type of fuel.

1.4. The use of biofuels and development directions

Russia's military aggression against Ukraine has exposed EU countries' dependence on fossil fuel imports and highlighted the need to secure the autonomy of the European Union's energy system. In the face of rising gas, oil and electricity prices, an alternative is the use of fuels from renewable sources, including biomass particularly from forestry and agriculture sector. Average annual biomass production from these sectors is 1,500 Mt dry weight, i.e., 1,000 Mt in agriculture and 0.500 Mt in forestry (Wierzbicki et al., 2023).

Biomass, also known as bioenergy, is one of the most important sources of renewable energy in Europe (2nd place) and world (3rd place). According to the EPA (United States Environmental Protection Agency) (US EPA, 2013) biomass encompasses various types of organic materials that can be processed and burned to produce energy. It should be produced and processed sustainably and efficiently for energy purposes to optimize greenhouse gas emission reductions and maintain ecosystem services.

Renewable energy sources meet less than quarter of the heating demand, with biomass accounting for half of this amount in heating, according to the International Energy Agency (IEA) from 2021 (IEA, 2025). Based on Eurostat data (Eurostat, 2025), among the countries that used renewable energy sources for heating and cooling (2021), including biomass, the highest share was recorded in Sweden (66.4%), Estonia (58%), Finland (58%), Latvia (57%), Denmark (51%) and Lithuania (50%). The lowest share was recorded in Ireland (6.3%), Netherlands and Belgium (8% each). The V4 countries recorded shares in Czech Republic 24.2%, Poland 21.0%, Slovakia 19.5% and Hungary 17.9% (Eurostat, 2025).

Renewable energy technologies have already developed to the point where they can compete with conventional energy systems. Renewable energy sources are usually local. They can significantly increase local energy security and thus reduce fossil fuel consumption, as well as support job creation, particularly in medium-sized enterprises, and promote regional development.

Biomass is a major source of primary energy, primarily used as a fuel in combustion processes. Biomass is generally considered to be all organic matter on Earth, including all biodegradable substances of plant and animal origin. Alternative fuels (biomass, biofuels) are typically of lower quality compared to conventional fuels (e.g., liquid fuels). Furthermore, the energy efficiency of devices powered by biomass (biofuels) is lower compared to those powered by high-quality conventional fuels. Furthermore, alternative fuels (biomass) often contain significantly more moisture than conventional fuels, which can lead to even more unfavorable situations. The presence of ballast in the form of moisture and minerals negatively impacts the effective calorific value of this fuel type, and this is more significant in the case of fuels with lower calorific values.

A significant problem (disadvantage) of biomass is also its relatively low mass, volume and energy density, which results in serious difficulties and increases the costs of transport, storage, preparation and dosing in combustion systems.

The development of biofuel market and technologies varies across EU countries. For example in Finland is biomass (primarily from forests) the main pillar of renewable energy. Its share is approximately 80% (414 PJ). More than half of the heat in the national heating system comes from biomass. The Finnish strategy focuses on optimizing the biomass value chain and developing biomethane infrastructure. Carbon dioxide capture technologies (BIO-CCS) and BIO-CCU processes are also being introduced, enabling the use of biogenic CO_2 for the production of biofuels and materials (Lenartowska, 2025).

The bioenergy sector has been thriving in Germany for many years. In Germany is currently changing its approach to biomass use although Germany is leader in pellet production in the European market. Biomass accounts for approximately 55% of the country's renewable energy, but the sector's growth rate is declining, particularly in the area of biogas. The German government is developing National Biomass Strategy for shift of approach in this field (NABIS), emphasizing the bioeconomy, resource efficiency and bioproducts, while slowly phasing out biomass energy production. Similar changes can be observed in Netherlands, which is changing its approach to biomass use in energy production, gradually phasing out its combustion in power plants and focusing on the bioeconomy. Although biomass accounts for 45% of renewable energy, its role in the energy sector will gradually decline in favor of more advanced applications, such as biofuels and biochemicals (Lenartowska, 2025, 2024).

One of Europe's leaders in biomass use is Austria, which accounts for 55% of the country's renewable energy. The main applications include residential heating and district heating, with more than half of installations relying on biomass. Austria is developing cogeneration and advanced biomass conversion technologies, such as production of synthetic gas and next-generation biofuels.

Italy is focusing on modernizing pellet and wood-fired heating systems, improving their environmental performance through condensing systems and advanced boiler filters. New technologies in this sector aim to reduce pollutant emissions in accordance with the requirements of the National Energy and Climate Plan (NECP).

France is focusing on the sustainable management of forest resources and the optimization of biomass use in heating and industry. Key activities include analyzing the forest carbon cycle, supporting sustainable timber harvesting and implementing energy transitions in line with the "Transitions 2050" scenarios, which outline pathways to achieving climate neutrality. France is aggressively developing biomass-based heating systems (Lenartowska, 2025, 2024).

Biomass currently accounts for 7.5% of the energy mix in Norway, but its importance is growing in industry and transport. Key investments include the production of biomethane and biochar as coke replacement in the steel industry. CO_2 capture and storage technologies are being implemented. Innovations in biomass logistics, aviation biofuels and biomass processing technologies are being promoted.

Sweden is investing heavily in the development of BECCS (Bioenergy with Carbon Capture and Storage) technologies, which capture and store biogenic CO_2. Leading projects focus on eliminating CO_2 emissions through the use of biomass in energy processes. The country is also developing transportation biofuels, implementing technologies for the production of sustainable aviation fuels and next-generation biofuels (Lenartowska, 2025, 2024).

Despite the different approaches of EU countries to the development of technology and the use of solid biomass, taking into account trade and own consumption, EU countries consume a total of over 1 billion tonnes of dry biomass per year.

1.5. Barriers to Biomass Combustion and Co-Combustion

Co-combustion biomass with conventional fuels in industrial or household applications is associated with number of barriers that can limit the efficiency and profitability of this process. The most important barriers include technical limitations of the equipment (Sahu et al., 2010), biomass quality (Paramonova et al., 2025), legal regulations, economic aspects, availability of biomass (fuel), greenhouse gas emissions, waste management, or simply skepticism and lack of knowledge.

Generating energy from solid biomass on large scale equipment is associated with certain technological limitations, which can be intensified by the biomass share increase in the fuel stream fed to the boiler (Gołuchowska et al., 2015). These limitations can negatively impact the operation of the installation, especially when using low-quality biomass, which primarily applies to direct co-combustion systems. Many furnaces and boilers are not designed to burn biomass, which can lead to energy efficiency issues and increased fuel consumption (McIlveen-Wright et al., 2011). Adapting equipment for co-combustion requires investment, which can be a barrier for many companies.

The physicochemical properties of biomass can make this material as technologically challenging fuel, significantly different from coal burned in power boilers designed for fossil fuels. Biomass itself has different physical and chemical properties, which also affect the combustion process. Using raw biomass with high moisture content, which significantly reduces the fuel's energy content per unit volume, can lead to combustion problems, increased pollutant emissions and ash deposition in furnace. Use of large fuel flows fed to the boiler is necessary for providing required amount of energy in the whole process is necessary when the high combustible content of biomass compared to coal alters the ignition and combustion conditions of the coal-biomass mixture in the boiler (Zuwała et al., 2010; Zuwała and Hrycko, 2005). In addition to its basic physicochemical properties, biomass also has different elemental composition than coal. Resulting hazards from the co-combustion process to boiler and non-boiler equipment may be caused by the relatively high chlorine content in biomass and the different chemical composition of ash compared to coal.

Legal regulations also limit the combustion and co-combustion of biomass. Regulations regarding pollutant emissions and fuel quality can be more or less restrictive in individual EU countries, making the introduction of biomass as a fuel difficult. Regulations covering air pollutant emissions, such as EU directives and national legislation, impose restrictions on the emission levels of greenhouse gases, particulate matter and other harmful substances. Co-combustion biomass must meet these standards, which may require additional investments in exhaust gas treatment technologies. Meeting emission standards can increase operating costs (Tomaszewski, 2020). Many regulations also require companies to report on emissions, fuel quality and environmental impact of their operations (Act of the Czech Republic, 2012). Companies are often required to obtain appropriate emissions permits and report their plans to the relevant authorities in case of biomass co-combustion. Sustainability regulations require that biomass has to be sourced from legal and environmentally friendly sources. This means that companies must be able to document that their raw materials are sourced sustainably. This process can be time-consuming and complex. This may also involve additional costs and administrative responsibilities.

The economic impact is also influenced by the costs of purchasing and transporting biomass, which can be higher than for conventional fuels and can impact energy sector, agriculture, forestry, timber industry and other local economies. This directly impacts the profitability of co-combustion. Biomass prices can vary depending on the type (e.g., pellets, wood chips, straw) and location. These costs has to be considered by companies planning to produce solid fuels or energy from biomass. High prices can impact project profitability. Transporting biomass can be expensive, especially if the raw materials come from rural locations. These costs include fuel, rental or operation of transport vehicles and handling fees. High transportation costs can limit the profitability of biomass purchases. For large orders or by collaborating with local suppliers, companies can achieve economies of scale, which lowers the unit costs of purchasing and transporting biomass. Effective logistics management can significantly impact overall operating costs. Biomass prices can be sensitive to changes in demand and supply, which can impact the stability of purchase and transportation costs. Unfavorable weather conditions or changes in agricultural policy can significantly increase biomass costs. Additional costs may also result from the need of adaptation of transport and transshipment infrastructure and production processes. In other hand these adaptations can contribute to improved economic outcomes and bring positive economic benefits to the regions where these investments are implemented. Benefiting from environmental policies offered by many countries, such as subsidies or payments for biomass producers and suppliers also improves economic outcomes. Such support can reduce purchase and transportation costs, making biomass more competitive compared to conventional fuels.

A significant factor limiting the feasibility and effectiveness of co-combustion of biomass with conventional fuels is the availability of raw materials. Biomass availability may be insufficient in some regions limiting its acquisition. High competition for raw materials, especially in regions where biomass is also used in other sectors (e.g., agriculture or food production), can lead to supply issues. Many types of biomass, such as straw and wood, are only available during certain seasons. Seasonality can affect supply stability and prices, which in turn impacts the profitability of co-combustion. Even when biomass is available, logistical challenges related to its transportation can pose a barrier. Long distances between the production site and the power plant increase transportation costs and delivery times, which impacts the effectiveness of co-combustion. Limited availability of high-quality biomass leads to problems with energy efficiency and pollutant emissions. Low-quality raw materials typically do not meet emission standards, which poses additional challenge and barrier. Limited access and increased interest in biomass as an energy source lead to increased competition in the market. This causes increase in raw material prices, which in turn affects the profitability of investments in co-combustion.

A significant factor in the adoption of biomass combustion and co-combustion and biomass-derived fuels is skepticism and lack of knowledge. Many people have negative view of the benefits, which can limit the implementation of new technologies. Biomass is considered climate neutral because CO_2 emissions during combustion are balanced by CO_2 absorbed during plant growth. There is a big problem with false belief among the public that burning biomass and solid fuels derived from it is the same as any other, and therefore pollutes the environment just like coal. This is usually due to lack of knowledge and understanding of co-combustion technology. Few people understand precise process and its benefits (e.g., reduced modernization costs for existing power plants). Many environmental organizations report that biomass combustion leads to deforestation, soil degradation and competition with food production. There are also numerous erroneous media reports that misinform the public, suggesting, for example, that all biomass combustion constitutes "greenwashing." There is lack of reliable analyses and data, which can lead to misconceptions about the environmental impact of biomass. Residents of regions with co-combustion plans often lack access to transparent data on emissions or biomass sources and this lack of information hinders the assessment of the actual environmental impact of these technologies. Skepticism and lack of knowledge should be countered through public education. Information campaigns should be conducted on the differences between coal and biomass, climate neutrality and biomass sources. Data on emissions, type of biomass burned and environmental impact should also be provided. The public should be informed that burning solid biomass fuels does not result in deforestation. Annual forest growth is greater than timber harvesting and biomass for solid fuel production often comes from wood industry waste or agricultural residues.

Biomass co-combustion generates waste that must be properly managed. Issues related to disposal of ash and other waste can pose additional challenges in implementing this technology, for which businesses and public must be prepared. Managing waste generated during biomass co-combustion is a key issue from the perspective of environmental protection, public health and legal compliance. Although biomass is perceived as a more environmentally friendly fuel, the process of co-combustion it with coal generates waste that requires appropriate management. The main waste products from biomass combustion are fly ash, bottom ash, slag and harmful gases. Ash contains heavy metals (e.g., cadmium, lead, arsenic) and inorganic compounds (oxides, sulfates). Their chemical composition depends on type of biomass and co-combustion ratio. Sometimes biomass ash can be more alkaline than coal ash. Slag forms at the bottom of the boiler and may contain particles of unburned biomass and other residues. The sulfur and chlorine content of biomass can lead to corrosion and formation of difficult deposits. Although these gases are not waste in the classic sense, their emissions (NO_x, SO_2, CO, dust, dioxins) must be controlled and filtered. Filters are essential in exhaust gas cleaning processes. The management of waste resulting from the co-combustion of biomass and solid fuels derived from it is regulated at the European Union level by the IED Directive 2010/75/EU (European Union, 2010) on industrial emissions. Additionally, each country has its own internal regulations, such as the Waste Act, the Regulation of the Minister of the Environment on the Waste Catalog and the Regulation on Permissible Emission Values from Installations. Good management of waste from biomass combustion involves recycling, reusing and potentially disposing of it. Harmless ash is used as an additive to cement and concrete for soil fertilization and land reclamation or after processing for soil stabilization.

Although biomass combustion and co-combustion are promoted as a way to reduce greenhouse gas emissions, there can be barriers related to the emissions of harmful substances themselves, which may be inconsistent with adopted climate goals. Biomass is generally considered CO_2-neutral fuel. It is assumed that the CO_2 produced during biomass combustion is offset by the CO_2 absorbed by the plant during photosynthesis. Biomass has to be harvested sustainably and the obligation to demonstrate sustainability criteria and reduce greenhouse gas emissions for biomass is reported from EU law, i.e., Article 38(2) and Article 38(5) of Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 (European Union, 2018b) on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 2012/601 (European Union, 2012). This obligation entered into force on 1 January 2022, regardless of the RED II Directive and implementing acts issued on its basis.

The issue of sustainable biomass harvesting is crucial for actual emission reduction. The biomass combustion process can generate other pollutants, but when biomass is co-combusted with coal, harmful gas emissions can be comparable to those produced by burning coal alone. Furthermore, emissions can depend on the type of biomass and the conditions under which the combustion process takes place. Overcoming these barriers requires collaboration between the public and private sectors, investment in new technologies and education about the benefits of biomass use.

Despite these barriers, investments in biomass-combustion CHP plants are growing. Examples include the latest CHP plants operating in various EU countries, which rely on biomass derived from local wood industry waste. These plants are co-financed by various EU and national programs. This results in reduced energy production costs and less dependence on imported fuels. Furthermore, integrating local businesses into the supply chain can stimulate their development and expanding the activities of companies (including forestry service providers) to include biomass production can diversify their revenues and increase financial stability. All of this can translate into market growth and biomass utilization.

2. BASIC PROPERTIES OF SOLID FUELS FOR THERMOCHEMICAL PROCESSES

For the purposes of energy utilization of biomass, technical analysis, elemental analysis and chemical analysis are performed, the gross and net calorific values are determined.

Gross Calorific Value (*GCV*, Q_s), or higher heating value, which includes the latent heat of condensation from the water vapor formed during combustion, and Net Calorific Value (*NCV*, Q_i), or lower heating value, which does not account for the water vapor's latent heat and is more practical for "as received" fuel.

The purpose of technical analysis is to generally assess the suitability of specific fuel for use in energy processes. Technical analysis includes determining the moisture, ash, volatile matter and bound carbon content (Kuglarz et al., 2018). Many researchers and laboratories use the thermogravimetric method (*TGA*) for technical analysis, which involves continuous recording of sample mass change as a function of time or temperature while heating at controlled conditions. State designation has been introduced for providing clear reference level for biomass fuel test results. For this purpose, four analytical states have been distinguished (Cai et al., 2017) – working condition (*r*), analytical state (*a*), dry state (*d* or *dry*) and ash-free condition (*daf*).

To assess the suitability of energy processing and the use of solid fuel in the form of wood chips and pellets in the selected thermochemical processing activities, or to evaluate the quality of solid fuel, it is necessary to know the properties that sufficiently characterize it. These are primarily:

- water content in fuel W (% wt.),
- ash content in fuel A (% wt.),
- elemental composition of fuel: content of carbon, hydrogen, nitrogen, sulfur and oxygen (% wt.),
- gross calorific value Q_s (MJ·kg^{-1}) and net calorific value of fuel Q_i (MJ·kg^{-1}),
- volatile and non-volatile combustible matter in fuel V (% wt.) and NV (% wt.),
- characteristic ash temperatures t_A, t_B, t_C (°C),

but also other physical-mechanical properties that are not analyzed in this part of the publication.

2.1. Elementary analysis

Elemental analysis evaluates the content of the basic elements that make up the organic matter of solid fuels: carbon, hydrogen, oxygen, nitrogen, sulfur, as well as other elements such as phosphorus and chlorine. The proportions of individual elements in solid fuels vary depending on the fuel type.

All solid fuels that occur in their natural (raw) state consist of three basic components: total water, ash (more precisely, ash content) and combustible matter. This composition can be expressed by the relationship:

$$W + C + H + O + S + N + A = 100\% \quad 2.1$$

where: W, C, H, O, S, N, A are the mass fractions of all water, carbon, hydrogen, oxygen, sulfur, nitrogen and ash in the original state of observed fuel (% wt.).

Water and ash form the non-combustible part of the fuel, which is also referred to as ballast or weight. Both of these components reduce the calorific value of the fuel. Their presence in the fuel directly affects the design of combustion equipment and is often a source of numerous difficulties during operation.

The combustible part of the fuel consists of carbon, hydrogen, sulfur and nitrogen. Of these elements, only carbon, hydrogen and sulfur participate in the actual combustion, i.e. exothermic reactions with air oxygen. Oxygen from the combustible acts as an oxidizer. The only component that does not participate in combustion is nitrogen. All three basic components of the fuel (water, ash, combustible) are very important factors in combustion and their properties affect not only the design of the combustion equipment, but also its operation (Malat’ak et al., 2010; Malat’ak and Vaculík, 2008; Rybín, 1985).

Carbon C ($Q_i = 33.9\ MJ\cdot kg^{-1}$) is the main carrier of thermal energy and is found in fuel in the form of organic compounds. Carbon compounds are one of the foundations of the world's energy industry, where fossil fuels such as natural gas and coal serve as an energy source for electricity production and heating.

Hydrogen H ($Q_i = 119.7\ MJ\cdot kg^{-1}$) is colorless, light gas, without taste or odor. It is flammable, burns with bluish flame, but does not support combustion. It is 14.38 times lighter than air and conducts heat 7 times better than air. When burning, hydrogen develops about 4 times more heat per unit weight than carbon, which has a positive effect on the calorific value of the fuel. The total hydrogen in the fuel consists of bound and unbound hydrogen. Bound hydrogen is the part of hydrogen that is bound to oxygen. This hydrogen consumes certain amount of heat to evaporate water. Unbound hydrogen is the part of hydrogen that remains after combining with the entire oxygen content in the fuel.

Sulfur S ($Q_i = 10.5\ MJ\cdot kg^{-1}$) is non-metallic chemical element of yellow color, relatively abundant in nature. It belongs to the group of so-called chalcogens. Sulfur is undesirable in fuel, although it increases the calorific value. The products of sulfur combustion have an adverse effect on the durability of the combustion equipment and pollute the surrounding atmosphere. Sulfur burns in air with blue flame, forming sulfur dioxide SO_2 and in small quantities sulfur trioxide SO_3. Sulfur emissions, due to the trace amount of sulfur contained in biofuel, do not pose any problems in terms of limit values (Malat’ak et al., 2010; Malat’ak and Vaculík, 2008; Obroučka, 2001).

Oxygen O_2 is gaseous chemical element that forms the second main component of the Earth's atmosphere. It is biogenic element and its presence is essential for the existence of most living organisms on this planet. When mixture of oxygen and hydrogen burns, temperatures of over 3,000°C can be reached and oxy-hydrogen flame is used to cut steel and melt metals with a high melting point, such as platinum metals. Oxygen is an undesirable part of biofuel, because it binds hydrogen and partly carbon to hydroxides, water and oxides (Malat’ak et al., 2010).

Nitrogen N is gaseous chemical element that forms the main component of the Earth's atmosphere. It is one of the biogenic elements that are the basic building blocks of living matter. Nitrogen is gas without color, taste or odor. It is not toxic or otherwise dangerous. Nitrogen in the atmosphere is made up of diatomic molecules that are connected by very strong triple bond. This triple bond results in its low reactivity. Nitrogen is an inert gas, which means that it reacts with other chemical compounds only at high temperatures and pressures. Nitrogen combines with most elements at high temperatures, e.g. with oxygen at a temperature of around 2,500°C. Nitrogen does not participate in combustion reactions and passes completely into the flue gases. Its presence reduces the content of other elements, which is reflected in decrease of the calorific value (Malat'ak et al., 2010).

Chlorine Cl is toxic, pale green gas, the second member of the halogen series. Chlorine also largely passes into the gaseous phase during combustion. The most limiting factor for the concentration of chlorine in fuel is its corrosive effect when combined with alkaline elements (Nielsen et al., 2000; Obroučka, 2001). The example of the elemental composition of wood biomass and selected biofuels is given in Table 2.1.

Table 2.1. Elemental composition of wood biomass and selected biofuels (Aniszewska et al., 2020; Malaťák et al., 2020; Werle, 2021)

Biomass	C	H	N	S	O	Cl
	% wt.					
Wood pellets	49.61	5.94	0.06	0.02	44.37	0.004
Wood chips	47-52	6.1-6.3	<0.3	0.05	38-45	0.02
Pine cones	45.70-	5.3-5.9	0.15-	<0.01	39.6-	-
Spruce cones	46.85	5.1-5.7	0.37	0.02	37.36	-
Spruce wood	49.80	6.30	0.13	0.02	43.20	0.005
Larch cones	51.9	5.7	0.8	<0.02	39.8	-
Beech wood	47.90	6.20	0.22	0.02	43.30	0.006
Willow wood	47.10	6.10	0.54	0.45	44.20	0.004
Poplar wood	47.50	6.20	0.42	0.03	44.10	0.004

The content of carbon, hydrogen and oxygen depends on the degree of metamorphism (biomass – carbon). As the degree of metamorphism increases, the carbon content increases significantly, while the oxygen content decreases and the hydrogen content drops slightly. In practice, the nitrogen and sulfur content do not depend on the degree of fuel metamorphism. The type of biomass and its origin determine the chlorine content and causing low-temperature corrosion, which negatively affects its thermal utilization process. For example, straw contains large amounts of chlorine, which is related to the commonly used plant protection products based on this element and its compounds.

2.2. Water content in solid fuels

Water is contained in every solid fuel. Like ash, water is a non-combustible component of the fuel, which reduces its calorific value and is therefore undesirable in the fuel. The water content in solid fuels varies widely from 0% to 60%. The water content in its original state can exceed 90% in some biomass species, such as peat. The natural water content in the fuel is reguled by its geological age. The younger the fuel, the more water it contains (Malat'ak et al., 2010; Trnobranský, 1996).

Water is bound in fuel in several ways. For routine analytical determination, free and bound water are important, which constitute all water in fuel. Free water can be separated from the fuel by centrifugation, dripping or filtration. Free water is also called mixed water. The remaining portion of all water is capillary bound water. This is divided into gross, hygroscopic and occluded water (He et al., 2013).

Gross water is determined by air drying of untreated fuel sample, in which gross water is determined. Gross water is then the difference in weight of the sample before and after drying. Drying the fuel at temperature of 105°C releases hygroscopic water from the fuel and this amount of water is referred to as residual water. Occluded water represents small amount of water that is not removed even by intensive drying and is only released at decomposition temperatures of the fuel (Malat'ak et al., 2010).

Transient water is the part of water that is lost during drying of biomass in air at ambient temperature, reaching state of sorption equilibrium with air humidity (Acharjee et al., 2011). Bound (hygroscopic) water describes water content in the fuel that remains after removal of transient moisture. The sum of transient and bound water is the total water, W_t.

The moisture content of biomass (Figure 2.1) is directly related to its type, season and atmospheric conditions (temperature and air humidity) (Čermák et al., 2024).

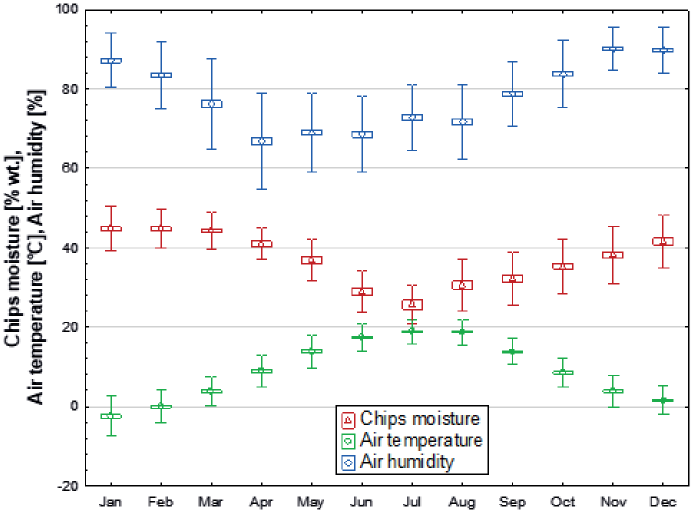


Figure 2.1. Moisture content, air temperature and air humidity of green wood chip samples in individual months followed for the years 2013-2019 (Čermák et al., 2024)

The water content of the fuel is reported in percentage by weight. The amount of mixed water, e.g. in sludge, is separated from the coal in centrifuge or filtered out. Mixed water is not included in the fuel sample and is reported separately (Malat'ak et al., 2010; Rybín, 1985).

2.3. Ash content in solid fuels

Mineral substances contained in solid fuel (natural and artificially refined) before its combustion are called ash. Ash is mostly composed of silicates, carbonates, sulfates and other compounds. The largest proportion of ash is formed by silicates of aluminum (kaolinite), calcium, magnesium and iron, free silicon dioxide, calcium and iron carbonate, smaller amount of iron sulfides (pyrite) and small amount of calcium sulfate.

Solid residue formed from the ash by burning fuel in fireplace is generally, but not entirely correctly, called ash. Ash is solid residue that is obtained by complete combustion of solid fuel at temperature of 800 ± 25°C in oxidizing atmosphere. In this process, the ash (original mineral components) decomposes into volatile products and non-volatile residue or releases crystal water (Malat’ak et al., 2010; Trnobranský, 1996). Carbonates decompose into carbon dioxide and metal oxides:

$$CaCO_3 = CaO + CO_2 \tag{2.2}$$
$$MgCO_3 = MgO + CO_2 \tag{2.3}$$
$$FeCO_3 = FeO + CO_5 \tag{2.4}$$

The above decomposition processes result in changes in weight and are the cause of the difference in weight between the original ash and the ash formed from it. These processes simultaneously incinerating the original mineral components, which is determined in the laboratory. The weight of the ash is less than the weight of the fly ashes. The weight of the ash can also increase by the oxidation of some oxides formed, i.e. by adding oxygen. For example, iron oxide is oxidized into ferric:

$$4FeO + O_2 = 2Fe_2O_3 \tag{2.5}$$

Alkaline-reacting oxides form sulfates with sulfur dioxide and oxygen:

$$2CaO + 2SO_2 + O_2 = 2CaSO_4 \tag{2.6}$$

Analysis of solid fuel ashes revealed that they are mainly composed of SiO_2, Al_2O_3, Fe_2O_3, FeO, CaO, MgO, MnO, Na2O, K_2O, SO_3, TiO_2 and P_2O_5. Various elements were found, e.g. Zn, Pb, As, Ge, Be, Ni, Cd and others in addition to these oxides (basic components of ashes). Depending on which of the above oxides predominates, the solid residues (slag, fly ash) have their characteristic properties (Bradna et al., 2016; Malat’ak et al., 2010; Trnobranský, 1996).

The ash content of plant-based fuels is very low. Wood biomass fuels have approximately 86% lower ash content than brown coal, which has the following positive benefits:

- when burning wood waste, the emission of solid ash particles will be reduced,
- when burning wood mass, the need for continuous removal of solid residues after combustion will be eliminated and only one-time ash removal after certain number of operating hours will be sufficient.

Ash resulting from the combustion of biomass contains mainly calcium, silicon, potassium, sodium, phosphorus and chlorine (Mlonka-Mędrala et al., 2020). The diversity of biomass as fuel means that both the biomass and the ash generated during its combustion are also characterized by high variability in heavy metal content. Due to the high content of mineral substances (ash), these fuels must be considered as technically more demanding fuels. The melting conditions of ash are significantly influenced by the concentration of these three elements (Ca, Mg, K). Calcium and magnesium increase the melting point, potassium and chlorides cause it to decrease (Malat'ak et al., 2010; Trnobranský, 1996).

Table 2.2. Example chemical composition of ash from selected types of wood biomass (% of dry matter) (Werle, 2021, 2014a, 2014b; Werle et al., 2019a, 2019b, 2011; Werle and Wilk, 2013)

	Fuel		
Chemical compound	Pine sawdust	Willow sawdust	Oak sawdust
SiO_2	24.50	2.14	6.64
Fe_2O_3	2.47	0.40	0.63
Al_2O_3	6.01	0.52	1.40
Mn_3O_4	2.23	0.05	2.30
TiO_2	0.34	0.05	0.11
CaO	23.50	39.40	17.30
MgO	5.90	3.45	3.12
SO_3	3.67	2.53	3.82
P_2O_5	3.15	6.12	3.97
Na_2O	0.84	0.21	0.31
K_2O	11.60	14.10	34.40
BaO	0.10	0.14	0.43
SeO	0.07	0.13	0.09
Cl	0.78	0.42	1.12

It should be noted that it can be used for various purposes, despite the drawbacks resulting from the chemical composition of ash (Table 2.2) and its impact on biomass energy utilization processes. Ash can be used as a mineral fertilizer rich in phosphorus and other micronutrients (Tosti et al., 2019), but this utilization is subject to compliance with the limits set by regulations, primarily in relation to the content of heavy metals in its elemental composition.

2.4. Gross and net calorific value of solid fuels

The combustible substances of the fuel are mixed and merged with oxygen and produce combustion products called flue gases during combustion process. This process is accompanied by the release of certain amount of heat, which for solid and liquid fuels is related to the mass unit kJ·kg^{-1} (under normal conditions: t = 0°C, p = 101.3 kPa, designation m^{3}N). In technical practice, the released heat is expressed as the gross calorific value Q_s or as the net calorific value Q_i of the fuel.

The gross calorific value Q_s is the amount of heat released during the complete combustion of one unit of fuel kg·m^{-1}, assuming that the flue gases cool to 0°C and that all the steam generated during combustion condenses. The flue gases leave and water turns into steam during the combustion of fuel in combustion plants with temperature higher than 100°C. The net calorific value of the fuel Q_i is more often used in thermal calculations.

The net calorific value of the fuel Q_i is the amount of heat released during the complete combustion of fuel unit when the flue gases cool to 0°C, while the moisture of the fuel remains in the flue gases as water vapor.

The net calorific value of the fuel is therefore lower than the gross calorific value by the amount of heat needed to heat water from the original fuel temperature to 100°C and by the specific heat of vaporization of water. The total amount of heat is considered to be approximately 2,500 kJ per 1 kg of moisture.

The net calorific value of the fuel is commonly calculated in practice because of the fact, when burning solid fuels in furnaces, the evaporated water with the flue gases leaves the chimney at higher temperature than the dew point of water vapor, so it does not condense, therefore it takes away some of the heat in the form of vaporization heat.

The dependence between the gross calorific value Q_{sr} and the net calorific value Q_{ir} can be expressed by the relationship according to ISO 1928 (*ISO 1928:2009*, 2009):

$$Q_i = Q_s - 24.42 \cdot (W + 8.94H), \quad kJ \cdot kg^{-1} \tag{2.7}$$

where:

W – is the water content in the analytical sample (%);
8.94 – coefficient for converting hydrogen to water;
H – hydrogen content in an analytical sample (%);
24.42 – value that corresponds to the energy consumed for heating and cooling 1% of water at temperature of 25°C.

The conversion of the net calorific value Q_{in} at total water content W_t to different total water content W_{ti} is carried out according to the formula:

$$Q_{in} = \frac{100 - W_{ti}}{100 - W_t} \cdot (Q_i + 24.42W_t) - 24.42W_{ti}, \quad kJ \cdot kg^{-1} \tag{2.8}$$

where:

W_{ti} – is the content of all water to which we are making the conversion (% wt.);
W_t – the total water content in the original sample (% wt.);
Q_i – net calorific value of the original sample (kJ·kg^{-1}, kJ·m^{-1}).

The gross calorific value can be determined most accurately by measurement in calorimeters (ČSN 44 1352). The gross calorific value is in technical practice measured and net calorific value is determined by calculation, which uses the results of the overall (elementary) or technical (immediate) analysis of the fuel. (Malat'ak et al., 2010). Another popular way to determine the gross calorific value is to use empirical equations (Channiwala and Parikh, 2002; Jenkins et al., 1998; Werle, 2021; Ye et al., 2013).

The fuel's calorific value (*LHV)* is of primary importance for right choice of energy use and depends primarily on the moisture content and chemical composition of the fuel (Figure 2.2). Characteristic feature of the calorific value is the relatively wide range of values it assumes. This is due to the diverse composition of the organic matter in the biomass during its harvest. Important factors include the plant species, the location of growth, the type and quality of the substrate, atmospheric conditions, the vegetation period, and many others. For the mentioned reasons, the calorific value of biomass („*daf*" state) should be generally calculated as random quantity with specified probability, assuming values within given range of interest. (Postrzednik, 2014, 2011).

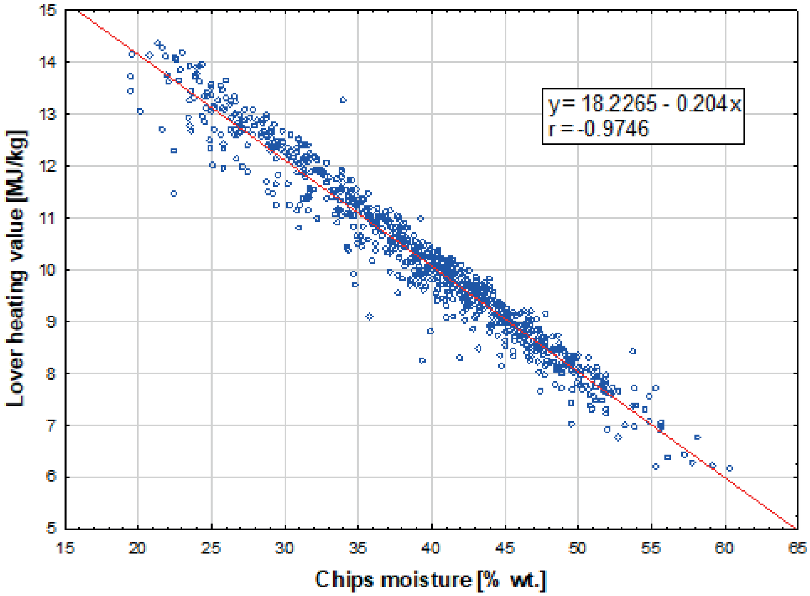


Figure 2.2. Dependence of calorific value (LHV) on moisture content in green wood chip samples (Čermák et al., 2024)

Depending on the type of plant, for biomass with 40–60% moisture content, the calorific value ranges from 5–11 MJ·kg^{-1}. For biomass dried to 10–20% moisture content, the calorific value is 15–18 MJ·kg^{-1}, and for completely dried biomass, it reaches over 19 MJ·kg^{-1}. (Table 2.3).

The calorific value of fuels from wood biomass depends primarily on the water content. For this reason, its value will vary within wide range. It is interesting that for wood materials, different types of wood have practically the same calorific value for given water content. This can be explained by the fact that the chemical composition of the fuel of different wood types is approximately the same. The common idea that hardwood has higher calorific value than softwood is wrong, because it is only matter of different specific gravity of these types of wood (Malat'ak et al., 2010; Trnobranský, 1996).

Table 2.3. Gross and net calorific value for selected types of wood biomass (Aniszewska et al., 2020; Aniszewska and Gendek, 2014; Čermák et al., 2022)

Type of biomass	Humidity	HHV	LHV
	%	MJ·kg^{-1}	
Pine cones	In the dry state	21.6	20.3
Spruce cones	In the dry state	21.1	19.9
Larch cones	In the dry state	21.9	20.6
White wood chips	In the dry state	20.15	18.83
Green wood chips	In the dry state	18.81	17.59
Brown wood chips	In the dry state	21.13	19.85
Branches	16-58	15.9	-
Pine	12	19.3	16.7
Spruce	-	15-16	-
Oak	13	18.6	14,3
Beech	-	19.2	-

2.5. Volatile combustible matter

Another important value, from the point of view of the combustion process, is the content and course of the release of volatile combustible matter from the fuel. Volatile combustible matter is the amount of gaseous substance that is released from the combustible matter of the fuel when it is heated in the absence of air. (Cai et al., 2017). Volatile combustible matter is part of the total combustible matter contained in the fuel. Volatile combustible matter consists of gaseous combustible substances that are released from the fuel when heated to certain temperature. The burning of volatile combustible matter appears as a flame. The method of determining volatile combustible matter in the fuel is specified in (*ISO 18123*, 2023).

The volatile combustible matter content of fuel depends on the geological age of the fuel. The younger the fuel is geologically, the higher has volatile combustible matter content. Anthracite and hard coal have the least volatile combustible matter content. Its content increases with brown coal and lignite, and peat and wood contain the most of this content. (Malat'ak et al., 2010). Volatile combustible matter significantly helps in the ignition of fuel in the firebox and stabilizes the combustion process. Younger fuels with higher proportion of volatile combustible matter ignite more easily than older fuels. (Trnobranský, 1996).

Biomass is characterized by high content of volatile matter, which affects the high reactivity of this fuel type and prefer it among other things in easier ignition (Werle, 2021; Werle et al., 2011).

If the volatile matter in the firebox does not burn, either because the firebox is not large enough or because it did not have enough oxygen, it leaves with the flue gases and creates loss of unburned combustible gases (chemical burnout loss). If the combustible gases reach places where they cool below the combustion temperature, some of their components (i.e. hydrocarbons) decompose and form soot/carbon black. This partly settles on the heating surfaces of the boiler and partly comes out of the chimney as dark smoke. (Malat'ak et al., 2010; Trnobranský, 1996).

There is generally known that the fuel with high content of volatile combustibles matter burns with a long flame. In the case where the gases do not have enough oxygen to burn, the flame is sooty. On the contrary, fuel with low content of volatile combustibles burns with a short flame and with volatile combustible content below 15% burns almost without a flame at high temperatures. The time course of the release of volatile combustibles is constant during combustion of moist wood materials. This can be explained by the fact that there is partial overlap between the phases of fuel drying and the release of volatile combustibles. The fuel drying phase slows down the release of volatile combustibles and the time course of the CO content in the flue gas does not show such changes as with dry wood waste (Trnobranský, 1996). There is necessary to pay attention for appropriate supply of combustion air in order to minimize the loss due to chemical imperfection of combustion. The amount of heat loss due to chemical imperfection of combustion depends on the relative CO content (%) in the flue gas (Malaťák et al., 2024).

For the high volatile combustion matter content in biomass is necessary special design solutions for combustion chambers, including introducing combustion air above the fuel bed. During torrefaction high volatile matter content in biomass causes excessive volatilization and contributes to the formation of large amounts of undesirable products such as tar and soot, as well as increasing the share of the liquid fraction generated during pyrolysis (Anukam et al., 2015; Singh Chouhan and Sarma, 2013).

2.6. Sulfur content in solid fuels

Sulfur occurs in solid fuels in various forms. Depending on the fuel components to which is sulfur bound, it is divided into organically and inorganically bound sulfur. Total sulfur is determined in solid fuels, which is given by the sum of combustible and non-combustible sulfur.

Higher sulfur content in solid fuels is unpleasant factor in operating conditions. According to experience and research activities in this area, higher sulfur content of over 1.8% in solid fuel and over 1.0% in liquid fuels (fuel oils) can cause noticeable damage during boiler operation (Rybín, 1985).

Combustible sulfur is converted into sulfur dioxide SO_2 during burning process of solid fuels. Under certain conditions (the presence of catalytic substances and combustion temperatures around 500°C), part of the sulfur dioxide is converted into sulfur trioxide SO_3.

This results in formation of sulfuric acid H_2SO_4 with water vapor. Condensed sulfuric acid is corrosive to pipes and iron parts of boilers, and also promotes the formation of cemented deposits on the heating surfaces of boilers in the area of lower flue gas temperatures. Air heaters or water heaters are often attacked by corrosion. Non-combustible sulfur passes into solid combustion residues (cinders, slags) (Ren et al., 2017; Rokni et al., 2018).

The advantage of wood biomass fuels is only trace content of sulfur and no harmful gaseous exhalation SO_2 is produced during combustion. The dew point temperature of the flue gases will also decrease as a result of wood biomass combustion process and the measured value will only be function of the water vapor content in the flue gases and the excess air. The dew point temperature of the flue gases during combustion process of wood will be significantly lower than in combustion of coal. By appropriately designing of additional heating surfaces of the boiler can be chimney loss reduced to minimum without risk of low-temperature corrosion of additional surfaces (Malat'ak et al., 2010; Trnobranský, 1996).

2.7. Characteristic temperatures of solid fuel ash

For the operation of various types of solid fuel furnaces, it is important to know the so-called ash melting point. This is the temperature at which all ash components melt. Ash melting occurs in a wide temperature range (200°C and more), at which the state of the ash changes. This change is characterized by three temperatures that are recorded when measuring the melting point:

- softening point t_A (°C),
- melting point t_B (°C),
- creep temperature t_C (°C).

The ash melting point determines how high can rise up the combustion temperatures in the furnace in order to avoid malfunctions in the combustion equipment, which is necessary to observe for combustion processes. These malfunctions can be caused by the melting of the ash on the grate and the filling of the gaps in the grate with slag. It means problem with the sticking of softened ash particles to the furnace walls and the formation of deposits, etc.

The ash melting point depends on the composition of the ash and the ambient atmosphere in the combustion chamber. Silicon dioxide and aluminum oxide have negative effect on increasing the melting point. On the other hand iron oxides, titanium oxides, calcium oxides, magnesium oxides, sodium oxides and potassium oxides reduce the melting point (Malat'ak et al., 2010; Rybín, 1985; Trnobranský, 1996).

Iron compounds have the greatest influence on the melting points of ashes. The melting points of ashes containing iron oxides are the lowest in strongly oxidizing atmosphere, which consists of oxygen, air, water vapor and carbon dioxide. Ash has slightly lower, but still high, melting points in strongly reducing environment. This consists of hydrogen and carbon monoxide, which are lowest in mixed environment (mixture of hydrogen and water vapor) (Malat'ak et al., 2010; Rybín, 1985; Trnobranský, 1996).

The melting points of ash in fuels from plant biomass are significantly influenced by the concentration of calcium, magnesium and potassium. While Ca and Mg increase the melting point, K and chlorides decrease it. Biofuels derived from woody biomass have higher melting points than those of straw due to the high content of Ca and Mg. Previous combustion tests and sources from literary sources show that for straw, whole cereal plants and hay, the temperature of the combustion space in the ash formation area should not be higher than 850 - 900°C and for woody material 1150°C (Malat'ak et al., 2010; Rybín, 1985; Trnobranský, 1996).

The contamination of heat exchange surfaces is also problem. The potassium-rich ash already sinters into glassy mass at about 850°C, which adheres very firmly to the lining of the combustion device and to the grate. During mechanical cleaning, layers of the lining peel off, and the actual removal of the ash is difficult. The gasification of the fuel (temperature 600°C) and the afterburning of the combustion gases (temperature up to 1,100°C) in larger furnaces (such as those in local heating plants) should always be separated (Rybín, 1985; Trnobranský, 1996).

2.8. Chemical composition of wood

Wood, as part of the lignocellulosic biomass, is the richest renewable source of carbon on Earth. Other lignocellulosics, such as agricultural residues, logging residues, herbaceous and woody energy crops and specialty crops, are abundant, cheap and renewable, which can make them an alternative to fossil fuels. Lignocellulosic biomass is mainly composed of three biopolymers (cellulose, lignin and hemicelluloses), in addition to minor components. Cellulose, hemicelluloses and lignin constitute approximately 90% of the dry weight of the plant (Scelsi et al., 2021).

Biomass contains lignin, cellulose and hemicelluloses (together these components are referred to as lignocellulose) in terms of chemical composition. Depending on the type and origin of the biomass amounts of above mentioned parts of lignocellulose can occur in different amounts and proportions (Werle, 2021; Werle et al., 2019a).

Cellulose ($C_6H_{10}O_5$) is the primary component of plant cell walls. It consists of several hundred to several thousand glucose units linked by β-1,4-glycosidic bonds. Lignin is the condensation product of three monomeric phenolic alcohols: trans-p-coumaryl, trans-p-coniferyl and trans-p-sinapyl. Hemicellulose is linear heteropolymer composed of sugars-hexoses: D-galactose, L-galactose, D-mannose, L-fructose and pentoses: L-rhamnose, arabinose, xylose, and D-glucuronic acid (Krajewski and Witomski, 2016; Mora-Pale et al., 2011; Zajonc et al., 2011).

Lignin is a three-dimensional amorphous biopolymer insoluble in water in its native form (Zakzeski et al., 2010). It is a complex molecular structure containing cross-linked polymers of phenolic monomers (coniferyl alcohol, coumaryl alcohol, sinaphyl alcohol) (Bajpai, 2016). It contains 65% carbon, 6% hydrogen and 29% oxygen (Fengel and Wegener, 1983). The amount of lignin varies between species and also between individual parts of wood, such as bark, springwood, summerwood, normal wood and pressurewood, branch wood, root wood; also according to cell types (parenchyma or fiber) and cell wall layers, such as middle lamella, primary and secondary wall layers (Börcsök and Pásztory, 2021). The highest concentrations of lignin were found in the middle lamella and in the corners of the cells; lower concentrations were found in the secondary cell walls (Fromm et al., 2003). Lignin plays a role in the defense mechanism of lignocellulosic biomass. Due to the insolubility and complexity of the lignin polymer, it is resistant to degradation by most microorganisms (Brandt et al., 2013). Lignin has a strong absorption capacity and is thermoplastic; the glass transition temperature of lignin begins at about 90°C; thermal softening lies between 120°C and 160°C and depends on the molecular weight. Moist lignin, as a component of wood, softens at about 100°C under suitable conditions and allows its molecules to deform in the cell walls. This phenomenon has many advantages and disadvantages. If we know exactly this process and the industrial areas where it can be used (wood welding, pellet production, composite board production with/without binder, solid wood bending, veneer production and solid wood surface densification), we can improve these industrial processes (Börcsök and Pásztory, 2021).

During thermal loading of wood, significant changes occur, especially in the surface layers. In addition to color changes, these are also reflected in chemical changes in the main components of wood and extractive substances (Čabalová et al., 2019). Boonstra (Boonstra et al., 2007) describes the relationship between the change in hemicelluloses during thermal treatment of wood and its mechanical properties. Of the main components of wood, hemicelluloses are the most thermally labile, even at relatively low temperatures (even in the case of natural aging of the material outdoors). Their degradation begins with deacetylation and the resulting acetic acid catalyzes the hydrolysis of glycosidic bonds in polysaccharides and subsequent reactions of the resulting monosaccharides (Esteves and Pereira, 2009). Unlike hemicelluloses, cellulose and lignin have a much higher thermal stability under many influences on wood (Čabalová et al., 2018).

The presence of lignin, cellulose and hemicellulose in biomass (Table 2.4) directly influences its utilization processes. In the case of methane fermentation, biomass containing more hemicellulose than cellulose demonstrates greater hydrolysis capacity. In the case of pyrolysis, these components are responsible for creation and determine shares of individual post-process fractions.

Table 2.4. Chemical composition of sample types of plant/wood biomass (Aniszewska and Gendek, 2014; Sharma et al., 2020; Wang et al., 2017, 2016)

Type of biomass	Cellulose	Hemicellulose	Lignin	Other
		% wt.		
Softwood	38.6-48.4	17.8-29.4	24.1-35.9	1.7-9.5
Hardwood	41.7-52.7	16.7-33.5	18.0-29.3	2.0-9.8
Pine	46.9	20.3	27.3	5.1
Spruce	43.0-45.6	20-29.4	27.6-28.2	1.7-5.9
Fir	45.0	22.0	30.0	2.6
Beech	43.9-45.0	28.4-33.5	20.0-29.1	2.0-3.0
Spruce cones	35.8-35.7	n.d.a.	60.9-61.46	6.97-6.66

Much research is being conducted worldwide on the role of cellulose in the pyrolysis process. The glucose bonds in cellulose are not stable at high temperatures and are prone to breaking. So during the pyrolysis process the cellulose structure undergoes rapid degradation.

(Aniszewska and Gendek, 2014; Wang et al., 2017, 2016, 2016). It can be stated that higher content of lignin results in higher thermal decomposition temperatures when assessing the role of lignin in this process in several research works (Greenhalf et al., 2013; Werle et al., 2019b, 2019a). Hemicellulose also significantly influences pyrolytic decomposition. Research has shown that biomass containing significant amounts of hemicellulose is more resistant to thermal decomposition than other fuels (Werle et al., 2019b).

3. TECHNOLOGIES FOR OBTAINING FOREST LOGGING RESIDUES

The management of logging residues, i.e. the remains of wood and vegetation after harvesting, can contribute to sustainable development and environmental protection. The main uses of residues include:

- energy biomass - residues can be processed into biomass, which directly or indirectly serves as fuel for generating heat or electricity,
- composting - shredding and composting residues produces valuable organic fertilizers that enrich the soil,
- mulching - leaving residues as shredded material mixed with soil. Applied to structurally disturbed surfaces (after fires, lost crops) can protect soil from erosion, retains moisture and limits weed growth, while also serving as organic matter that enriches the soil with nutrients for future generations of the forest,
- ecological construction - wood from residues can be used to produce wood-based materials used in the construction of wooden structures, furniture, etc.,
- charcoal production - through the pyrolysis process, residues can be converted into charcoal (biochar), which is used in horticulture and as a filter material,
- industrial applications - residues can be used in the paper industry or as a raw material for biofuel production.

The use of forest logging residues for electricity and heat production is crucial from the perspective of environmental protection and reducing greenhouse gas emissions. The process of harvesting and processing forest logging residues for energy biomass can currently be implemented using various techniques and technologies (Figure 3.1). Logging residues can be used in two basic ways. First, in unprocessed form (branches, undersized pieces of wood, treetops) or processed (wood chips) for direct combustion; and second, in processed (shredded) form for further processing (e.g., torrefaction) and the production of refined fuels (pellets, briquettes).

The physical parameters should be taken into account during considering technologies for obtaining forest biomass for energy purposes, such as small material volume ratio in the unit of wood volume (m^3) and high initial moisture content.

The volumetric coefficient for logging residue loads ranges from 0.15 to 0.20, while for wood chips it is 0.4. Compared to roundwood, which has volumetric coefficient of 0.6-0.7, these values are many times lower. Biomass is characterized by low bulk density, which further complicates its storage and transportation. Low energy density per hectare is also an important characteristic of biomass. . This value depends on the biomass origin and storage method, which significantly determine the water content of the wood.

The moisture content of forest biomass immediately after harvesting varies and depends on the harvesting period and the type of wood. These values are typically around 60-70%. Depending on the harvesting technology, there are three ways to reduce water content: natural drying of residues on the logging surface (in bulk or in stacks), protecting stored logging waste from precipitation (covering the stacks) and harvesting wood during months of slower growth.

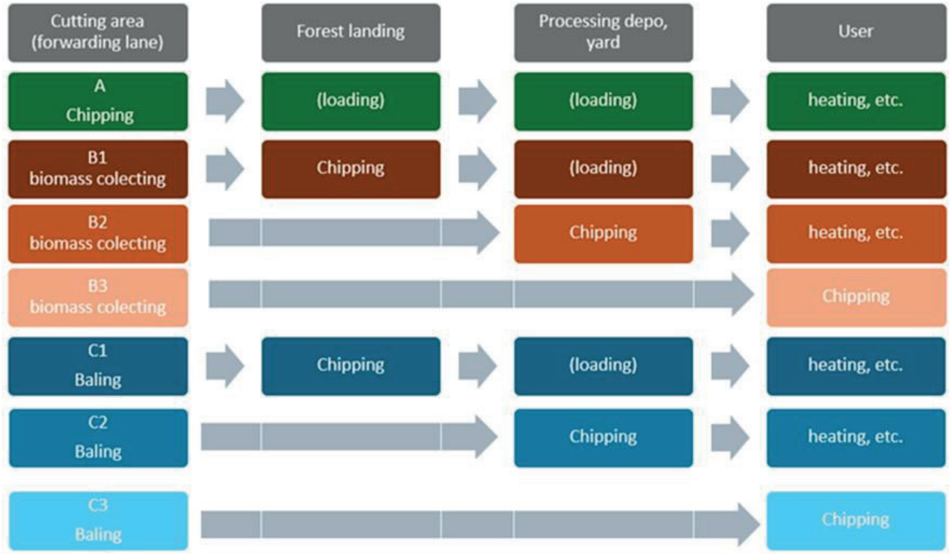


Figure 3.1. Technological systems of biomass production (Vares et al., 2005)

The best location for storing logging residues is in piles in open area with free air circulation in south-north direction. The piles of logging waste dry out effectively during the summer. Drop in moisture content from initial moisture content of approximately 60% to approximately 30% has been observed under favorable conditions (Gendek and Nurek, 2016; Moskalik and Gendek, 2019).

Three basic types of technologies for harvesting logging residues for energy purposes can be distinguished differing in the form of the raw material that will be exported to the recipient. The residues are assumed to be exported in bulk, in packages, and in the form of chips.

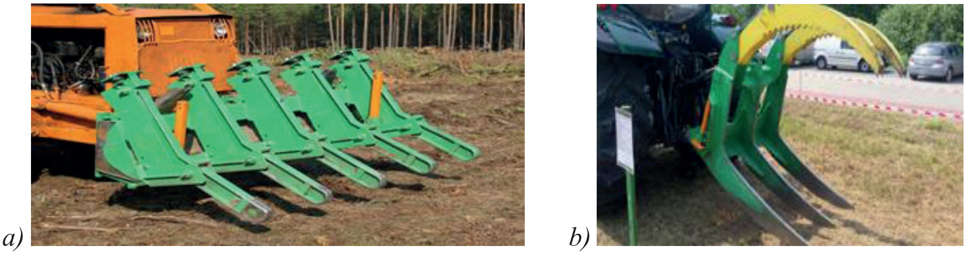
Crucial activity after timber harvesting is the accumulation of residues, which significantly increases the efficiency of subsequent technological operations. Organizing forest biomass storage should consider the following factors: storage location, type of material stored and storage period. These factors determine the storage area and its technical infrastructure.

When logging residues are harvested for energy purposes, they are typically initially collected along operational trails located near the cut areas and then further processed. This occurs during thinning stands and in felling stands managed with complex felling methods (Moskalik, 2013).

3.1. Harvesting and removal of loose branches and tree tops

When branches need to be quickly cleared from forest areas, especially in clear-cut areas or areas affected by forest disasters, they are collected in piles (Figure 3.2) or in banks. Branch rakes or special rakes with grab mounted on agricultural or skidder tractors, as well as on front-end loaders are used for this purpose (Figure 3.3). Collected material is then transported away or crushed on-site and cleared area is subjected to further regeneration procedures.

Figure 3.2. Piles of logging residues on forest surfaces (Photo: G. Szewczyk, P. Tylek)



a) *b)*

Figure 3.3. Branch rake mounted on forestry tractor (a), rake with grab mounted on agricultural tractor (b) (Photo: P. Tylek)

Specialized forwarder-type skidding tractors with stanchions or movable sides (Figure 3.4) or agricultural tractors with timber skidding trailers can also be used to move logging residues (branches, tree tops) across forest areas (skidding).

a) *b)*

Figure 3.4. Forwarder with stanchions (a) and movable sides (b) for skidding logging residues from forest areas (Photo: P. Tylek, A. Gendek)

Loose logging residues have low bulk density, making their removal and transport, especially over long distances, inefficient. This has led to demand for so-called BIO forwarders with hydraulically clamped full sides, which enable compaction of the transported material. This design protects firstly transported material and secondly loading and unloading technological parts. The medium-sized forwarder with standard cargo space can accommodate approximately 5 cubic meters of fresh residue. Extending cargo space rearward and installing additional stakes allows increasing in cargo capacity to 8-14 cubic meters.

Loose removal of branches and treetops is inefficient due to their low density and low load-fill factor. Standard trucks and tractor-trailers are used for this purpose. This technology is not very popular and rarely used.

3.2. Baling/bundling/balloting of felling residues

The technology for bundling (balloting) logging residues was developed in Sweden at the beginning of the 21st century (Asikainen et al., 2001). This technology is based on collecting logging residues from forest areas and compacting them in special head, creating bales with a diameter of approximately 0.7-0.8 cm and a length of approximately 2.6-3.2 m (Figure 3.5). According to Moskalik et al. (Moskalik et al., 2014) the average volume of one bale should be approximately 0.9 metric cord (stcm). To determine the volume of wood in a bale, it is recommended to use conversion factor of 0.4. Depending on the type of branches that were baled and the compressibility of the bale, the value of this factor may vary and is usually between 0.35 and 0.45.

Figure 3.5. Examples of bales with even front surfaces prepared for transport, made with Timberjack baler in continuous operation (a) and with uneven fronts, made with Valmet baler (b) (Photo:: P. Tylek, A. Gendek)

Bale-making technology employs two types of bale-forming machines and devices (Figure 3.6). The former operate continuously. Residues are collected from the forest floor and fed to compacting head that wraps branches with plastic tape via binding unit. In this system, the compacted and bound residue is cut off using chainsaw. This method of bale production produces even bale faces, facilitating subsequent loading and transport. The bale length can be freely adjusted within certain range (usually from approximately 2.5 m to approximately 3.2 m) and adapted to the subsequent means of transport. The second type of machines, operating in step-by-step system, produces bales in closed chamber. Each bale is produced individually, and their length is limited by the length of the compacting chamber (usually approximately 2.6 m). The heads of resulting bales are irregular, with ends of branches sticking out of them. The bales produced are less dense than those produced in continuous system.

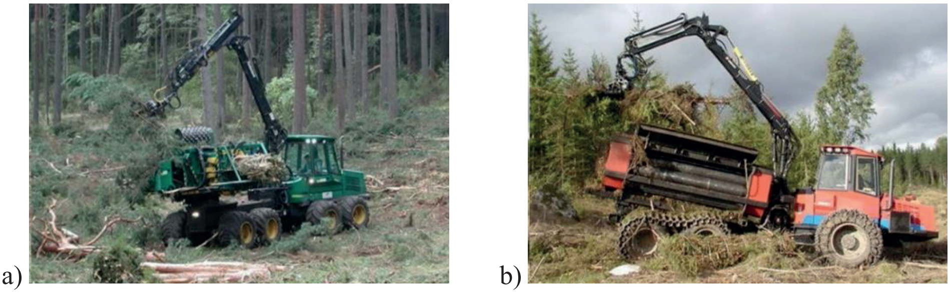

a) b)

Figure 3.6. Tomberjack baler (a) and Valmet baler with closed chamber for packing logging residues (b) (Photo: A. Gendek, Valmet)

Both mentioned technologies have their advantages and disadvantages if considering bale storage and natural removal of moisture from wood. Continuously produced bales, due to more compressible binding of branches, require smaller storage areas. Evenly cut ends and highly dense branches are less efficient at removing moisture. Bales produced in closed-chamber machines, with unevenly shaped end surfaces and lower density, are characterized by better internal air permeability and improved moisture removal. In the other hand this metod require more storage space.

Depending on the machine and bale production system used, the work efficiency ranges from approximately 6 to even 30 bales per hour (Ghaffariyan et al., 2011; Jablonski and Chlebowski, 2012; Moskalik et al., 2016).

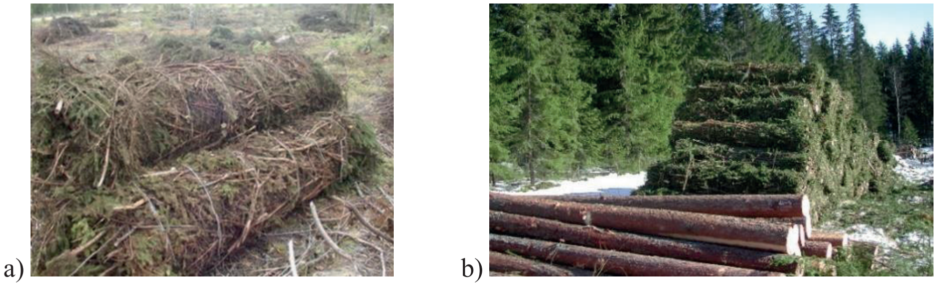

a) b)

Figure 3.7. Bales stored on the forest surface before harvesting (a) and prepared for transport along the forest road (b)

The next step in the baling technology of logging residues is skidding them to storage location along the forest road. Skidding is performed using forwarders or agricultural tractors with self-loading trailers. This process is equivalent to overshot skidding of roundwood. After skidding, the bales are stacked (Figure 3.7) and transported to the end user by roundwood transport vehicles. Trucks and tractor-trailers with stanchion trailers are used. These vehicles are often equipped with hydraulic crane for loading and unloading the bales.

3.3. Chipping of logging residues

Chipping of logging residues can be carried out directly on the forest surface, along the transport road or outside the forest area, e.g. on the recipient's site (Rumpf et al., 2016).

Chipping directly on the forest surface (Figure 3.8), both after clear-cuts and after maintenance operations, is performed by machines moving primarily along technological trails. The chipper moves along the trails established by the harvesting machine on the logging site, where harvesting was carried out. In logging operations conducted with petrol chainsaw, the chipper operator determines and establishes the route and technological trails. This technology typically utilizes self-propelled chippers equipped with hopper for collecting chips. Once the hopper is filled, the bulk material is hauled to export road, where containers for transport or tractor-trailers with bulk material transporters are waiting. At the roadside, the chips are poured from the chipper hopper into container or trailer and transported to the recipient. Chipping on the cut surface was widespread until the mid-1990s. Nowadays, this technology is used less often, for example in Sweden the share of this method has dropped to 10%.

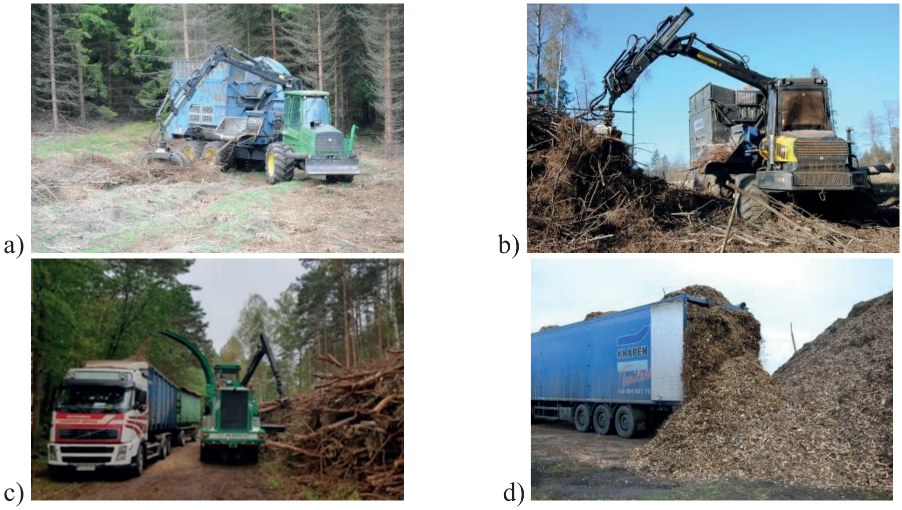


Figure 3.8. Chipping of logging residues directly on the forest surface (a), from the stack to the chipper container (b), from the stack directly to the container on the transport vehicle (c) and unloading of chips at the recipient's site (d) (Photo: A. Gendek, P. Tylek).

More popular method for chipping residue is chipping from piles located on the edges of logging areas or along forest roads. In this case, the first stage involves skidding the residue from the forest surface and collecting it in piles. Skimming is performed using specialized forestry tractors such as forwarders, forwarders with movable sides, or agricultural tractors with skidding trailers. Chipping occurs directly at the pile. Depending on the type of chipper, chipping can be carried into its hopper or directly into the container (semi-trailer) of the transport vehicle (Figure 3.8). Chipping directly onto the transport vehicle is very common in

Scandinavian countries, where this method accounts for approximately 80%, i.e. in Sweden. This method provides the highest efficiency because it allows for continuous and uninterrupted operation of the chipper.

Chipping outside the forest area is combined with the technology of harvesting and transporting loose branches and the technology of baling logging residues (Jodlowski, 2004). Both bales and branches are chipped at the recipient's site. In these cases, stationary electric chippers are often used as addition to mobile chippers. On the other hand, this technology requires appropriate work organization and technical equipment at the recipient's site (Figure 3.9). The site may also include equipment for sorting chips into different quality classes and fractions for direct combustion or processing into refined fuel.

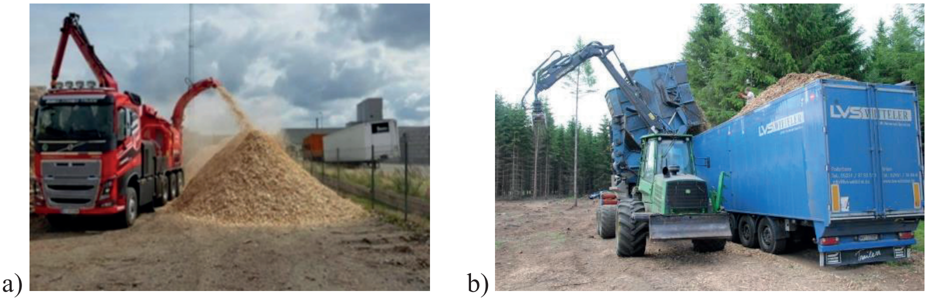


Figure 3.9. Chipping at the technological site of the end user of forest biomass (a), pouring from the container onto the truck (b) (Photo: P. Tylek, A. Gendek)

4. MACHINES AND EQUIPMENT

4.1. Material preparation machines

Biomass for the production of agglomerated biofuels can come from various sources (woody biomass, green biomass, straw, mixtures, etc.), which directly affects its physical, mechanical and chemical properties (particle size, specific density, bulk density, moisture content, etc.). Before the raw material can be agglomerated, it must be subjected to homogenization process. One of the most important steps in the production of pellets and other solid biofuels is material grinding, because it affecting the energy intensity of production. In the technological process, grinding can be divided into two stages: primary raw grinding and final smooth grinding.

Initial crushing of the input material into particles up to approximately 50 mm in length is usually performed for subsequent drying. Depending on the form of the input biomass, initial crushing is performed using chippers (woody biomass), as shown in Figure 4.1, or shredders (e.g., straw, green biomass).

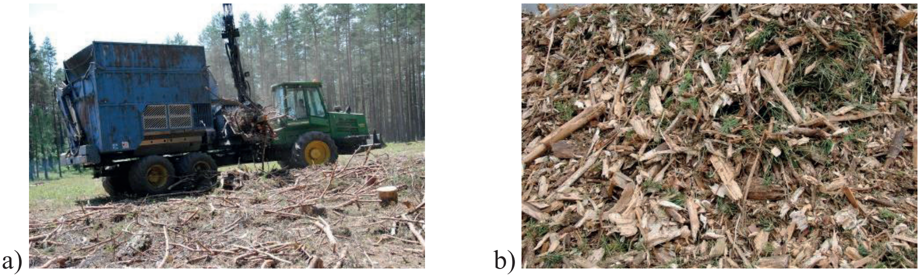


Figure 4.1. Chipping of logging residues directly on the forest surface using BRUKS 804CT mobile chipper (a), chipped spruce logging residues (b) (Photo: A. Gendek)

Commercially available chippers are in a wide range of power and efficiency. For home and garden use are designed the smallest one, typically have capacity of up to 1 $m^3 \cdot h^{-1}$ and are used to shred branches with diameters up to approximately 70 mm. They are powered by electric or combustion engines and material is fed manually into feeder. Professional chippers have capacities ranging around several dozen $m^3 \cdot h^{-1}$ and can shred wood of various sizes and diameters depending on the application. The largest models can be used to shred whole trees with diameters up to several dozen centimeters. Material is usually fed into the feeder using gripper mounted on hydraulic crane in these largest devices.

Based on the design of the working unit chippers are divided into disc, drum and auger types. Based on mobility there are two main groups that can be distinguished: stationary and mobile. Depending on the method of transport there can be distinguished on self-propelled, trailed and mounted chippers.

The disc chippers have found widespread use in shredding woody biomass thanks to their simple design. The disc-type operating unit (Figure 4.2.) operates vertically or at slight angle to material feed axis. Material is cut and shredded by set of two or more cutting knives mounted radially on the disc's surface. The quantity and shape of the knives depends on the chipper's design and operating parameters, such as the drive motor power, disc diameter, rotational speed, etc. Blades (from 4 to 10) are attached to the disc, perpendicular to its side surface, generating air stream that moves the produced chips to the outlet collector, from where they are directed to stack or container.

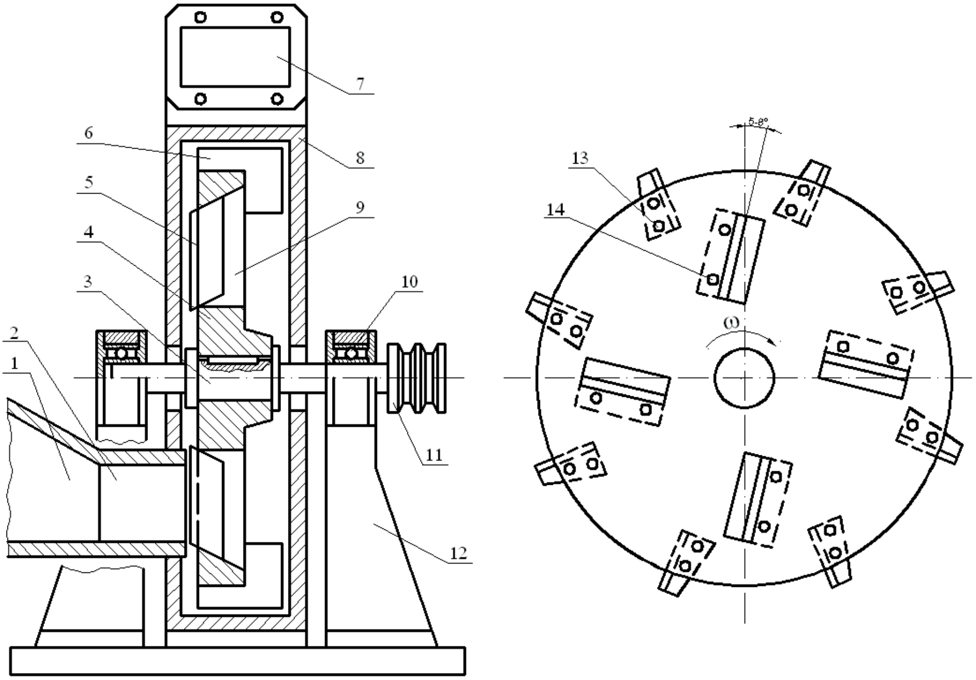


Figure 4.2. Disc chipper working unit: 1 – feed chute, 2 – throat, 3 – shaft, 4 – disc, 5 – knife, 6 – blade, 7 – chips outlet collector, 8 – body, 9 – knife slot, 10 – bearing, 11 – drive wheel, 12 – chipper frame, 13 – blade mounting bolt, 14 – knife mounting bolt (Gendek and Więsik, 2015)

Material is shredded by cutting a short slice of wood with chipper knives moving at high speed diagonally against the wood fibers. The wood is supported by counterknife located at outlet. During cutting, longitudinal stresses cause wood to separate along the annual growth rings, creating chips. The distance between the knife's cutting edge and the counterknife (shear bar should be 0.5-1.0 mm) determines quality and uniformity of resulting chips, especially for high-moisture material.

Instead of classic flat cutting knives with straight cutting edge are sometimes used circular knives (Figure 4.3). Such knives allow for longer service intervals of the cutting mechanism due to the three times greater total length of the cutting edges, but they require specialized grinders for sharpening.

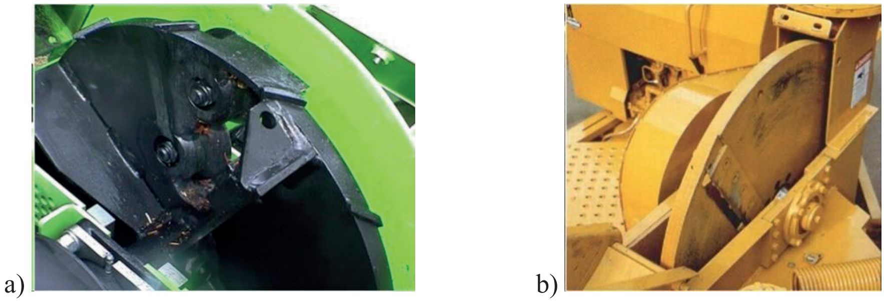


Figure 4.3. Working unit of disc chipper with flat (a) and circular (b) knives (Photo: P. Tylek)

Second group are drum chippers, characterized by more compact design and higher efficiency compared to disc chippers. The drum chippers are primarily designed for shredding logging residues and wood in forestry, shredding wood waste in sawmill and furniture industries, and shredding wood in pulp and paper industry. The working unit (Figure 4.4) consists of drum with two to six knives placed on its side.

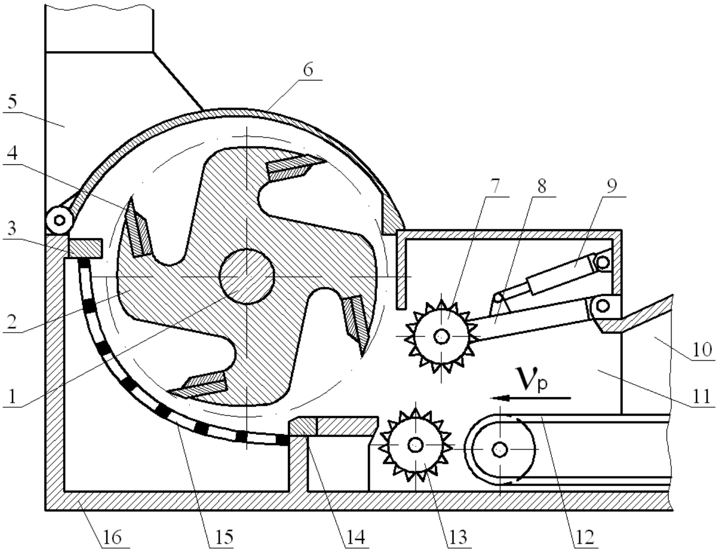


Figure 4.4. Drum chipper working unit: 1 - shaft, 2 - drum, 3 - upper counter knife, 4 - cutting knife, 5 - chips collector, 6 - cover, 7 - upper feed roller, 8 - rocker arm, 9 - hydraulic cylinder, 10 - feed chute, 11 - inlet, 12 - conveyor, 13 - lower feed roller, 14 - lower counter knife, 15 - sieve, 16 - body (Gendek and Więsik, 2015).

As the drum rotates, the knives move in arc corresponding to drum radius. The angle between the knife edge and the fibers varies during operation, resulting in uneven particle size distribution. The drum diameter, depending on the chipper's capacity, ranges from 400 mm (capacity 20-30 $m^3 \cdot h^{-1}$) to 800-1300 mm (capacity 50-80 $m^3 \cdot h^{-1}$). Depending on the drum design, it can be solid, hollow, or segmented with two or more knives. The knife-drum connection can be rigid or swinging.

The most important feature of drum chippers is the drum design, which significantly impacts the machine's operation, service requirements and performance. Solid drum is thick cylindrical main part whose length is 2-6 times its diameter. Chippers with this type of drum are most common in forestry because of its very durable design, high efficiency and relatively low maintenance requirements. Produced chips cannot penetrate the interior of the machine due to the drum's heavy construction. The hollow drum (Figure 4.5) consists of discs reinforced at both ends of the shaft and knife holders connecting the discs. The knives are arranged and operate similarly to those in solid drum chipper. The difference is that chips can penetrate the drum cavity. This design allows production of larger chips than with solid drum. The segmented drum consists of separate elements that can be placed on the ribbed main shaft in any order and at any angle thanks to the ribbed sleeve formed on its elements.

Material resting on the shear bar is cut off by the cutting edge of the knife in drum chippers, similarly to disc chippers. After this operation the longitudinal forces lead to the separation of particles at the boundary of the annual rings. The distance between the knife's cutting edge and the shearbar edge is 0.2-0.5 mm thanks to more rigid and stable design of the drum chipper's working unit and avoidance of drum deformation during operation. This design improves cut quality and enables shredding of species such as willow, poplar and green plants. Final chips are characterized by high uniformity of main fraction, which affects subsequent transport and drying of chips. Chip size is regulated by varying the drum's rotational speed and the material feed rate.

The drum chippers are often used in wood processing plants as stationary machines powered by electric motors in addition of forestry utilization.

Figure 4.5. Working unit of a multi-knife drum chipper with a visible sorting screen and a screw conveyor (Photo: P. Tylek)

The third group of biomass shredding machines are screw chippers, which do not employ impact cutting, and are therefore characterized by high operational stability. The knives are mounted spirally on cone (Figure 4.6), and the fed material is shredded by cutting edge shaped like screw coil. This shape causes to material simultaneously drawning in and shredding.

Disadvantage of this design is inability to continuously adjust chip size, which can be achieved by replacing the screw with different pitch. Drum chippers produce lower-quality chips, similar to disc chippers. Screw chippers are primarily used for shredding woody materials and are not suitable for shredding green biomass or straw. This type of chipper is primarily suitable for shredding fresh material with high moisture content. Angle grinders mounted on special guide are used to sharpen the screw's cutting edges. The screw is refurbished using hardfacing method.

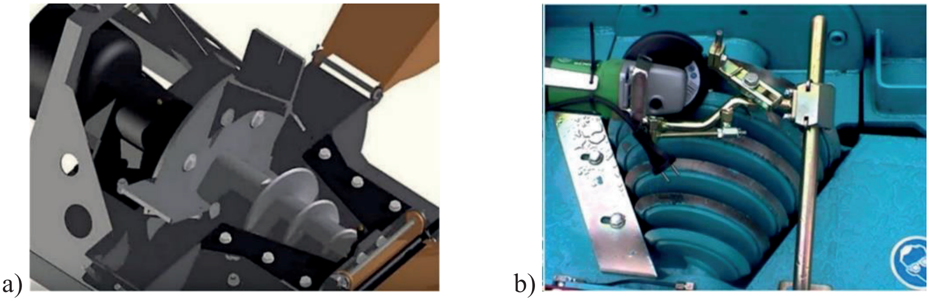


Figure 4.6. Diagram of the working tool of screw chipper (a) (Čabalová et al., 2021; Krilek and Kováč, 2013), auger of chipper aggregated with agricultural tractor (b) (Photo: P. Tylek)

In addition to the chipper designs mentioned above, alternative solutions are also emerging, such as a chipper that cuts wood along the grain (Figure 4.7). This type of mechanism is characterized by reduced energy requirements. Output material has irregular dimensions, chips are so long and fibrous, which makes further pressure agglomeration difficult or even impossible. This type of chipper is primarily suitable for shredding fresh material with high moisture content and small diameters.

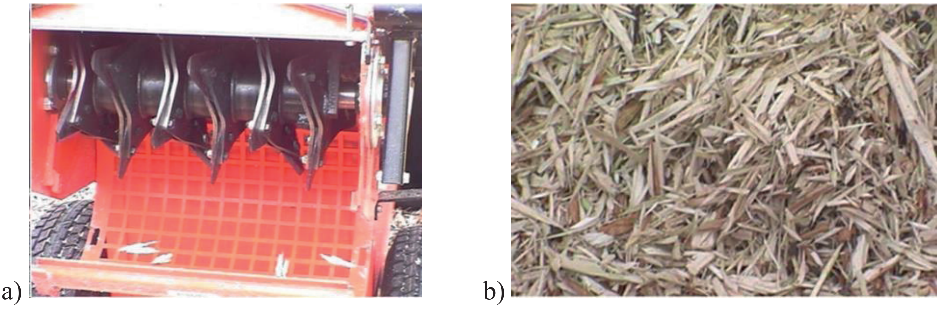


Figure 4.7. Working mechanism of chipper cutting along the grain (a), chips cut along the grain (b) (Photo: P. Tylek)

Crucial component of wood chippers is the feed/inlet unit, whre is material collected and evenly feeded into the shredding unit. Design of this unit is in the case of roundwood chipping not so important, but in the case of branch chipping it can directly affect process efficiency. In this case there can be stated that greater feed capacity, more stable material supply and shredding process in whole. Post-felling residues are usually heavily contaminated with minerals, which significantly accelerate dulling of cutting mechanisms. In this case are the best choice openwork feed units that also function as screens. These can be chain or caterpillar feeders (Figure 4.8).

Figure 4.8. Power unit of chipper with openwork structure: chain (a), caterpillar (b) (Photo: P. Tylek)

Input material undergoes final grinding before agglomeration process. Final grinding, also known as milling, is intended to obtain small particles (typically <5 mm), achieving uniform geometry and granulometric composition optimal for pellet or briquette production. The grinding process can be omitted while maintaining the required final product quality with good initial grinding in the case of briquetting, that significantly reducing production costs. In the pellet production process, grinding should achieve particle size of <3 mm. Final grinding is typically performed using beater and knife grinders equipped with screens of specific mesh size (Figure 4.9).

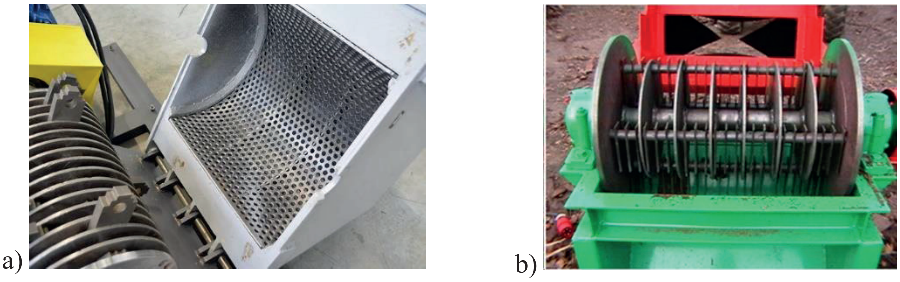


Figure 4.9. Working elements in biomass shredders: Stella HMX 60 shredder with tilting beaters and sieve (a), ML-SC20 shredder with fixed knives (b) (EMI Maszyny, 2025)

Material is first crushed by hammers and then passed through screen with an appropriate mesh size in hammer mills (shredders), which partially encircles drum with hammers. The particle size is adjusted by replacing screens with holes of a diameter adapted to the agglomeration process. Screens with mesh sizes of 3-8 mm are typically used in pellet production, while 8-15 mm are used for briquetting. The efficiency of grinding process depends primarily on type of material used and its moisture content, but also on granulometric composition and size of screen holes. Hammer mills are primarily used for final grinding of straw and grass biomass; they are not usually used for grinding wood chips.

The grinding process takes place in two phases in knife mills, similarly to hammer mills. Material is cut in the initial phase by placing it between fixed knives on the machine body and movable knives mounted on the working shaft. In the second stage, material is passed through screen with a specific mesh size. Hammer mills can grind both grass plants and woody biomass (wood chips) thanks to use of knives with sharpened cutting edge. Material moisture and type have lesser impact on process efficiency. This type of machine is sensitive to stones or metal, which can be introduced along with shredded material. This negative feature requires use of additional safety measures in industrial applications in the form of metal detection and capture devices (magnetic separators) or stone separators. From technical perspective, the main characteristics of shredders are size of hopper, rotor mass, rotor diameter, number of knives, distance of the knife edge from the disc/drum plane, screw pitch and rotor speed. These technical factors determine the most important characteristics of shredding, which are chip quality, material flow and technological characteristics of obtained/final chips.

4.2. Machines and devices for agglomeration – pelleting

Pellet production technology is not complicated. This techology originating from the production of pelleted animal feed. Production line components are characterized by greater durability due to better component resistance during palletizing of biomass. Many biomasses palletizing machines with varying degrees of technological advancement are available on market. Capacities ranging from approximately 100 to 10,000 $kg \cdot h^{-1}$. The world's largest processing plants produce over 1 million tons of pellets annually.

Producing pellets from wood waste or energy crops is complex and requires carefully designed process line and pelletizing machine. It's important to understand that raw material must be pre-treated before agglomeration. It should have defined particle size (< 5 mm for briquettes and < 3 mm for pellets), low moisture content (10-15%), and be free of contaminants.

Pelleting machine is designed to produce pellets from hard materials, most often with particles size of sawdust (< 3 mm). The general structure of pelleting machine is shown in Figure 4.10.

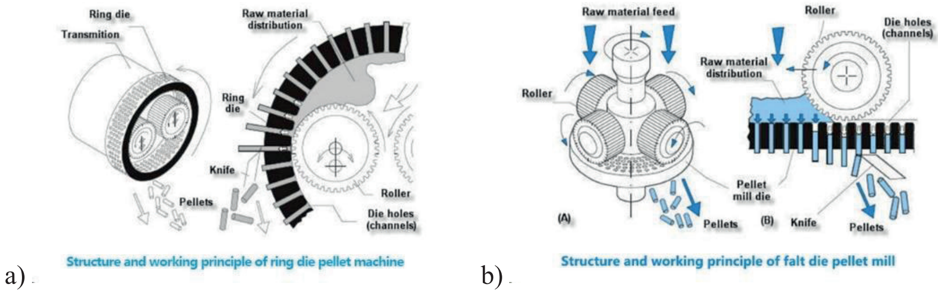
The material state, design of technology and process factors are important for proper course of granulation in pelleting machine and for obtaining high-quality pellets (Flizikowski and Mroziński, 2016). These include, among others, the quality of the raw material used for agglomeration, the type of die, the length and diameter of the holes, the speed and thickness of the material layer being agglomerated, and the rotational speed of the rollers.

There are two types of pelleting machines available on the market based on their design, divided into rotary and cylindrical. The latter are significantly less common.

Figure 4.10. Example of pellet machine with description of main structural elements (GEMCO Energy, 2025)

The operating principle of rotary pelleting machines involves cyclically forcing crushed material through series of cylindrical holes in the die. Forcing is performed via pressing rollers. The shape and length of the channels in the die are designed to match the properties of the pelleted material. The material pressed into the holes encounters frictional resistance. This creates pressure and heat required for the pelleting process. Resulting pellet is broken (sheared) by breaking element (usually knife) to standardize its length after passing through the holes in pelleting die.

Rotary pelleting machines (Figure 4.11) are divided into two groups depending on the type of die used: with ring die or plate die (flat in the form of disc).



a) b)

Figure 4.11. Diagram of rotary pelleting machine operation: ring (a), plate (b) (GEMCO Energy, 2025)

Ring die pellet machines are manufactured with moving die or moving roller configuration. Ring die pellet machines most often operate using centrifugal extrusion system using one, two, or three rotating pressing rollers, pressing wood pulp against the inner surface of the die. Pellets are extruded outside the die and then sheared to the desired length.

Ring die pellet machines are characterized by high-quality and durable die (thick, hardened stainless steel) and rollers. An example MZLH35 pellet machine (Figure 4.12) consists of conditioner, feed screw and pelletizer. The feed screw evenly feeds raw material into the pelletizer, where it is pressed through the die openings under the pressure of the rollers.

Figure 4.12. Ring pellet machine MZLH35 (POLEXIM, 2008)

Plate-type rotary pelleting machines (Figure 4.13) with a set of conical or cylindrical compaction rollers force material through the profiled die openings. The flat die mounting eliminates dangers of high rotational speeds and high torques that occur with ring-type dies. The low speed of the take-up shaft prevents vibrations. The compaction chambers of flat pelleting machines are free from the spatial constraints that occur with rings. Use of large bearings is necessary for large-diameter compaction rollers. There are two types of plate rotary pelleting machines. In the first type, the rollers rotate around their own axis and additionally around the die axis (Figure 4.11). In the second type, the die rotates around its axis, while the rollers remain stationary (GEMCO Energy, 2025).

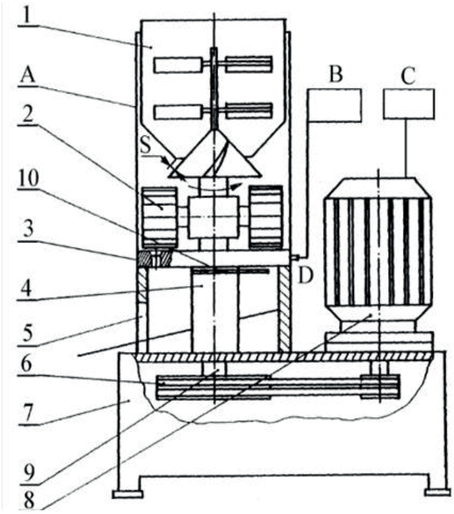


Figure 4.13. The schema of structure of the pelleting-briquetting device with flat matrix: A - the universal pelleting-briquetting device, B - record-keeper of temperature, C - record-keeper of power consumption, D - thermocouple, l- feeder (with non-gradual control), 2- compacting rolls, 3- the stationary flat matrix, 4- casing of the driving shaft, 5- pour out

of the agglomerate, 6- transmission belt, 7- basis, 8- electric engine, 9- the driving shaft, 10- cutting knife (Hejft and Obidziński, 2012)

The efficiency of rotary pelletizing machines depends directly on the working surface of the die, and is function of its circumference and width. It also depends on the surface area of the rollers pressing against the die, which is determined by the width and number of rollers.

Efficiency is also determined by relative speed of the die and the pressure rollers, as well as the thickness of the compressed layer of raw material, which is limited by the roller diameter and pressure force.

The pelleting process is highly energy-intensive (depending on the material being processed, energy consumption can range from approximately 10-15 to approximately 80-100 $\mathrm{kWh \cdot t^{-1}}$ of product).

Roller pelletizers (Figure 4.14) are characterized by high compression pressure, high efficiency and high productivity. Material is continuously compacted between two synchronously and counter-rotating rollers in these pelletizers. Material is fed between the rollers continuously, most often using screw transporter, which also pre-compacts the fine-grained material. The material is fed into the gap between the rollers.

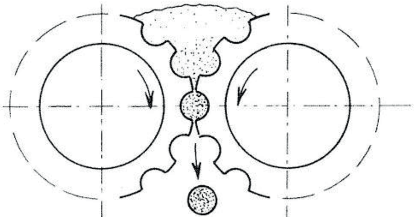


Figure 4.14. Schematic diagram of a roller braiding machine (La Meccanica, 2025)

Another technology is pellet presses with two pressing dies, based on the centripetal extrusion concept. Pellet production technology in this system requires appropriate crushing, material quality and moisture observing, and appropriate proportions of ingredients to be granulated.

4.3. Pellet burning boilers

Biomass combustion requires appropriate technological solutions tailored to the fuel. Only 20% of biofuel mass on average consists of non-volatile carbon compounds, which burn on grate in traditional boiler (in lignite 45-60%, in hard coal 60-80%, and in coke over 95%). The remaining 80% are volatile compounds that burn above the grate, emitting intensely over a relatively narrow temperature range. Efficient combustion of this biomass type of fuel requires special techniques and boilers (Figure 4.15). These has to ensure dynamic and thermal conditions necessary for complete combustion of volatile products of thermal decomposition of biomass. Inappropriate equipment and technological solutions result in increased, often severe, emissions of harmful substances into the atmosphere, which can negate the beneficial ecological effects of woody biomass. Incomplete combustion also leads to economically disadvantageous reduction in process efficiency.

Biomass boilers can be broadly divided into manual-feed designs, known as batch boilers, and automated feeder boilers. Batch boilers are primarily designed for combustion of wood. Boilers designed for combustion of bulk solid fuel derived from biomass (wood chips, pellets, briquettes, and others) have various designs. These include fluidized-bed boilers, pulverized-fuel boilers, and stoker-fired boilers.

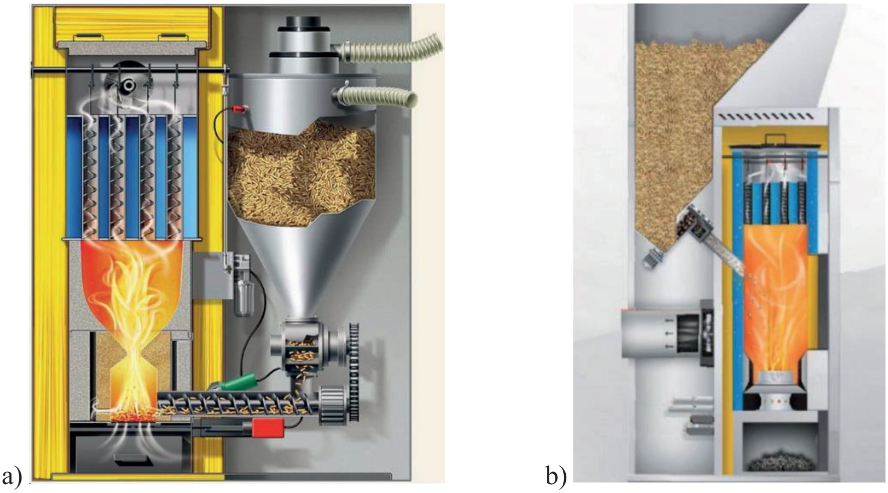


Figure 4.15. Example diagrams of pellet boilers: a) lower combustion boiler with screw feeder (AMM INVESTMENT, 2025), b) fluidized bed boiler (Hydrogaz, 2024)

Fluidized-bed boilers are characterized by the best operating parameters and the highest efficiency (reaching over 80%). The fuel is burned in a suspended form, achieved by the appropriate air velocity flowing through the chamber, carrying the finely divided particles. This air velocity must be greater than the settling velocity of the fuel particles and additional material (sand, ash).

Pulverized-fuel boilers are widely used in commercial power plants. They have separate fuel feed system for biomass and waste. They are typically equipped with modern flue gas cleaning systems, which allow them to meet current environmental requirements related to harmful emissions. Key element of pulverized-fuel boiler is pre-burner, which feeds fuel (shredded wood) into the thermally insulated combustion chamber. Fuel is ignited by starter burner, which is used during ignition. Residues from biomass combustion are transported from grate to hoppers beneath grate and then to slag trap. Hot exhaust gases are directed to appropriate nozzles. Biomass with wide range of moisture content, calorific value, grain size, and origin can be burned in the pre-burner.

Grate-fired boilers are equipped with stepped grate or retort-type burner. The chamber is made of heat-resistant concrete designed in the former for operation at temperatures up to 1550°C. The use of multi-stage grate (e.g., two-stage) allows for separate control of the fuel feed time and the primary and secondary air zones. The basic components of retort-fired boilers include pellet burner, screw feeders (for fuel transport to the combustion hopper) or scraper conveyors (for fuel transport when changing the feed height or for horizontal transport), and exhaust gas discharge system. The fuel combustion process is controlled by lambda sensor – its readings regulate amount of primary and secondary air supplied to the combustion chamber.

The design of pellet boiler burner allows for high-efficiency, smooth fuel combustion across a wide power range. Supplied fuel must be of appropriate quality for achieving high efficiency combustion, particularly to content of minerals that will not burn. Fuel parameters that change during storage must be taken into account, such as moisture content due to water absorption from the air and dust content that can incrase during logistic operations.

Manufacturers' failure can lower the quality standards and pellet production technology can also pose problem. Producers use low-quality raw material by using barkless or shredded wood with high proportion of bark between the bark particles. They also use wood containing high proportion of mineral impurities, primarily quartz absorbed in bark or extracted directly from ground during harvesting and transport.

The bark contained in pellets burns at higher temperature than pure wood, which increases the temperature in the combustion chamber. This increased temperature causes ash vitrification and slag formation. Even at normal combustion temperatures, slag appears as precipitate on burner components, with small growing over time. The resulting slag and slag precipitates reduce combustion chamber volume and clog air supply nozzles, thus hindering fuel combustion. Further effect of non-stoichiometry combustion is increased CO content in exhaust gases.

4.3.1. Examples of current modern combustion plants for solid fuels

The most common types of current modern solid biomass combustion plants are based on the principles of:

- bottom feeding – retort feeding, when pellets are pushed through the retort (elbow) into the combustion chamber by a screw feeder,
- gravity feeding – pellets are pushed out of the hopper by a screw feeder above the grate, where they then fall,
- gasification combustion equipment for wood logs and briquettes,
- burner firebox – burner (bowl or cylindrical) with its own feeder, combustion air fan – pellets are fed into the burner by gravity.

4.3.2. Bottom-firing combustion equipment

Hot water combustion devices with bottom loading for solid fuels (Figure 4.16.) are intended primarily for heating family houses, cottages, small businesses, etc. The main parts of the combustion device are based on the principle of fuel bottom loading. The combustion device is located under the exchanger, which consists of cast iron grate, ceramic reflector, retort, i.e. cast iron elbow for fuel supply, and air mixer. The ceramic reflector directs combustion, reduces dustiness, reflects heat back into the burner, and thus helps to achieve perfect combustion. The cast iron elbow for fuel supply is equipped with holes for equalizing pressure of combustion air inside the retort, which prevents flame from flashing into the feeder during the combustion process. There is ash drawer under the combustion chamber. Next to the boiler is fuel tank, which opens into the screw feeding device. There must be also emergency fire extinguishing tank behind the fuel tank, which also leads to the screw feeder. The combustion air fan is located in front of the fuel tank and is connected to the mixer. The amount of combustion air can be regulated by throttle on the fan. (Malat'ak et al., 2010).

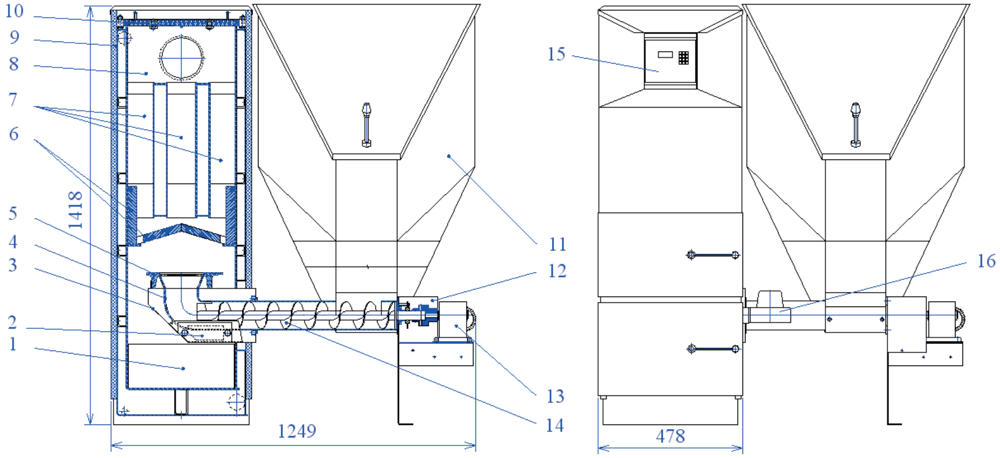


Figure 4.16. Diagram of combustion device with bottom loading – automatic hot water boiler BENEKOV ling. Explanations: 1 – ash drawer, 2 – cleaning hole of mixer, 3 – air mixer, 4 – retort, 5 – grate, 6 – ceramic reflector, 7 – lamellas of convection part, 8 – flue gas discharge, 9 – insulation of combustion device, 10 – heating water outlet, 11 – fuel tank, 12 – transmission, 13 – engine, 14 – fuel feeder, 16 – fan with throttle (Malat'ak et al., 2010)

4.3.3. Combustion plant with self-ignition

Combustion device with self-loading (Figure 4.17.) can be used for burning various types of solid biofuels (wood, plant pellets, grain, ...). The combustion device works in the principle where screw conveyor transports fuel from hopper to fall/inlet, from where it falls into the burner space. The diffuser ensures more even distribution of fuel over grate area. Fuel is combusted in the burner space and uncombustable residues are pushed out by the grate into the ash pan. If the boiler is equipped with additional ash removal device, instead of the ash pan is there trough with screw conveyor that takes the ash into the ash pan. The grate is driven by reverse operation of filling conveyor drive. Flue gases flow through the exchanger, where transfer heat to heating water. Cooled flue gases exit through outlet of combustion chamber into chimney. Air required for combustion is supplied by positive pressure fan. Primary air is supplied to fuel through the gaps in the grate. Secondary air is supplied to burner through fuel fallout and openings in rear wall of the burner.

The most important part of the combustion device is the burner space. The burner space is lined with special quality ceramic fittings. The rear wall is equipped with ignition air openings in the lower part and secondary air openings in the upper part. Fuel diffuser is located on the rear wall below the outlet from the fallout. The bottom of the combustion space is grate equipped with movable grates. In the vertical wall below the outlet from the burner space there is an opening for removing ash from the space under the grate. Ashpan is hung on this wall so that its rear wall forms the closure of the removal opening.

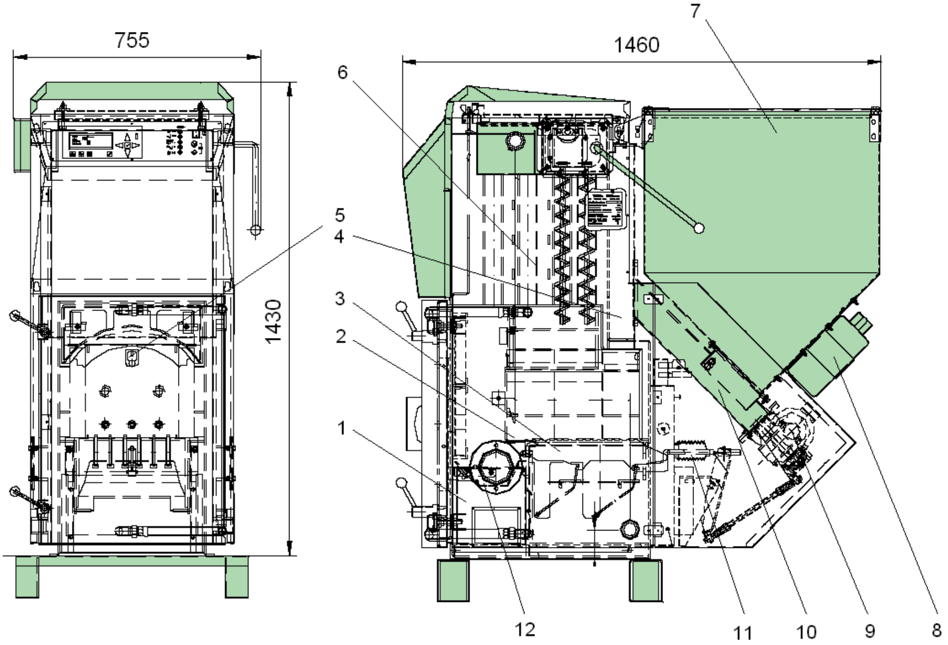


Figure 4.17. Diagram of combustion device with gravity feeding – automatic hot water boiler VERNER. Explanations: 1 – ash pan, 2 – burner compartment, 3 – grate, 4 – fuel fallout, 5 – fuel diffuser, 6 – turbulators, 7 – hopper, 8 – extinguishing device, 9 – gearbox with electric motor, 10 – screw conveyor, 11 – grate drive; 12 – ash chute (Malat'ak et al., 2010)

The grate under the screw conveyor is a lever mechanism for driving the grates. The hopper is equipped with a lid in the lower part of the rear wall in case it is necessary to intervene in the space of the screw feeder (hard object gets stuck).

The air supply includes fan with non-return valve, chamber for heating the ignition air with spiral ignition rod, primary air control diaphragm and pair of secondary air control diaphragms. The ventilation is connected to the fuel fallout by hose. This ensures overpressure in the fuel fallout, which prevents smoke from entering the feeder and hopper during operation.

Turbulators are located in the last pass of the flue gas exchanger. They are hung on movable holder with control lever, which allows easy cleaning of last pass of the exchanger during operation. Turbulators (vortices) are sheet metal spirals that ensure turbulent flow of flue gases through the heat exchanger tubes, significantly improving heat transfer (Malat'ak et al., 2010).

4.3.4. Gasification combustion plant

- Gasification combustion devices (Figure 4.18.) are designed for burning lump wood in the form of logs or briquettes on the principle of generator gasification using exhaust fan that extracts flue gases from the boiler or blows air into the boiler. Part of the combustion device consists of fuel hopper, which is equipped with refractory fitting in the lower part with longitudinal opening for the passage of flue gases and other gases. The afterburning space below it is equipped with ceramic fittings. In the rear part of the combustion device body there is vertical flue gas channel, equipped with fire valve in the upper part. The upper part of the flue gas channel is equipped with exhaust nozzle for connection to the chimney (Malat'ak et al., 2010).

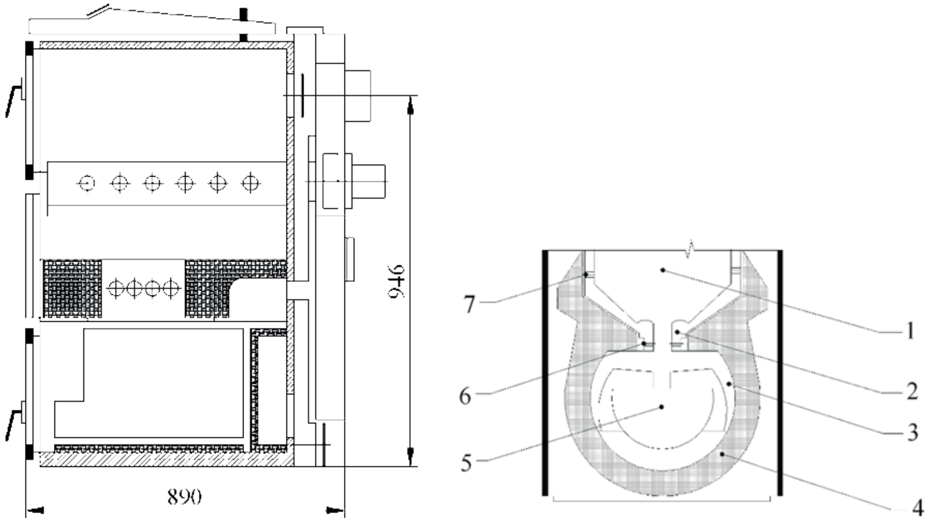


Figure 4.18. Diagram of the gasification combustion device – ATMOS wood gasification combustion device. Explanations: 1 – firebox, 2 – nozzle, 3 – air inlet, 4 – boiler body, 5 – spherical space, 6 – seal, 7 – firebox screen (Malat'ak et al., 2010)

4.3.5. Combustion equipment with burner firebox

Combustion devices with burner firebox for wood pellets are intended primarily for heating family houses, smaller communal buildings, cottages and smaller establishments or business buildings.

The main part of the combustion device is the burner firebox, which is schematically shown as part of Figure 4.19. The burner body itself is box-type weldment made of high-alloy material with lower inclined fuel inlet. The fuel is transported by built-in feeder driven by electric motor with gearbox. The slot nozzle assembly ensures the supply of combustion air so that supplied fuel is controlled and completely burned while it remains in the burner combustion chamber. Spent fuel is then moved over the overflow edge of the combustion chamber into the ash pan.

The internal space of the burner body itself is connected to air fan. Fan speed can be regulated in wide range in connection with required boiler output or type of used fuel. The function of the afterburning ceramic grate is to increase turbulence of flue gases before entering the exchanger itself, to additionally utilize unburned gaseous combustible residues on hot surface of the ceramic and to direct flow of flue gases through the exchanger (Malat'ak et al., 2010).

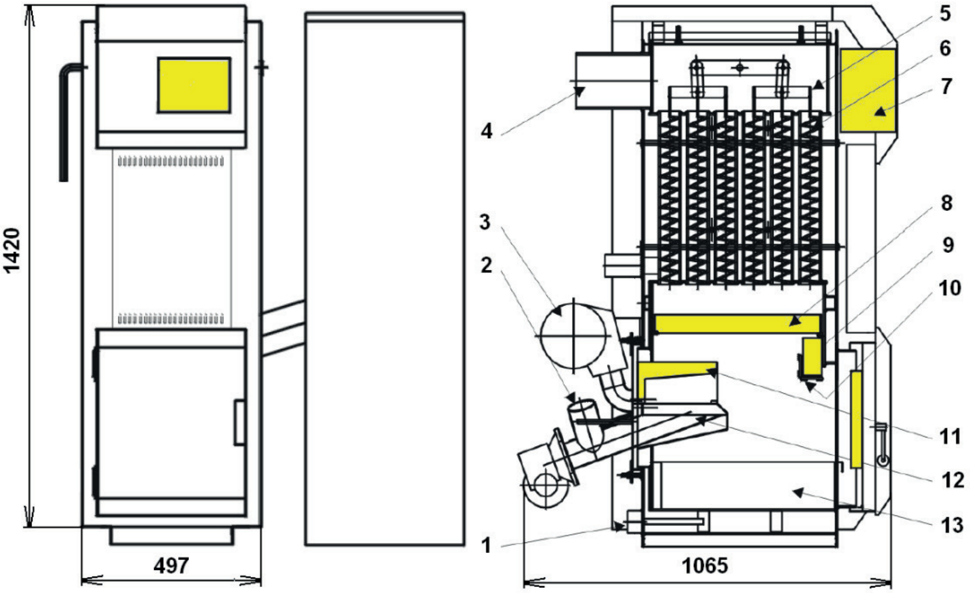


Figure 4.19. Scheme of combustion equipment with burner firebox – Hot water automatic boiler PONAST. Explanations: 1. el. heating element; 2. fuel inlet; 3. fan; 4. flue gas exhaust; 5. exchanger cleaning; 6. turbulators; 7. control unit; 8. ceramic grate; 9. ceramic shield; 10. shield holder; 11. ceramic reflector; 12. burner; 13. ashtray (Malat'ak et al., 2010)

4.4. Pellet storage

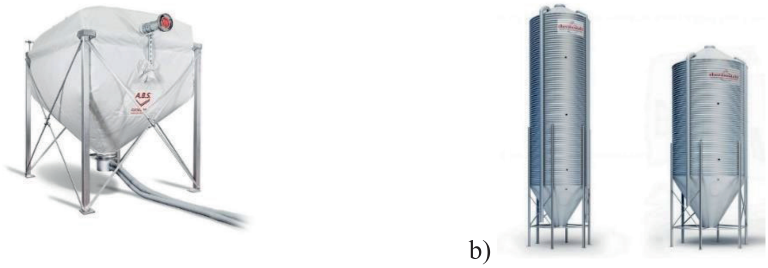
Pellets can be considered as fuel material that is very susceptible to crumbling and cracking. To maintain the standard quality, finished pellets should be stored under appropriate conditions. Wood pellets, due to their hygroscopic nature, should be stored in cool and dry place. Pellets should be isolated from heat sources and adequately protected from changing weather conditions. Moisture is the main enemy of pellets, as it can cause disintegration of pellets. Pellets are most often stored in various types of external tower silos (vertical or horizontal – container-type) or in separate internal warehouses or hangars. Various types of pellet storage tanks are also available: above-ground and underground, including metal or plastic (polyester) tanks. Pellets can be filled into the tanks manually or automatically. If pellets are packed in bags, they should be stacked on pallets in covered area, sheltered from rain.

Packaging and storing pellets in plastic bags is the optimal storage solution (Figure 4.20 a) for products intended for retail resale or stored at the end user, e.g. in household near heating boiler. When storing pellets in bags, it is advisable to provide additional protection against contact with ground. Bags weighing approximately 25 kg are typically placed on pallets, which creates additional insulation from floor moisture. Plastic spacer can be placed on the pallet to facilitate separation of fuel from surface and further reduce risk of mold occurence. Pallets are very durable, so pellets can be stacked in bags at relatively high height, thus keeping fuel away from areas prone to moisture accumulation. Storage areas for pellets in bags should be dry, well-ventilated and protected from potential flooding. Special care should be taken when storing fuel. The room in which pellets will be stored must meet fire protection requirements. This means, among other things, that it cannot be left loose in boiler room directly next to boiler, as this may cause a fire.

Another way to package and store pellets is to use big bags (Figure 4.20 b) which can hold up to 1,000 kg of pellets, depending on bag size and pellet density. The best place to store these types of bags is in dry and covered area, the same principle as for storage in bags. Big bags are stacked directly on ground or on pallets, and stacking height depends on available handling and loading equipment. Typically, they can be stacked in one or two layers.

Figure 4.20. Storage of pellets in plastic bags placed on pallets (a), in big bags (b)

Large-scale pellet storage often involves use of tower silos or concrete, wooden, or plastic tanks (Figure 4.21). Depending on their size and location, these tanks can be external (resistant to environmental conditions) or internal (for indoor use).

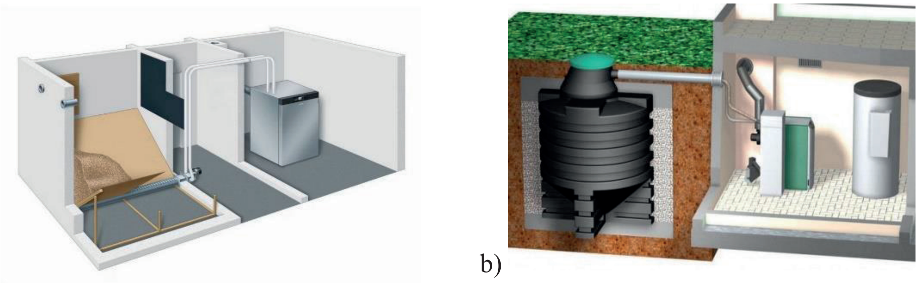


a) b)

Figure 4.21. Bulk pellet storage tanks: Flexio Standard polyester tank (a) (ECO-PRIUS, 2025), Thermostal steel external tanks (b) (ThermoStahl, 2017)

These tanks can store anywhere from approximately 500 kg to several tons of pellets. Advantage of this type of tank is the ability to mount pellet feeders directly to the boiler.

Another storage method is storing pellets loosely in rooms. If these rooms are directly adjacent to the boiler room, these rooms are usually equipped with a sloping wooden floor, which causes pellets to automatically slide towards center, ensuring reliable pellet supply (Figure 4.22). The plaster on the walls must be stable and not flaking for prevention of fuel contamination. Special coat of paint or tiled wall surface is best.



a) b)

Figure 4.22. Pellet storage: (a) pellet storage room with sloping floor and feeding system to the boiler (Viessmann PL, 2023), (b) underground tank with automatic pellet feeding system to the boiler (instsani.pl, 2017)

Underground outdoor storage facility is beneficial solution where fuel storage space is limited and dedicated room in building is not available and high annual pellet demand is normal. Underground tanks are constructed as concrete bunkers, single- or multi-chamber steel tanks, or plastic tanks. They are available in various capacities, up to several dozen cubic meters. Due to the necessary earthworks and increased leak-tightness requirements, underground tank costs are typically higher than other pellet storage systems.

Several issues must be considered for ensuring smooth operation of pellet storage facility. For example, adequate protection against moisture is crucial. Water reduces calorific value of pellets and increases heating costs. It also causes pellets to stick together, disrupting both the power supply and the automatic operation of the heating system.

The underground storage facility must be completely sealed and resistant to groundwater. All penetrations through the tank walls must be pressure-tight with expansion seals.

Additionally, storage facility must be equipped with gravity ventilation system with outlet pipe located adjacent to building or as freestanding structure.

The general fire safety requirements are set by regulations regarding combustion appliances or their local and national equivalents. For example, dedicated storage facility in Poland is only required if planned pellet storage capacity exceeds 10,000 liters. Because fire regulations vary by location and country, fire protection requirements may also vary.

Underground tanks are typically connected to building with large-diameter PVC pipe (usually 200 mm) containing two pressure lines – one feeding fuel to the boiler hopper and the other returning air to the tank. Depending on solution, emptying large underground tanks can be accomplished using active systems or screw conveyors with pellet feeders.

Wood pellets are typically delivered by tanker truck. Pellets are then blown into the storage system through hose with a maximum length of 30 meters. The tank should be located 30 meters from the nearest truck access point for avoiding delivery problems.

5. COMBUSTION, PYROLYSIS AND GASIFICATION PROCESSES AND PRODUCTS

5.1. Combustion processes

Combustion is defined as the oxidation of substances to the final products of the reaction with maximum heat release. Combustion sometimes occurs without light effect. The combustion process is defined as rapid oxidation, which, after introduction, occurs spontaneously in the presence of oxidizer and is accompanied by development of heat and light effect. Each combustion process is possible only in certain interval of values of parameters determining combustion process, such as air speed, amount of excess air, etc. During combustion occures exothermic oxidation reactions, endothermic thermal decomposition reactions, physical processes of mixing fuel and air streams, exchange of mass and heat, etc. The diffusion-kinetic theory of combustion explains this complex process from physical and chemical perspective, qualitatively analyzes influence of individual factors on the course of combustion, generalizes experimental results, etc. The total fuel combustion time is given by the time of physical preparation of fuel and oxidizer for ignition τ_f and the time of chemical reaction itself τ_{ch}, i.e.:

$$\tau = \tau_f + \tau_{ch}\mathrm{w} \qquad 5.1$$

If the mixing of fuel and air is incomparably faster than the course of the chemical reaction ($\tau_f < \tau_{ch}$), combustion process is governed by chemical laws and the burning process is called kinetic combustion. In the opposite way the burning time is determined by the time required for mixing, the burning takes place in the diffusion region, i.e.$\tau_{ch} < \tau_f$ (coefficient y expresses overlapping of times τ_f and τ_{ch}) (Malat’ak et al., 2010; Malat’ak and Vaculík, 2008; Sazima et al., 1989).

5.2. Kinetic combustion

The combustion process in the kinetic region is determined by the course of chemical reactions of the fuel and oxidant. The kinetics of chemical reactions is the science of the rate of chemical reactions and the dependence of the factors of this rate, which are the composition and concentration of reacting substances, the temperature and pressure at which the reactions take place, the influence of catalysts, etc. The speed of chemical reaction depends on the size of the reaction space, the amount of reaction products per unit of time. The initiation and course of the reaction depend on number of properties of the reacting substances, on the creation of suitable conditions for the reaction, etc. According to chemical kinetics, an elementary reaction occurs by the collision of molecules or their disintegration (Sazima et al., 1989).

The chemical reaction between substances A and B, which results in products C and D, is represented by a stoichiometric equation:

$$n_A A + n_B B <=> n_C C + n_D D \qquad 5.2$$

where:

n_A, n_B, n_C, n_D are the numbers of molecules in the elementary process.

The arrows indicate the direction of the direct and reversible reactions. Reactions occurring in both directions are reversible. Some reactions occur in practically only one direction and are therefore called irreversible reactions. Irreversible reactions occur until the initial reagents are exhausted. They occur in cases where the products of the reaction are removed from the reaction zone or when the rate of reversible reactions is very low compared to the rate of direct reactions.

Chemical reactions are divided into homogeneous and heterogeneous reactions according to the phases of the fuel and oxidant. Homogeneous reaction occurs between substances in the same phase. Heterogeneous reaction occurs between fuel and oxidant in different phases. In practice, homogeneous reactions of reagents occur in the gas phase, such as gaseous fuel in mixture with air, evaporated vapors of liquid fuel with air, volatile fraction of carbon with air, etc. An example of heterogeneous reaction is the combustion of solid carbon with oxygen from the air (Malat'ak et al., 2010; Malat'ak and Vaculík, 2008; Sazima et al., 1989).

The rate of chemical reaction can be expressed as the rate of formation of product molecules, using the usual dependence:

$$v_1 = k_1 \cdot C_A^{n_A} \cdot C_B^{n_B} \qquad 5.3$$

where:

k_1 – is the proportionality coefficient or reaction rate constant,

C_A, C_B – are concentrations of substances, expressed, for example, by the number of molecules per unit volume.

Exponents n_A and n_B determine the order of the reaction according to the given reagent. The total order of the reaction is equal to the sum of the partial orders, i.e.:

$$N = n_A + n_B \qquad 5.4$$

If the reaction proceeds in the reverse direction, i.e. if the reaction is reversible, its rate is:

$$v_2 = k_2 \cdot C_C^{n_C} \cdot C_D^{n_D} \qquad 5.5$$

where:

C_C a C_D – are the concentrations of the products of the direct reaction.

In reversible chemical reactions, equilibrium is established at $v_1 = v_2$. From this condition, the equilibrium constant can be determined:

$$K = \frac{k_1}{k_2} = \frac{C_C^{n_C} \cdot C_D^{n_D}}{C_A^{n_A} \cdot C_B^{n_B}} \qquad 5.6$$

The equilibrium constant determines the composition of the system at equilibrium. The direct reactions of the combustion process are exothermic reactions of oxidation of the combustible components of the fuel and intermediate products of the combustion process, while the heat released is the thermal effect of the reaction. The reversible reactions of the combustion process are endothermic reactions of thermal decomposition or dissociation, e.g. carbon dioxide CO_2 to carbon monoxide CO and oxygen O_2, or water vapor H_2O on hydrogen H_2 and oxygen O_2. The heat required for dissociation reactions to occur is the so-called dissociation heat Q_{dis} ($kJ \cdot m^{-3}$). Dissociation reactions CO_2 and H_2O are starting to be practically applied at combustion temperatures above 1500°C.

The rate of chemical reactions is affected by temperature and pressure. As the temperature increases, the rate of reaction increases. For the reaction to proceed, the combining molecules must have sufficient activation energy ΔE to overcome the energy barrier (Sazima et al., 1989).

The dependence of the reaction rate on temperature is very significant. The effect of pressure on the rate of chemical reaction is not evident in first-order reaction, since it involves the breakdown of molecules. The effect of pressure is evident in second-order and higher-order reactions. For second-order reaction, the reaction rate is proportional to pressure. Since real combustion reactions are first- and second- order, increase in pressure is reflected in increase in the combustion rate (Sazima et al., 1989).

Heterogeneous reactions are practically surface reactions, occurring e.g. during the combustion of solid carbon or during the combustion of gases on the surface of solid catalyst. During the course of these reactions, there are significant deviations from the course of homogeneous reactions, manifested by the formation of fractional and zero-order reactions (Malat’ak et al., 2010; Malat’ak and Vaculík, 2008; Sazima et al., 1989).

5.3. Diffusion combustion

In the diffusion combustion region, the intensity of mixing of fuel and oxygen lags behind the rate of chemical reaction, thus regulating the course of the combustion process as a whole. Diffusion combustion occurs in the vast majority of technical combustion processes. The rate of diffusion combustion is determined by physical factors. In this region have no effect the properties of the fuel and oxidizer to the rate of combustion but are mainly applied the type of gas and air flow, the distribution of speeds, concentrations and temperatures in the gas and air flow, the shape and dimensions of the bodies flowing around, the heat exchange between the flow and the surroundings, etc. The volatile fraction of the combustible material burns out during combustion of solid fuels by the diffusion homogeneous principle (Malat’ak et al., 2010; Malat’ak and Vaculík, 2008; Sazima et al., 1989). The rate of diffuse heterogeneous combustion can be expressed by the relationship:

$$v = \beta \cdot (C_{od} - C_{st}) \qquad 5.7$$

where:

β – is the gas exchange coefficient,

C_{od} – oxygen concentration in the reaction volume,

C_{st} – oxygen concentration on the particle surface.

Difference Δv between diffusion and kinetic velocity forms reserve that could be used to increase the burning rate by improving the physical aspect of the combustion process, e.g. by intensifying mixing processes without flame interruption. Faster oxidation reactions take place on the surface during combustion of coke particles, $C + O_2 = CO_2$ and slower reduction, so-called gasification reactions:

$$C + CO_2 = 2\,CO \quad (172.92\,kJ \cdot Mol^{-1}) \qquad 5.8$$

$$C + H_2O = H_2 + \,CO \quad (131.9\,kJ \cdot Mol^{-1}) \qquad 5.9$$

$$C + 2H_2O = CO_2 + 2H_2 \quad (87.615\,kJ \cdot Mol^{-1}) \qquad 5.10$$

These gasification reactions consume heat to release carbon atoms from the carbon lattice. The first two reactions occur when the gas volumes are doubled, as one molecule of a triatomic gas is split into two molecules of a flammable gas, which results in a local increase in gas pressures. The resulting flammable gases burn in the boundary layer at the particle surface according to the equations:

$$2CO + O_2 = 2CO_2 \quad (566.92\,kJ \cdot Mol^{-1}) \qquad 5.11$$

$$2H_2 + O_2 = 2H_2O \quad (484.32\,kJ \cdot Mol^{-1}) \qquad 5.12$$

In these reactions, on the contrary, the volume of gases decreases, because the resulting number of molecules is smaller and local negative pressure is created (Sazima, 1989). At lower combustion temperatures of carbon particles, oxidation reactions take place on the surface $C + O_2 = CO_2$, combustion takes place in the kinetic region and oxygen is present on the particle surface. At higher temperatures, combustion takes place in the diffusion region, since the intensity of the O_2 supply to the surface inhibits the possible course of the chemical reaction, the proportion of gasification reactions increases compared to direct oxidation. Since the released flammable gases CO, H_2 react with oxygen diffusing to the particle surface, the amount of oxygen on the surface decreases. At temperature of about 2,000°C, free oxygen disappears at the surface, and thus the chemical composition of the layer on the particle changes. Gasification reactions allow the particle to burn out at higher temperatures even in places with a lack of oxygen (Malat'ak et al., 2010; Malat'ak and Vaculík, 2008; Sazima et al., 1989).

5.4. Gasification of solid fuels

Gasification of solid fuels is a process in which gaseous fuel is obtained. The endothermic reactions that occur during gasification and consume heat occur in three ways:

- Bouord reaction, in which the carbon contained in the fuel is gasified by reduction with carbon dioxide:

$$C + CO_2 = 2CO \qquad 155\,MJ \qquad 5.13$$

- Heterogeneous reaction with water vapor, carbon is gasified by reduction with water vapor:

$$C + H_2O = CO + H_2 \qquad 118\,MJ \tag{5.14}$$

$$C + 2H_2O = CO_2 + 2H_2 \qquad 90\,MJ \tag{5.15}$$

- Methane reaction, methane gasification reaction proceeds according to the relationship:

$$C + 2H_2 = CH_4 \qquad 88\,MJ \tag{5.16}$$

The above methods of carbon gasification in solid fuels show that individual endothermic reactions produce carbon monoxide CO, hydrogen H_2 and methane CH_4, which are components of fuel gas (Malaťáková et al., 2021; Obroučka, 2001; Rybín, 1985; Trnobranský, 1996). The importance of the aforementioned gasification reactions, enabled by the high temperature of the flame, lies, among other things, in the fact that during the combustion process of coal particles, these reactions allow the gasification of the combustible material even in areas of the flame with a local lack of oxygen, where the only "oxidant" is carbon dioxide or water vapor (Sazima et al., 1989).

In addition to the reactions of carbon with CO_2, the gasification of carbon by water vapor molecules is also important according to the above equations of endothermic reactions with water vapor, in which hydrogen and carbon monoxide are formed. In this process, the H_2 and CO molecules diffuse themselves from the fuel grain into the space where they meet oxygen and burn. These new water vapor and carbon dioxide molecules partially return to the fuel grain, from which they consume another part of the combustible material during gasification. This is repeated until the carbon is completely gasified. The gasification of carbon by water vapor occurs faster than the gasification by carbon dioxide. This is due to the fact that the molecular speed of water vapor is about 1.5 times greater than that of CO_2. The molecular speed of hydrogen is also about 3.7 times greater than the speed of carbon monoxide molecules. Water vapor molecule is able to gasify more carbon atoms than CO_2 molecule at the same time, which also needs more reaction heat to do so. The high mobility of water vapor and hydrogen molecules explains why the presence of water vapor in flame accelerates combustion processes (Malaťáková et al., 2021; Obroučka, 2001; Rybín, 1985; Trnobranský, 1996).

5.5. Stoichiometry of combustion processes

Stoichiometric calculations of combustion processes complement fuel characteristics and are the basis for any thermal calculation. They are especially important for solving wide range of design problems, as well as for checking the operation of existing combustion plants. These calculations determine:

- amount of oxygen (air) required for complete combustion of the fuel,
- amount and composition of the flue gases,
- specific gravity of the flue gases,
- adiabatic, theoretical and practical combustion temperature (Malat’ak et al., 2010; Obroučka, 2001).

5.6. Calculations of air consumption and flue gas quantity

According to the conditions that are created for the combustion process, we distinguish:

***Complete combustion** is combustion in which all combustible components in the fuel are combusted, so that the resulting combustion gases no longer contain combustible components*.

Complete combustion with theoretical excess of air (L_{min}), which can be calculated from the stoichiometric relations of the combustion equations, can only be achieved with completely perfect mixing of fuel with air and under ideal combustion conditions. The air (oxygen) consumption is greater than the theoretical one for ensuring perfect combustion in practical operation and this depends on the type of fuel, combustion equipment, combustion area (diffusion or kinetic), etc. We are then talking about the so-called excess of combustion air, which is smaller when fuel is mixed with air more precisely. The ratio between the actual and theoretical air consumption is called the excess air coefficient (n) and is equal to:

$$n = \frac{L_{skut}}{L_{min}} = \frac{O_{skut}}{O_{min}} = \frac{20.95}{20.95 - O_2} = \frac{CO_{2max}}{CO_2} \qquad 5.17$$

Excess air is necessary to ensure perfect combustion. On the other hand, it is necessary to take into account the harmfulness of too much excess air. The more air is involved in combustion, the more heat is carried away by the flue gases, and then combustion temperature and fuel efficiency decrease. Therefore, it is necessary to use an optimal excess air (Malaťák et al., 2020; Malaťák et al., 2022; Malaťák et al., 2023).

***Incomplete combustion** is combustion in which there is a certain content of combustible substances in the flue gases.*

This type of combustion always occurs when $n < 1$. However, it can also occur when $n = 0$ or $n > 1$, when the fuel and oxidant are not perfectly mixed. This type of combustion, which worsens the thermal efficiency of combustion, is undesirable in most cases and is used exceptionally for combustion for technological reasons. The basic stoichiometric relationship for the incomplete combustion of carbon is:

$$C + 0.5O_2 = CO + heat \qquad 5.18$$

$$12\ kg + 16\ kg = 28\ kg + 123\ MJ$$

$$12.01\ kg + 0.5 \cdot 22.39\ m^3 = 22.37\ m^3$$

If only half the volume of oxygen is consumed during combustion of carbon to CO than when burning CO_2 completely. The calorific value of CO is 12,645 $kJ \cdot m^{-3}$. Due to the significantly higher reaction rate of hydrogen combustion compared to carbon combustion, the loss of unburned hydrogen is practically zero even at $n < 1$. The oxygen content in the flue gas is a measure of excess air only if combustion is complete.

*If the flue gases contain both carbon dioxide CO_2 and carbon monoxide CO, we speak of **mixed combustion**.*

Calculation of air consumption and flue gas quantity can be carried out in the following ways:

- according to the data of elemental analysis using stoichiometric equations (analytical method),
- using approximate formulas, different for different types of fuels (based on calorific value),
- using graphical methods.

For the combustion of selected samples, only the first of the above methods is considered, i.e. based on stoichiometric calculations (Malat'ak et al., 2010; Obroučka, 2001). Dry air of simplified composition is also considered as an oxidant:

a) By volume: 21% O_2, 78.05% N_2. From this composition, the ratio of oxygen, nitrogen and air can be calculated from the relationship:

$$O_2 : N_2 : air = \frac{21}{21} : \frac{78.05}{21} : \frac{100}{21} = 1 : 3.716 : 4.76 \tag{5.19}$$

b) By mass: 23.2% O_2, 75.47% N_2. Similarly, we determine the ratio by the relationship:

$$O_2 : N_2 : air = \frac{23.2}{23.2} : \frac{75.47}{23.2} : \frac{100}{23.2} = 1 : 3.253 : 4.31 \tag{5.20}$$

The volume and mass composition of dry air without water vapor, neglecting noble gases contained in minute quantities, is given in Table 5.1.

Table 5.1. Volume and mass composition of dry air (Malat'ak et al., 2010; Obroučka, 2001)

Gas	Volume composition (% vol.)	Mass composition (% wt.)
O_2	21.000	23.200
N_2	78.050	75.474
Ar	0.920	1.280
CO_2	0.030	0.046

The atmospheric air used for combustion contains a certain amount of water vapor, which depends on the air temperature t_v and the relative air humidity φ. The volume of water vapor per 1 m^3 of dry air at temperature t_v:

$$v_{H_2O} = \phi \cdot \frac{p_s}{p_c - p_s \cdot \phi} \quad (m_N^3 \cdot kg^{-1}) \tag{5.21}$$

where:

p_s – is the water vapor pressure at temperature t_v (kPa);
p_c – total pressure of moist air (kPa).

The coefficient that expresses the volumetric amount of water vapor contained in the air, at a given relative humidity and air temperature, has the value:

$$v = 1 + \phi \cdot \frac{p_s}{p_c - \phi \cdot p_s} \tag{5.22}$$

Its value is usually approximately $v = 1.04$.

For precise calculations of the volume of combustion products (flue gases) and the required volume of combustion air, the molecular weight of the individual elements of the combustible material is used. The molecular weights of the elements are given in Table 5.2.

Table 5.2. Molecular weights of elements in a flammable substance (Malat'ak et al., 2010; Obroučka, 2001)

Element	Kilomol	
	Mass (kg)	Volume (m^3)
Hydrogen (H)	2.016	22.39
Carbon (C)	12.01	22.39
Oxygen (O)	32.00	22.39
Sulphur (S)	32.06	22.39
Nitrogen (N)	28.02	22.39

5.7. Combustion of solid fuels

Using the molecular weights of individual elements, the relationships for oxidation reactions in combustion can be expressed by stoichiometric equations. Combustion of carbon to carbon dioxide:

$$C + O_2 = CO_2 + heat \qquad 5.23$$

$$12\ kg + 32\ kg = 44\ kg + 406.3\ MJ$$

$$12.01\ kg + 22.39\ m^3 = 22.27\ m^3$$

The calorific value of 1 kg of pure carbon is 33.85 MJ·kg^{-1}.
Hydrogen combustion to water vapor:

$$2H_2 + O_2 = 2H_2O + heat \qquad 5.24$$

$$2\ kg + 16\ kg = 18\ kg + 241\ MJ$$

$$4.032\ kg + 22.39\ m^3 = 44.81\ m^3$$

The calorific value of 1 kg of hydrogen is 120.5 MJ·kg^{-1}.
Combustion of sulfur to sulfur dioxide:

$$S + O_2 = SO_2 + heat \qquad 5.25$$

$$32\ kg + 32\ kg = 64\ kg + 290\ MJ$$

$$32.06\ kg + 22.39\ m^3 = 21.89\ m^3$$

The calorific value of 1 kg of sulfur is 9.0625 MJ·kg^{-1}.
For the conversion of other elements and moisture (water) into the gaseous phase, the following applies:
For nitrogen:

$$N = N_2 \qquad 5.26$$

$$28.013\ kg = 28.013\ kg$$

$$28.013\ kg = 22.39\ m^3$$

For oxygen:

$$2O = O_2 \qquad 5.27$$

$$31.999\ kg = 31.999\ kg$$

$$31.999\ kg = 22.39\ m^3$$

For humidity it applies:

$$H_2O_{liquid} = H_2O_{vapor} \qquad 5.28$$

$$18.015\ kg = 18.015\ kg$$

$$18.015\ kg = 22.41\ m^3$$

All volumes and masses of combustion air and flue gases in the equations are given under so-called normal conditions, i.e. at temperature t = 0°C and pressure p = 101.325 kPa (Malat’ak et al., 2010; Malat’ak and Vaculík, 2008; Obroučka, 2001; Rybín, 1985; Sazima et al., 1989; Trnobranský, 1996).

5.7.1. Mass combustion

Theoretical amount of oxygen for complete combustion:

$$O_{min} = \frac{32}{12}C + \frac{32}{4}H + \frac{32}{32}S - \frac{32}{32}O \qquad (kg \cdot kg^{-1}) \qquad 5.29$$

Theoretical amount of air for perfect combustion:

$$L_{min} = O_{min}\frac{100}{23.4} \qquad (kg \cdot kg^{-1}) \qquad 5.30$$

Real amount of air for perfect combustion:

$$L_{skut} = O_{min} \cdot \frac{100}{23.2} \cdot n \qquad (kg \cdot kg^{-1}) \qquad 5.31$$

Theoretical mass quantity of dry flue gas:

$$m^{s}_{sp_{min}} = \frac{44}{12}C + \frac{64}{32}S + N + 0.75474 \cdot L_{min} \qquad (kg \cdot kg^{-1}) \qquad 5.32$$

where:

C, H, O, S, N, W – are the relative amounts of carbon, hydrogen, oxygen, sulfur, nitrogen, and any water in the original fuel ($kg \cdot kg^{-1}$);

n – excess air coefficient (–).

Mass quantity of wet flue gas:

$$m_{sp}^{v} = m_{CO_2} + m_{SO_2} + m_{H_2O} + m_{N_2} + m_{O_2} + m_{Ar} \qquad (kg \cdot kg^{-1}) \tag{5.33}$$

Mass quantity of dry flue gas:

$$m_{sp}^{s} = m_{CO_2} + m_{SO_2} + m_{N_2} + m_{O_2} + m_{Ar} \qquad (kg \cdot kg^{-1}) \tag{5.34}$$

where:

$$m_{CO_2} = \frac{44}{12} C + 0.00046 \cdot L_{skut} \tag{5.35}$$

$$m_{SO_2} = \frac{64}{32} S \qquad (kg \cdot kg^{-1}) \tag{5.36}$$

$$m_{H_2O} = \frac{18}{2} H + W + (v - 1) \cdot L_{skut} \qquad (kg \cdot kg^{-1}) \tag{5.37}$$

$$m_{N_2} = N + O_{min} \cdot \frac{75.474}{23.2} \qquad (kg \cdot kg^{-1}) \tag{5.38}$$

$$m_{O_2} = O_{min} \cdot (n - 1) \qquad (kg \cdot kg^{-1}) \tag{5.39}$$

$$m_{Ar} = 0.0128 \cdot L_{skut} \qquad (kg \cdot kg^{-1}) \tag{5.40}$$

Expression of individual flue gas components in %:
Theoretical mass concentration of carbon dioxide in dry flue gas:

$$CO_{2_{max}} = \frac{\frac{44}{12} C}{m_{sp_{min}}^{s}} \cdot 100 \qquad (\%\, wt.) \tag{5.41}$$

Theoretical mass concentration of sulfur dioxide in dry flue gas:

$$SO_{2_{max}} = \frac{\frac{64}{32} C}{m_{sp_{min}}^{s}} \cdot 100 \qquad (\%\, wt.) \tag{5.42}$$

Mass concentration of flue gas components in wet flue gas:

$$CO_2 = \frac{m_{CO_2}}{m_{sp}^{v}} \cdot 100 \qquad (\%\ wt.) \tag{5.36}$$

$$H_2O = \frac{m_{H_2O}}{m_{sp}^{v}} \cdot 100 \qquad (\%\ wt.) \tag{5.37}$$

$$SO_2 = \frac{m_{SO_2}}{m_{sp}^{v}} \cdot 100 \qquad (\%\ wt.) \tag{5.38}$$

$$N_2 = \frac{m_{N_2}}{m_{sp}^{v}} \cdot 100 \qquad (\%\ wt.) \tag{5.39}$$

$$O_2 = \frac{m_{O_2}}{m_{sp}^{v}} \cdot 100 \qquad (\%\ wt.) \tag{5.40}$$

(Malat'ak et al., 2010; Malat'ak and Vaculík, 2008; Obroučka, 2001; Rybín, 1985; Sazima et al., 1989; Trnobranský, 1996)

5.7.2. Volumetric combustion (values of real molar volumes of gases)

The calculations were made using the values of real molar volumes of gases. Theoretical amount of oxygen for perfect combustion:

$$O_{min} = \frac{22.39}{12.01}C + \frac{22.39}{4.032}H + \frac{22.39}{30.06}S - \frac{22.39}{31.99}O \qquad (m^3 \cdot kg^{-1}) \tag{5.41}$$

Theoretical amount of air for perfect combustion:

$$L_{min} = O_{min} \cdot \frac{100}{21} \qquad (m^3 \cdot kg^{-1}) \tag{5.42}$$

Real amount of air for perfect combustion:

$$L_{skut} = O_{min} \cdot \frac{100}{21} \cdot n \qquad (m^3 \cdot kg^{-1}) \tag{5.43}$$

Theoretical volume of dry flue gas:

$$v^{s}_{sp_{min}} = \frac{22.27}{12.01}C + \frac{21.89}{32.06}S + \frac{22.40}{28.013}N + 0.7805 \cdot L_{min} \quad (m^3 \cdot kg^{-1}) \tag{5.44}$$

where:

C, H, O, S, N, W – are the relative amounts of carbon, hydrogen, oxygen, sulfur, nitrogen, and any water in the original fuel (kg·kg^{-1}),

n – excess air coefficient (–).

Volumetric amount of wet flue gas:

$$v^{v}_{sp} = v_{CO_2} + v_{SO_2} + v_{H_2O} + v_{N_2} + v_{O_2} + v_{Ar} \qquad (m^3 \cdot kg^{-1}) \tag{5.45}$$

Volumetric amount of dry flue gas:

$$v^{s}_{sp} = v_{CO_2} + v_{SO_2} + v_{N_2} + v_{O_2} + v_{Ar} \qquad (m^3 \cdot kg^{-1}) \tag{5.46}$$

where:

$$v_{CO_2} = \frac{22.27}{12.01}C + 0.0003 \cdot L_{skut} \qquad (m^3 \cdot kg^{-1}) \tag{5.47}$$

$$v_{SO_2} = \frac{21.89}{32.06}S \qquad (m^3 \cdot kg^{-1}) \tag{5.48}$$

$$v_{H_2O} = \frac{44.81}{4.032}H + \frac{22.41}{18.015}W + (v - 1) \cdot L_{skut} \qquad (m^3 \cdot kg^{-1}) \tag{5.49}$$

$$v_{N_2} = \frac{22.40}{28.013} N + O_{min} \cdot \frac{78.05}{21} n \qquad (m^3 \cdot kg^{-1}) \qquad 5.50$$

$$v_{O_2} = O_{min} \cdot (n - 1) \qquad (m^3 \cdot kg^{-1}) \qquad 5.51$$

$$v_{Ar} = 0.0092 \cdot L_{skut} \qquad (m^3 \cdot kg^{-1}) \qquad 5.52$$

Expression of individual flue gas components in % vol.:

Theoretical volume concentration of carbon dioxide in dry flue gas:

$$CO_{2_{max}} = \frac{\frac{22.27}{12.01} C}{v^s_{sp_{min}}} \cdot 100 \qquad (\%\ vol.) \qquad 5.53$$

Theoretical volumetric concentration of sulfur dioxide in dry flue gas:

$$SO_{2_{max}} = \frac{\frac{21.89}{32.06} S}{v^s_{sp_{min}}} \cdot 100 \qquad (\%\ vol.) \qquad 5.54$$

Volumetric concentration of flue gas components in wet flue gas:

$$CO_2 = \frac{v_{CO_2}}{v^v_{sp}} \qquad (\%\ vol.) \qquad 5.55$$

$$H_2O = \frac{v_{H_2O}}{v^v_{sp}} \qquad (\%\ vol.) \qquad 5.56$$

$$SO_2 = \frac{v_{SO_2}}{v^v_{sp}} \qquad (\%\ vol.) \qquad 5.57$$

$$N_2 = \frac{v_{N_2}}{v^v_{sp}} \qquad (\%\ vol.) \qquad 5.58$$

$$O_2 = \frac{v_{O_2}}{v^v_{sp}} \qquad (\%\ vol.) \qquad 5.59$$

(Malat'ak et al., 2010; Malat'ak and Vaculík, 2008; Obroučka, 2001; Rybín, 1985; Sazima et al., 1989; Trnobranský, 1996)

5.7.3. Combustion temperatures and their calculation

The combustion temperature is one of the basic properties that characterizes fuel with respect to its technological use. The temperature in the working space of the combustion device also depends on the achievable flame temperature, which determines the use of the optimal technological production process. The combustion temperature can be determined from the heat balance equation, which determines the heat input and output during fuel combustion:

$$Q_{ch} + Q_p + Q_{vz} = Q_{sp} + Q_{ned} + Q_{dis} + Q_z \qquad (kJ \cdot kg^{-1}) \qquad 5.60$$

where heat intake:

Q_{ch} – is the chemical heat, which is determined by the calorific value of the fuel (kJ·kg^{-1});

Q_p .. – enthalpy of preheated fuel.

$$Q_p = c_p \cdot t_p \qquad (kJ \cdot kg^{-1}) \qquad 5.61$$

Q_{vz} – is the enthalpy of the preheated air.

$$Q_{vz} = c_{vz} \cdot t_{vz} \cdot n \cdot L_{min} \qquad (kJ \cdot kg^{-1}) \qquad 5.62$$

heat output:

Q_{sp} – is the enthalpy of the flue gas (kJ·kg^{-1}, kJ·m^{-3}).

$$Q_{sp} = V_{sp} \cdot c_{sp} \cdot t_{sp} \qquad (kJ \cdot kg^{-1}) \qquad 5.63$$

Q_{ned} – are chemical and mechanical noncombustibles (kJ·kg^{-1}, kJ·m^{-3});
Q_{dis} – dissociation heat (kJ·kg^{-1}, kJ·m^{-3});
Q_z – heat output to the furnace structure and into the surroundings (kJ·kg^{-1}, kJ·m^{-3}).

In the above equations:
c_p, c_{vz}, c_{sp} – is the specific heat capacity of fuel, air, flue gas (kJ·kg^{-1}·K^{-1}, kJ·m^{-3}·K^{-1});
t_p, t_{vz}, t_{sp} ..– temperature of fuel, air, exhaust gas (°C);
n – excess air coefficient (–);
L_{min} – theoretical (minimum) amount of air needed to burn unit of fuel (m^3·m^{-3});
V_{sp} – amount of flue gas (m^3·m^{-3}).

Flue gas temperature, which characterizes the combustion temperature of the fuel:

$$t_{sp} = \frac{Q_{ch} + Q_p + Q_{vz} - Q_{ned} - Q_{dis} - Q_z}{V_{sp} \cdot c_{sp}} \qquad (°C) \qquad 5.64$$

(Malat'ak et al., 2010; Malat'ak and Vaculík, 2008; Obroučka, 2001; Rybín, 1985; Sazima et al., 1989; Trnobranský, 1996)

5.7.4. Basic types of combustion temperatures

Since the actual combustion temperature depends not only on the properties of the fuel but also on the conditions of the combustion process, its determination in practice is very difficult. Therefore, in solving this problem, various types of combustion temperatures are used, which are easier to determine, but always provide solution with certain limitations.

1) Adiabatic combustion temperature t_a determines the properties of the fuel. This temperature with respect to the fuel characterizes the adiabatic conditions both in the supply and in the heat removal, and determines the conditions of perfect combustion at $n = 1$. At other temperatures, the adiabatic conditions with respect to the fuel itself are no longer observed, so the adiabatic conditions are considered only with respect to the combustion process itself, but not with respect to the fuel. The definition of the adiabatic temperature implies that in the equation 5.60 is $Q_p = 0$; $Q_{ned} = 0$; $Q_{dis} = 0$; $Q_z = 0$; $n = 1$. Under these conditions, the adiabatic combustion temperature can be expressed by the relationship:

$$t_a = \frac{Q_n}{V_{sp.min} \cdot c_{sp}} \qquad (°C) \qquad 5.65$$

where:
$V_{sp,\,min}$ – is the volume of flue gas at $n = 1$ ($m^3 \cdot kg^{-1}$, $m^3 \cdot m^{-3}$).

2) Theoretical combustion temperature t_t is used as a comparison for the same and different fuels under different or the same combustion process conditions. This temperature allows changing the combustion air consumption values ($n \geq 1$), fuel enthalpy value ($Q_p \geq 0$) and specific enthalpy of air ($Q_{vz} \geq 0$). For the theoretical combustion temperature, the following applies $Q_{ned} = 0$, $Q_{dis} = 0$, $Q_z = 0$, $n \geq 1$, so it is determined by the equation:

$$t_t = \frac{Q_n + Q_p + Q_{vz}}{V_{sp} \cdot c_{sp}} \quad (°C) \qquad 5.66$$

Calculating the theoretical combustion temperature and similarly other temperatures is difficult because the value of the specific heat capacity of the flue gases in the equations changes depending on the temperature. We will list the most commonly used calculation methods: ***Iterative solution*** (iteration – repetition of calculations, a step towards achieving results) consists in choosing an assumed temperature value, for which we look up the specific heat capacity of the flue gases in the tables and substitute it into the equation 5.60. If the temperature is different from the selected one, the calculation must be repeated, choosing a temperature closer to the calculated temperature.

The solution using flue gas enthalpy is based on the equation 5.64, shaped on the equation:

$$t_t \cdot c_{sp} = \frac{Q_n}{V_{sp}} + \frac{Q_p}{V_{sp}} + \frac{Q_{vz}}{V_{sp}} = \frac{Q_n}{V_{sp}} + \frac{c_p \cdot t_p}{V_{sp}} + \frac{c_{vz} \cdot t_{vz} \cdot n \cdot L_{min}}{V_{sp}} \quad (kJ \cdot m^{-3}) \qquad 5.67$$

where:
$t_t \cdot c_{sp} = i_{sp}$ – is the total specific enthalpy of the flue gas ($kJ \cdot m^{-3}$);
$\frac{Q_n}{V_{sp}} = i_{ch}$ – flue gas enthalpy corresponding to the calorific value ($kJ \cdot m^{-3}$);
$\frac{c_p \cdot t_p}{V_{sp}} = i_p$ – flue gas enthalpy corresponding to fuel preheating ($kJ \cdot m^{-3}$);
$\frac{c_{vz} \cdot t_{vz} \cdot n \cdot L_{min}}{V_{sp}} = i_{vz}$– flue gas enthalpy corresponding to combustion air preheating ($kJ \cdot m^{-3}$).

The calculation is performed assuming that the specific enthalpy of the flue gas varies within a temperature difference of 100 °C. We select two temperatures differing by 100 °C, such that the calculated enthalpy of the flue gas is within the range corresponding to the two selected temperatures. The values of the enthalpy of the flue gas for the selected temperatures are read from the tables. We then find the temperature corresponding to the calculated specific enthalpy of the flue gas by interpolation.

3) Practical combustion temperature t_p respects the actual combustion conditions, including heat dissipation to the surroundings and other loss items. To calculate the practical combustion temperature, all items in the equation must be considered 5.64, so the equation:

$$t_p = \frac{Q_{ch} + Q_p + Q_{vz} - Q_{ned} - Q_{dis} - Q_z}{V_{sp} \cdot c_{sp}} \quad (°C) \qquad 5.68$$

When calculating, it is necessary to take into account the previously considered items as well as heat losses resulting from chemical and mechanical underburning (Q_{ned}) and heat dissipation to the environment (Q_z). The difficulty of this calculation led to the introduction of a simplified indicative calculation using the pyrometric effect (η_{pyr}) from the equation:

$$t_p = t_t \cdot \eta_{pyr} \quad (°C) \qquad 5.69$$

where:

η_{pyr} – is pyrometric effect characterizing heat losses for certain types of furnaces. (Malat'ak et al., 2010; Malat'ak and Vaculík, 2008; Obroučka, 2001; Rybín, 1985; Sazima et al., 1989; Trnobranský, 1996)

5.8. Combustion equipment up to a thermal output of 100 kW for the combustion of solid biofuels in the form of wood chips and pellets

5.8.1. Combustion of solid fuels in layer

When assessing combustion device for combustion of solid biofuels in layer, it is necessary to take into account the basic functional elements that every grate fireplace must meet (Figure 5.1.):

- fuel supply to the grate and combustion air supply to the firebox/combustion chamber,
- moving (raking) the fuel layer on the grate,
- removing solid residue after combustion and removing gaseous combustion products (flue gases) from the firebox/combustion chamber.

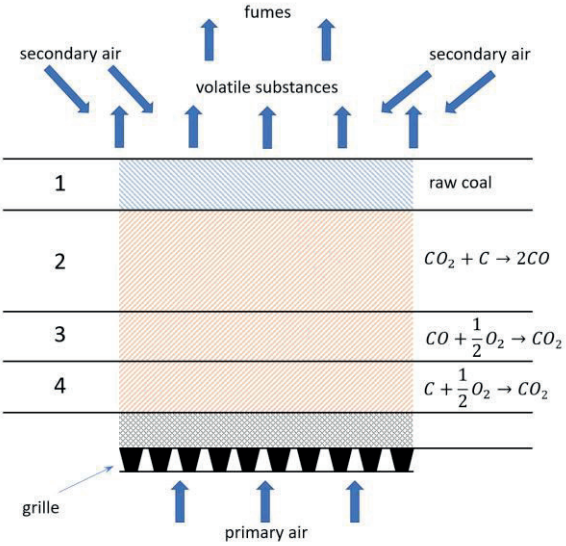


Figure 5.1. Individual phases of the combustion process in the fuel layer (Malat'ak et al., 2010; Rybín, 1985)

The basic requirements for grate fireplaces include:

- perfect fuel combustion with minimal excess combustion air,
- ensuring the best conditions for heat removal from flue gases to the heating surfaces,
- possibility of rapid regulation of the heat load of the fireplace,
- easy cleaning of the heating surfaces on the flue gas side,
- high reliability of operation,
- simple and undemanding operation.

The combustion process is divided into several phases, which in fact intertwine. Fresh fuel is fed to the layer, where the heat of the burning part of the layer quickly heats it up and the volatile combustible material is expelled from it. Secondary combustion air, fed into the space above the fuel layer, enables the volatile combustible material to burn out.

Primary combustion air enters the fuel layer through the gaps in the grate. It passes through layer of solid ash, which acts as an insulating layer between the intensive combustion area and the grate (Figure 5.1.). Above the first layer of slag is the first oxidation zone, where oxidation reactions with oxygen occur on the surface of the fuel particles. This is where carbon monoxide CO is mainly produced:

$$C + \frac{1}{2}O_2 = CO \tag{5.70}$$

Carbon monoxide, after combining with oxygen, changes into carbon dioxide CO_2 in the second oxidation zone:

$$CO + \frac{1}{2}O_2 = CO_2 \tag{5.71}$$

Each of these reactions is highly exothermic and releases heat. In this phase of the combustion process, oxygen is consumed and carbon dioxide is reduced in the following reduction zone by the influence of carbon according to the reaction back to carbon monoxide:

$$CO_2 + C = 2CO \tag{5.72}$$

Since this reaction is endothermic (it consumes heat), the combustion temperature will drop. However, in the following moments, after contact with the oxygen of the secondary air, the CO will burn to CO_2 (Malat'ak et al., 2010; Rybín, 1985).

5.8.2. Solid biofuel combustion plants

It is possible to manufacture solid biofuel combustion equipment with a minimum output of 5 kW which currently meet the conditions for the efficiency of the combustion process and the lowest possible impact on the environment. The most common fuel in these combustion equipment is lump wood (logs), wood chips, pellets and briquettes (Aniszewska et al., 2025; Čermák et al., 2024, 2022; Gendek et al., 2018a). The combustion process takes place in the following four stages:

- phase of drying, evaporation of water from the fuel,
- phase of releasing the gaseous component of the fuel,
- phase of burning the gaseous component of the fuel,
- phase of burning solids, especially carbon.

Biomass is specific in that among solid fuels it contains the highest proportion of gaseous substances released by pyrolysis (75 to 85%) that do not burn on the grate, but in the air between the grate and the chimney (this is called a long flame). This has unavoidable consequences for the design of furnaces:

- only a small part of the oxygen required for the oxidation of solid fuel residues on the grate is supplied under the grate (primary air),
- larger part of the oxygen is supplied to the flow of escaping gases into the space behind the grate (secondary air),
- space immediately above the grate (or behind it) cannot be designed as heat exchanger, but as heat-retaining space (with fireclay lining), the task of which is to keep the gases and the supplied oxygen at the required ignition temperature (Malat'ak et al., 2010; Trnobranský, 1996).

From the above it follows that truly efficient and environmentally friendly combustion of solid biofuels is possible only in specially designed furnaces, and not in power units designed for other fuels (coal, coke), in which the function of secondary air does not play such significant role. In unmodified furnaces for fossil fuels, combustion of solid biomass is usually technically possible, but it is associated with both their unacceptably low efficiency, i.e. with low utilization of combustion heat, and with emissions of environmentally undesirable products of incomplete combustion (Carroll and Finnan, 2013).

In general there is possible to state that the output of furnace is rising with drier input material, larger surface area of material that burns (this is why wood briquettes are made with central hole, increasing their surface area) and more material that burns simultaneously. The design of furnaces and the preparation of material for combustion, both in terms of adjusting its size and humidity, depend on these basic dependencies (Nimitpaitoon et al., 2023).

The maximum water content in wood waste, with regard to combustion, is limited by the requirement that the temperature in the combustion chamber be at least 900°C. This requirement is because when the temperature falls below 900°C, a reaction occurs in the unburned gases in the flue gas, see equation:

$$CO_2 + C = 2CO \qquad 5.73$$

which at temperatures below 900°C runs to the left and changes to the shape:

$$2CO = CO_2 + C \qquad 5.74$$

where carbon C is excreted in the form of soot. However, this is very undesirable phenomenon that should be avoided during operation (Malat'ak et al., 2010; Trnobranský, 1996).

Lower water content in fuel corresponds to shorter time required for its drying during combustion. After this stage, release of volatile combustibles occurs, which must be mixed with combustion air in order to burn it completely. In the case of fuel transport by air (pneumatic transport) to combustion chamber, fuel will be surrounded by layer of transport and combustion air at the same time (Malat'ak et al., 2010; Trnobranský, 1996). The influence of negative pressure in firebox and the influence of diffusion will lead to idealized creation of air envelope. The actual shape of air envelope will of course be influenced by operating conditions of boiler/combustion device. When volatile combustible matter is released from fuel, it mixes with combustion air and thus achieves complete combustion. If larger fuel particles are not enough to burn in air, they will burn out on fixed grate, under which combustion air is also supplied. (Malat'ak et al., 2010; Rybín, 1985; Trnobranský, 1996).

With higher water content in fuel, time required for particle to burn out will be longer than time it remains in suspension. This will also eliminate desirable effect of combustion air envelope and it will no longer be possible to burn such wet fuel in suspension.

For smaller thermal outputs of combustion devices up to approximately 100 kW, devices for lump wood waste are used, which operate on the principle of gasification of wood mass. The resulting gas passes through narrow slot, into which secondary combustion air is supplied. In the narrow slot, the gas is perfectly mixed with the combustion air, which has positive effect not only on the thermal efficiency of the boiler, but also on improving the environment (Trnobranský, 1996).

Most small combustion plants have bottom combustion of fuel (Figure 5.2.). These boilers differ from conventional solid fuel boilers in the principle of combustion. They are designed for pyrolytic distillation can occure during combustion of fuel, during which all combustible components of fuel are gasified. Combustion takes place in three-stage process in individual zones:

1. zone – drying and gasification of wood mass,
2. zone – combustion of wood gas on nozzle with supply of preheated secondary air,
3. zone – afterburning in uncooled combustion chamber.

Only combusted flue gases reach the heat exchange surfaces of exchangers. This controlled combustion system guarantees high efficiency for the boilers. The heating output is continuously adjustable from 40 to 90% (Malat'ak et al., 2010; Trnobranský, 1996).

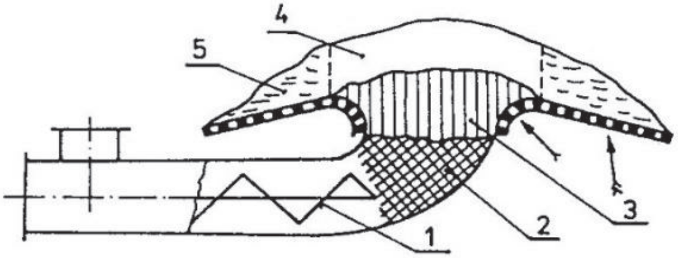


Figure 5.2. Diagram of combustion device with bottom fuel supply. Keys: 1 – fuel supply 2 – drying zone, 3 – volatile combustible matter release zone; 4 – volatile combustible matter burnout zone; 5 – coke residue burnout zone (Trnobranský, 1996).

The design of heat exchangers and quality of insulation materials used are constantly being improved for increasing efficiency of furnaces and making better use of temperature of flue gases. The exchangers are used to preheat primary or secondary air in some cases, or in other cases they can be also used for hot air heating. Hot air heating elements are now often used in fireplaces, which significantly increases their efficiency compared to classic types.

5.9. Gasification

Gasification is a thermochemical process in which hydrocarbons are gradually oxidized with water vapor from fuel (or gasification medium) and subsequently reduced to flammable gases, distillation products and mineral residues. Gasification is incomplete combustion, meaning that we supply less air than is needed for complete combustion. This incomplete combustion produces carbon monoxide (CO), which is the main flammable component of produced gas and by-products (H_2, CH_4, CO_2, N_2 a H_2O) (Makwana et al., 2023; Malaťáková et al., 2021; Pohořelý et al., 2012; Tezer et al., 2022). From thermochemical point of view, the biomass gasification process is complex and involves many steps, including:

- thermal decomposition of fuel into gas, condensing vapors and charcoal, so-called pyrolysis,
- thermal splitting of vapors into gas and solid carbon,
- gasification of solid carbon with steam or carbon dioxide,
- partial oxidation of flammable gases, secondary components and solid carbon.

The chemical energy contained in fuel is transformed into pressure energy of steam or water during combustion process. In contrast to combustion process, the transformation occurs into another type of chemical energy during gasification, which is bound to the gaseous phase. There is thermal equilibrium between the reactions consuming heat (endothermic) and the reactions producing heat (exothermic) (Malaťáková et al., 2021; Pohořelý et al., 2012).

Biomass gasification as one of the options for energy use of biomass has number of advantages over other methods of use:

- possibility of using cogeneration,
- conversion of solid fuel with large specific volume into gaseous fuel with possibility of combustion in thermal engines,
- possibility of using various alternative solid fuels,
- technological advantages.

5.9.1. Processes occurring during gasification

The processes used in gasification depend on the design parameters. Several processes are used in wood gasification technologies – see Figure 5.3. Gasification involves several more or less spatially connected phases. There are four processes in total: drying – pyrolysis – oxidation – reduction.

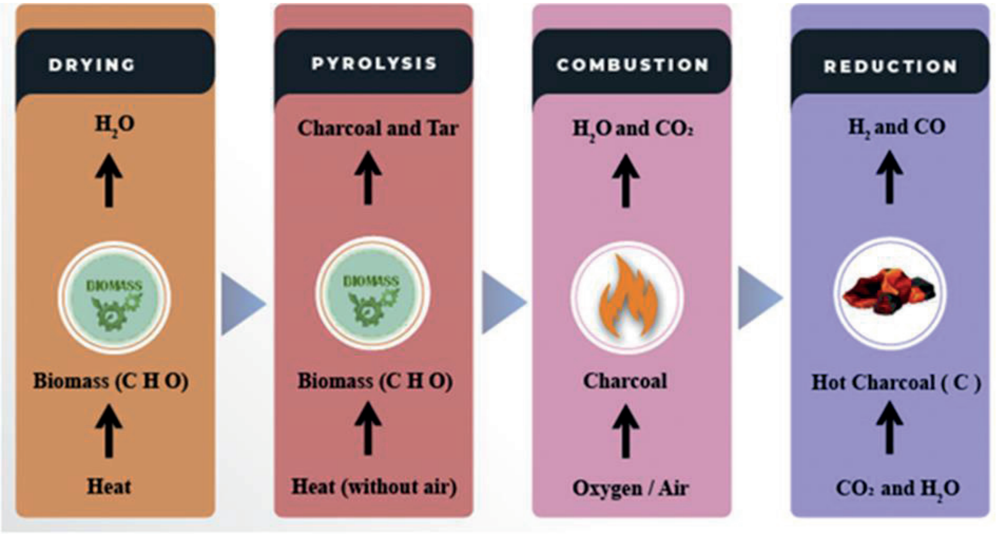


Figure 5.3. Stages of the gasification process (Hussain et al., 2023)

Gasification uses several thermochemical processes that follow each other. The ongoing stages of each process are spatially and temporally divided into individual phases. This division can only be realized in fixed-bed reactor. In reactor operating with buoyancy gasification (so-called fluidized bed reactor), the individual phases cannot be divided, but all phases occur simultaneously in the entire reactor (Alauddin et al., 2010).

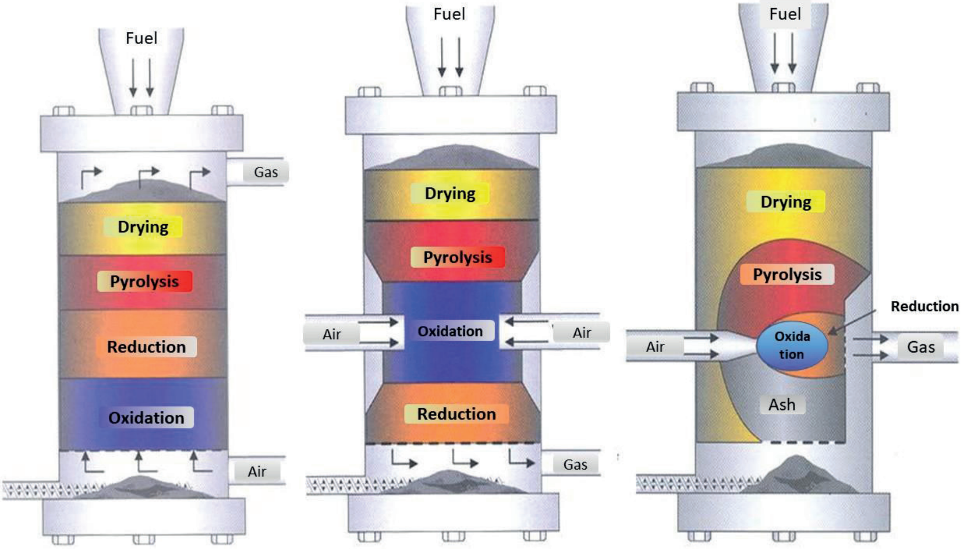


Figure 5.4. Course of reactions in fixed bed reactors (Pohořelý et al., 2012)

The slide reactor is the most common type of gasification reactor used for biomass gasification, see Figure 5.4. It is classified according to the mutual flow direction of the gasification medium and fuel into counterflow, coflow and crossflow.

In these processes, the bands are divided into:

- fuel drying – heating of fuel with evaporation of bound water,
- pyrolysis – thermal decomposition of fuel into gaseous components, condensing vapors, semi-coke, subsequent thermal splitting of vapors into gas and solid carbon,
- oxidation – partial oxidation of flammable gases, and other components and solid carbon,
- reduction – gasification of solid carbon with steam or carbon dioxide.

Processes are mainly influenced by:

- operating temperature and temperature profile in the reactor,
- operating pressure in the reactor,
- moisture content in the fuel and gasification medium,
- reaction surface,
- residence time of the components in the reactor.

a) Heating and drying zone

The fuel is dried at temperature of up to 200°C, during which the water bound in the fuel evaporates. This phase requires the supply of a relatively large amount of heat, as the reactions taking place are strongly endothermic. The heat required for drying the fuel is part of the heat released in the oxidation zone, this heat is spread either by conduction or convection. Since large amount of energy is required for heating and drying biomass, charge with water content of less than 30% is generally preferred, optimally up to 15%. With higher fuel moisture decrease overall efficiency of converting chemical energy of wood into chemical energy of produced gas. Steam generated from evaporated water can react further in the reduction zone of reactor (in the case of co-current type of reactor), or it passes into gas (in the case of counter-current reactor) (Higman and van der Burgt, 2003; Malat’ak et al., 2010; Pohořelý et al., 2012).

b) Pyrolysis zone

Pyrolysis is the thermal decomposition of fuel without access to oxidizing medium (oxygen, air). Solid, liquid and gaseous products are formed during this process. Formation of these products is influenced by chemical composition of fuel and these can influence pyrolysis process parameters. Pyrolysis takes place in the temperature range of 300°C to 700°C, volatile substances are released and higher-molecular organic substances are decomposed into lower-molecular ones and molecules with long chains are split into shorter ones. During pyrolysis, chemical bonds of starting substances are broken down to form new products. The actual course of the pyrolysis process consists in the splitting of smaller molecules from the original molecules with long chains. It depends on the type and properties of the starting material, its moisture content, pyrolysis temperature and reaction time (Higman and van der Burgt, 2003; Pohořelý et al., 2012).

For wood, pyrolysis reactions begin at temperatures of 300–375°C, see Table 5.3. In the temperature range between 300°C and 500°C, dry distillation occurs, during which branch chains of high-molecular organic substances are cleaved and transformed into gaseous and liquid organic products and solid carbon (semi-coke). With further increase in temperature, the products of dry distillation are further cleaved and transformed in the temperature range of 500°C to 700°C. Stable gaseous substances such as hydrogen H_2, carbon monoxide CO, carbon dioxide CO_2 and methane CH_4 are formed both from liquid organic substances (the main components are water vapor and tar substances) and from solid carbon (Malat'ak et al., 2020; Ochodek and Najser, 2014; Pohořelý et al., 2012).

Table 5.3. Examples of temperatures and products of pyrolysis decomposition of wood mass (Pohořelý et al., 2012)

Biomass component	Temperature	Decomposition product
Hemicellulose	<350°C	CO_2, water, biochar, tar, hydrocarbons
	> 350°C	Mainly tar
Cellulose	<300°C	Water, CO_2, CO and biochar
	> 300°C	CO, CO_2, H_2, biochar and tar containing aldehydes, ketones and organic acids
Lignin	<500°C	CO, CO_2, water, methanol and tar
	> 500°C	H_2 and CO

The typical chemical composition of the solid pyrolysis residue obtained by slow pyrolysis is 80-85% solid carbon (semi-coke), 15-20% volatile matter and 0-2% ash. The ash content depends on ash content of wood mass. The volatile matter content depends on pyrolysis process parameters. The main parameters influencing the course of pyrolysis are:

- pyrolysis temperature – with increasing temperature, proportion of gaseous components of gas increases,
- heating rate – with rapid heating, mainly liquid products are formed, slow heating ensures formation of gaseous products and less tar,
- pyrolysis pressure – in combination of increased pressure and temperature around 500°C, products of pyrolysis are mainly liquid products, at other temperatures, under increased pressure, proportion of gaseous components and carbonaceous residue increases, which is used to produce charcoal,
- granulometry and moisture content of wood,
- residence time of wood in pyrolysis zone – longer residence time ensures smaller proportion of liquid products in gas.

Pyrolysis of woody biomass is complex process that includes series of gas/gas and gas/wood reactions between reagents and products. The most important zone in gasification is the pyrolysis zone, which greatly influences the quality of resulting products and is consequently limiting for entire gasification. Individual types of biomass differ in their chemical composition, physical properties and reactivity of components, which is why resulting pyrolysis products are very diverse. Due to higher oxygen content and thermally labile polymers (cellulose, hemicellulose), biomass is significantly more reactive than brown coal (Higman and van der Burgt, 2003; Malat'ak et al., 2020; Pohořelý et al., 2012).

c) Oxidation zone

The oxidation zone is located in the gasification medium inlet area. The exothermic combustion reaction in this area supplies necessary heat for the endothermic reaction of the gasification process. When using the gasification medium of oxygen or air (stoichiometric coefficient between 0.3 and 0.5), oxidation layer with temperature between 800–1500°C is formed in the inlet area of this medium. The oxidation of carbon and gaseous pyrolysis products proceeds according to the following equations:

Partial oxidation of solid carbon:

$$C+\frac{1}{2}O_2 \rightarrow CO \qquad \Delta H=-111\,kJ\cdot mol^{-1} \tag{5.75}$$

Complete oxidation of solid carbon:

$$C+O_2 \rightarrow CO_2 \qquad \Delta H=-394\,kJ\cdot mol^{-1} \tag{5.76}$$

Carbon monoxide oxidation CO:

$$CO+\frac{1}{2}O_2 \rightarrow CO_2 \qquad \Delta H=-2813\,kJ\cdot mol^{-1} \tag{5.77}$$

Hydrogen oxidation H_2:

$$H_2+\frac{1}{2}O_2 \leftrightarrow H_2O \qquad \Delta H=-242\,kJ\cdot mol^{-1} \tag{5.78}$$

Methane oxidation CH_4:

$$CH_4+2O_2 \leftrightarrow CO_2+2H_2O \qquad \Delta H=-802\,kJ\cdot mol^{-1} \tag{5.79}$$

Partial oxidation of solid carbon according to equation /5.75/ is necessary, since the formation of carbon monoxide from solid carbon corresponds to the conversion of solid biomass into combustible gas. Complete oxidation of carbon according to equation /5.76/ is desirable only to the extent that heat is required for the entire gasification process. Although the reactions of carbon monoxide oxidation /5.77/ and methane oxidation /5.79/ provide reaction heat, these reactions are not desirable, since CO_2 and H_2O are not combustible and therefore do not increase the calorific value of the produced gas. The passage of pyrolysis products through oxidation zone (in co-current generator) results in very significant reduction in tar content in gas exiting the reactor (Higman and van der Burgt, 2003; Malat'ak et al., 2020; Pohořelý et al., 2012).

d) Reduction zone

Combustible substances in produced gas are formed by the reduction of carbon dioxide CO_2 to carbon monoxide CO (Boudoudard reaction) and water vapor H_2O to hydrogen H_2

(heterogeneous water gas reaction). At the same time, carbon can react with hydrogen to form methane CH_4. All of these reactions contribute to the production of gaseous fuel. The reactions take place in the absence of oxygen, which reduces the temperature of the gas and most of the carbon is combusted or reduced to carbon monoxide CO, or leaves the reactor in ash as unburned fuel:

Boudouard reaction:

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H = 173\ kJ \cdot mol^{-1} \tag{5.80}$$

Heterogeneous reaction of water gas formation:

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H = 131\ kJ \cdot mol^{-1} \tag{5.81}$$

Heterogeneous methane formation:

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H = -87\ kJ \cdot mol^{-1} \tag{5.82}$$

Simultaneously with these gasification reactions, other reactions also occur:
Homogeneous water gas reactions:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41\ kJ \cdot mol^{-1} \tag{5.83}$$

Homogeneous methane formation:

$$2CO + 2H_2 \leftrightarrow CH_4 + CO_2 \qquad \Delta H = -247\ kJ \cdot mol^{-1} \tag{5.84}$$
$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H = -41\ kJ \cdot mol^{-1} \tag{5.85}$$

Homogeneous carbon dioxide reduction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \Delta H = 41\ kJ \cdot mol^{-1} \tag{5.86}$$

The final gas consists of carbon monoxide, hydrogen, methane, water vapor, carbon dioxide and nitrogen (Higman and van der Burgt, 2003; Malat’ak et al., 2020; Pohořelý et al., 2012). The following factors influence the reactions in individual zones::

- operating temperature and temperature profile in the generator,
- operating pressure,
- moisture content,
- reaction surface,
- residence time of particles in the generator.

5.9.2. Properties of gasification products

a) Gaseous products

The use of gas from the gasification process as a substitute for natural gas has already been solved, and the area of electricity production in cogeneration units is currently also being offered (Makwana et al., 2023; Tezer et al., 2022). The main obstacle to the expansion of gasification technologies is meeting the requirements for quality and purity of the produced gas. The produced gas has low calorific value, the Wobbe index $W = Qs \cdot (\rho_{pl}/\rho_{air})-0.5$ is only 10% of the value of natural gas. Impurities in the produced gas cause operational problems in gasification technology devices, i.e. gradual clogging of pipes and fittings, sticking of working and heat exchange surfaces in subsequent devices. No gasification generator is able to produce clean gas for direct use in internal combustion engines or turbines, therefore it must always be cleaned (Makwana et al., 2023; Tezer et al., 2022). The individual types of impurities can be divided into the following categories:

- solid pollutants (TPS),
- tar,
- nitrogen-containing compounds,
- alkaline compounds,
- sulfur compounds,
- halogen compounds (chlorine, fluorine).

Gaseous products formed during fast pyrolysis represent approximately 5% of the energy content of biomass and 25–30% in the case of slow pyrolysis. At temperatures above 500°C, 75–90% of volatile combustible matter is produced. The main components include carbon monoxide CO (up to 95%), carbon dioxide CO_2, methane CH_4, hydrogen H_2, water vapor H_2O and the remainder up to 100% is nitrogen N_2. The calorific value of the produced gas ranges from 3.5 to 8.9 $MJ \cdot m^{-3}$. The pyrolysis products are qualitatively and quantitatively influenced by the course of the process. (Malat'ak et al., 2020; Pohořelý et al., 2012).

b) Solid pyrolysis products

Solid pollutants contained in the gas leaving the gasification reactor are defined as the solid phase including unreacted fuel particles (semi-coke), inorganic substances (ash), or fluidized bed material. The main source of solid particles is ash. During gasification, inorganic base of fuel remains in bed and is removed through grate, or it can be carried away by gas out of reactor. The concentration of solids in gas depends on design of generator (type of reactor and gas velocity in generator) and on ash content of fuel (Malat'ak et al., 2020; Pohořelý et al., 2012). Another significant source of solid pollutants are impurities contained in the fuel (inert material mixed into the fuel during its processing - e.g. soil, etc.) and incompletely reacted fuel - ungasified carbon residue. During the gasification process in the reactor, fuel particles reduce their volume and are subsequently carried away by the gas flow. A certain proportion of dust also consists of soot. Gas with high solids content is typical for fluidized bed gasifiers with bubbling and circulating beds, due to the turbulent conditions inside the reactor (Alauddin et al., 2010). The typical chemical composition of solid pyrolysis residue obtained by slow pyrolysis is 80-85% solid carbon (semi-coke), 15-20% volatile matter and 0-2% ash. The ash content depends on ash content of biomass (Vassilev et al., 2010). The content of volatile substances depends on the pyrolysis process parameters (Malat'ak et al., 2020; Pohořelý et al., 2012).

c) Liquid products

Pyrolysis liquids are called pyrolysis oils, which are very well known as products of slow pyrolysis processes, where these are mostly used for chemical applications (now replaced by the petrochemical industry). Pyrolysis liquids from biomass are complex of dark brown, viscous, diametrically opposed and acidic products. Mostly, pyrolysis liquids are contaminated with varying amounts of solids and also water which keeps bio-oil in liquid form (Sutton et al., 2001). The water content is around 20% by weight based on dried raw material (10% by weight), this value increases in the case of wet raw material. Water also comes from chemical processes during pyrolysis (Makwana et al., 2023; Malat'ak et al., 2020; Pohořelý et al., 2012; Tezer et al., 2022).

d) Tar

The composition and concentration of tar itself depend primarily on the distribution of reaction conditions in the reactor, especially on reaction temperature, residence time at given temperature, pressure in the reactor and to certain extent on physicochemical properties of fuel. Tar usually contains diverse mixture of substances, especially pyrolysis products, and therefore its description in terms of chemical composition is often quite difficult. For simplified characterization of the properties of tar is used simple classification based on the degree of its transformation into the so-called primary, secondary and tertiary tar. Degree of transformation of tar:

- primary tar – acids, aldehydes, alcohols, furans, etc.,
- secondary tar – mainly more stable phenols and olefins,
- tertiary tar – alkyl aromatics (styrene, xylene, toluene, ethylbenzene), PAH (indene, naphthalene, pyrene, methylnaphthalenes).

Primary tar is present in significant quantities in gas in counter-current reactors, and tertiary tar is usually produced in co-current and fluidized bed reactors.

The amount of tar in gas is significantly affected by temperature. Tar content in gas decreasing with increasing temperature, which is used in the thermal cracking of tar, but its thermal stability increases sharply, which causes significant problems in its complete removal (Makwana et al., 2023; Pohořelý et al., 2012; Tezer et al., 2022).

e) Nitrogen-containing compounds

The majority of nitrogen in the produced gas is in the form of N_2 and its amount depends mainly on the type of gasification medium. In addition, nitrogen is also found in the form of compounds, where the main nitrogen-containing compounds in the raw gas from biomass gasification are ammonia (NH_3) and hydrogen cyanide (HCN). The dominant mechanism for the formation of NH_3 is conversion of nitrogen contained in fuel. The proportion of formed amount of both compounds (NH_3 and HCN) varies in accordance with characteristics of fuel (Makwana et al., 2023; Pohořelý et al., 2012; Tezer et al., 2022).

The content of nitrogenous substances in gas is undesirable, especially with regard to its further use, whether by combustion in burners or in internal combustion engine, as subsequent combustion leads to formation of nitrogen oxides NOx and permitted emission limits could be exceeded (Juszczak, 2016, 2014).

f) Alkaline compounds

The ash content of biomass fuel is low, but some of its components can cause operational problems. For example, biomass contains significant amounts of alkali salts and potassium, which form low-melting minerals and can cause operational problems by evaporating at gasification temperatures and leaving generator with gas or by causing ash to sinter inside reactor (Rybín, 1985).

These are mainly sodium and potassium compounds (e.g. Na_2O, K_2O, KOH, KCl, ...). During combustion or gasification, alkalis evaporate and form various compounds, such as KOH or KCl, which immediately react with chlorine and sulfur.

For alkaline compounds present in gas, it is not only their quantity that matters, but also their composition, which affects physical properties of ash, such as softening, melting and evaporation points. Alkali evaporated in the gasification process form deposits on cooler surfaces of pipes and apparatus (especially heat exchangers). If alkaline compounds are not removed, these pass through entire system and problem of condensation and deposits may reappear after used combustion equipment - gas turbine, etc. (Makwana et al., 2023; Pohořelý et al., 2012; Tezer et al., 2022).

Another problem is the high-temperature corrosion of used metal construction materials, which can be caused by alkali salts, especially if vanadium is present as catalyst for the corrosion reaction. The deposition of alkali salts is usually solved by cooling gas and separating fine particles on which salts condense (Makwana et al., 2023; Malat'ak et al., 2020; Pohořelý et al., 2012; Tezer et al., 2022).

g) Sulfur compounds

In general, biomass contains low percentage of sulfur. For example, sulfur content in woody biomass is usually below 0.1% by weight, while in grasses and stalks it can reach up to 0.5% by weight. During gasification, sulfur present in biomass is mostly converted into hydrogen sulfide H_2S or sulfur oxides SOx, depending on the conditions in reactor. For most applications using gas produced by biomass gasification as fuel, there is no need to remove sulfur compounds. A potential problem with the occurrence of sulfur even at low concentrations is when using certain types of catalysts - for example, metal catalysts used for tar removal are sensitive to presence of sulfur, which must therefore be removed from gas before contact with catalyst. Together with chlorine, fluorine and alkali salts, sulfur is corrosive to metal structural materials (Makwana et al., 2023; Malat'ak et al., 2020; Pohořelý et al., 2012; Tezer et al., 2022).

Sulfuric, hydrochloric and hydrofluoric acids, which cause not only corrosion but also degradation of oils used for lubricating internal combustion engines. When operating an internal combustion engine with catalytic converter, permissible sulfur content is several times lower than when operating without it. For removal of sulfur (H_2S, SOx), well-tested wet scrubber devices are available in practice, or it can be removed by reaction with suitable sorbent.

h) Halogen compounds

Chlorine occurs in small concentrations in biomass and most often reacts with hydrogen during gasification. It appears in produced gas in the form of hydrogen chloride HCl. Chlorine can also cause increased formation of hazardous substances that persist in the environment for a long time (so-called persistent organic pollutants). Halogen compounds have corrosive effect on steel construction materials. In cases where equipment is frequently shut down, acids (sulphuric, hydrochloric and hydrofluoric) are formed inside equipment, causing corrosion and also degradation of oils used to lubricate internal combustion engines (Makwana et al., 2023; Malat'ak et al., 2020; Pohořelý et al., 2012; Tezer et al., 2022).

5.9.3. Gasification reactors

During the development of gasification technologies, reactors in various designs have been developed, constructed and tested. Reactors can be divided according to different aspects:

According to the reactor design:

- with fixed bed (moving bed) – co-current, counter-current, cross-flow,
- with fluidized bed,
- with entrained flow.

According to the gasification medium:

- steam,
- steam-oxygen mixture,
- oxygen,
- air.

According to the heat source for gasification:

- autothermal or direct gasification reactor – heat supplied by combustion of part of the biomass,
- allothermal or indirect gasification reactor – heat supplied by indirect heating (separation of gasification and combustion zones) or from external source via heat exchanger.

According to the pressure in the reactor:

- atmospheric,
- pressure (Jílková and Gál, 2018).

5.10. Pyrolysis / torrefaction

Pyrolysis (*pyros* Gr. = fire, *lysys* Gr. = splitting, degradation by fire) is defined as a set of thermochemical degradation reactions occurring in the absence of oxygen, or in the presence of oxygen, but partial oxidation of biomass does not occur. The process occurs at relatively low temperatures of 500-800°C compared to gasification of 800-1000°C. The products of pyrolysis are mostly gases, liquids and coal. The composition of these products depends on the pyrolysis processing method and the reaction parameters.

- Fast or flash pyrolysis

Fast or flash pyrolysis is used for maximum production of gases and liquid products, providing mainly thermal benefit. The distribution and composition of reaction products during pyrolysis processing depends on the appropriately selected type of pyrolysis process: slow or fast pyrolysis, type of technological process: fixed bed reactor = Fixed Bed, Dawndraft or Updraft Pyrolyser, or fluidized or circulating bed reactor, Fluidized Babbling Bed FBB or Circulated Bed and on reaction conditions: temperature, residence time of biomass particles in reactor and heating rate (Weber and Quicker, 2018).

- Slow/low temperature pyrolysis

Slow pyrolysis is known as carbonization and is mainly used for charcoal production. Slow/low temperature pyrolysis is characterized by low heating rate ($< 10°C \cdot s^{-1}$), low reaction temperature (< 400°C), and long residence time of volatiles and solid coal residues in reactor (hours to several days) (Weber and Quicker, 2018). Primary volatile substances released by biomass pyrolysis are retained in reactor and further broken down into secondary products to form gases and tars. Solid residues are converted into charcoal in resulting product. Dry distillation occurs in temperature range of 300 – 500°C, during which chains of high-molecular organic substances are broken down and converted into gaseous and liquid organic products and semi-coke (Chen et al., 2015). After increasing the temperature to 500 – 700°C, the products of dry distillation are further broken down and transformed from liquid organic substances and solid carbon into gaseous substances – hydrogen H_2, carbon monoxide CO, carbon dioxide CO_2 and methane CH_4.

- Torrefication

Torrefaction, as a method of thermal biomass treatment, can be defined as a slow pyrolysis process that takes place at temperatures ranging from 200 to 300°C. The residence time of the feedstock in the reactor ranges from 15 minutes to 3 hours, depending on the reactor type, its characteristics, and the type of feedstock. During the torrefaction process, external energy must be supplied. In typical biomass torrefaction process, there is simultaneous loss of mass and chemical energy of the feedstock. Torrefaction process increases concentration of feedstock's chemical energy from the point of view mass-to-energy ratio (Kopczyński and Zuwała, 2013). The purpose of torrefaction is to increase the calorific value of biomass fuel, reduce moisture and volatile matter, increase carbonization, improve grindability and increase the fuel's hydrophobicity.

The torrefaction process produces solid, liquid and gaseous products. The main product is torrefaction biomass, also known as torrefacted biomass. Torrefacted biomass is homogeneous, hydrophobic material, and compared to unprocessed biomass, it has increased resistance to biological agents. (Bridgeman et al., 2008). By-product of the torrefaction process is process gas, which can be used to carry out the torrefaction process (autothermal process).

- Torrefication of woody biomass

One of the possible modifications of woody biomass for its better use in energy sector is the torrefaction technology (van der Stelt et al., 2011). This process leads to reduction in the moisture content of woody biomass, its sterilization and increase in its energy potential (Chen et al., 2015). During torrefaction, woody biomass is converted into product with properties similar to coal (Phanphanich and Mani, 2011). The advantage of raw material modified in this way is replacement of fossil fuels (brown and black coal) for production of thermal and electrical energy (Tumuluru et al., 2011; Weber and Quicker, 2018). Another advantage is that there is no need for large investments into existing technology of coal-fired heating and power plants when co-firing with coal (Schipfer and Kranzl, 2019). Another advantage is possibility of financing projects for conversion of energy or industrial facilities to use torrefied wood biomass from saved emission allowances traded within the ETS (Starfelt et al., 2015).

Torrefied woody biomass has three main advantages over traditional biomass, which are: higher calorific value (Jeníček et al., 2025), higher energy density (Chen et al., 2021) and improved physical properties such as dimensional stability, uniformity and hydrophobicity (Tripathi et al., 2016). All this results in overall reduction in production and transport costs, reduction in storage capacity, lower demands on production plant equipment and increased safety during handling in storage facilities (Thengane et al., 2022). On the other hand, torrefaction of woody biomass causes significant loss of energy stored in volatile combustibles, which are released when heated to temperatures above 300°C (Liu et al., 2008).

In terms of elemental composition in the raw state of woody biomass, the oxygen to carbon ratio is approximately ≥ 1 (Jeníček et al., 2025). The torrefaction process reduces this ratio below 1, and with increasing torrefaction temperature there can be achieved O/C ratio of less than 0.4 (Spokas, 2010). The higher calorific value of the torrefied material is due to the decreasing oxygen content (Aniszewska et al., 2020). This causes the calorific value to increase from 17 $\mathrm{MJ \cdot kg^{-1}}$ for raw woody biomass to 27 $\mathrm{MJ \cdot kg^{-1}}$ for torrefied woody biomass (Wilk et al., 2016). When the oxygen content in the torrefied material decreases, the amount of hydrogen also decreases (Wannapeera et al., 2011). Due to the decrease in the oxygen and hydrogen content in the material, or more precisely, due to the decrease in hydroxyl groups in the material, which occurs during thermal processing, the resulting material exhibits hydrophobic behavior (Weber and Quicker, 2018).

Published results show that torrefaction technology has significant potential in the areas of replacing fossil fuels with renewable energy sources in the form of torrefied wood biomass (Cha et al., 2016). The advantage of this technology is that it can be operated both in high-power units and in small and mobile units, which are already available on the market to lesser extent (Thengane et al., 2022). Results from studies show that the integration of torrefaction and cogeneration unit at full load is beneficial (Sermyagina et al., 2016, 2015). From the information found, it is clear that the torrefaction principle was tested only on selected fuelwood, but complete data from the field of torrefaction of wood waste are missing.

The torrefaction itself, which is produced from renewable biological resources, increases the diversification of the use of renewable energy sources and is therefore zero-emission technology (Meyer et al., 2011). Given that torrefaction has properties similar to solid fossil fuels (Chen et al., 2021), it is relatively easy to convert current coal-based technologies to non-thermally processed biomass for direct combustion (Malaťák et al., 2022, 2020), or use in gasification technologies (Malaťáková et al., 2021). The most favorable environmental and energy results are achieved when co-combusting torrefied biomass into the form of biochar replacing fossil coal (Peters et al., 2015). Another option is using torrefied biomass as soil amendment instead of energy purposes, which increases carbon sequestration in the soil (Ippolito et al., 2012; Tunklová et al., 2022).

Table 5.4. Physicochemical changes and torrefaction-related changes in biomass properties (Chen et al., 2021)

Raw biomass	Physicochemical transformation	Torrefied biomass
High moisture content	Dehydration	Low moisture content
Hygroscopic	Dehydration Dehydroxylation Decomposition of amorphous cellulose Nonpolar tar in pores	Hydrophobic
Higher O/C and H/C ratio	Less decarbonation Dehydration Oxygen removal Deacetylation Demethylation Degassing	Lower O/C and H/C ratio
Lower calorific value	Dehydration Charring Dehydrogenation Oxygen Removal Dehydroxylation	Higher calorific value
Poor grindability	Hemicellulose decomposition	Improved grindability
Low resistance to biodegradation and poor durability	Lignin Modification Hemicellulose decomposition	Higher resistance to biodegradation and greater storage capacity

5.11. Torrefaction equipment

There are many designs of torrefaction reactors (reactors for the torrefaction process). Reactors can be classified based on followed factors: heat carrier (gas, exhaust gas, filling), heat transfer mechanism (convective, microwave, conduction through the wall, mixed), heat transfer method (direct, indirect), gas-solid contact method (plug-flow, drum, flow), and working unit design (rotary-drum, screw, multi-zone, moving bed or fluidized bed, cyclonic, microwave).

The design of reactor depends on its construction, that differ in structure and operating principle. The basic designs are discussed below.

Convection reactor. This is the most common type of reactor used for torrefaction, in which hot gas flows past biomass particles. Relative velocity between feedstock particles and gas is responsible for convective heating of biomass. Hot gas can be completely inert or contain a small amount of oxygen. Depending on the type of bed (moving or stationary), particles may or may not move relative to the reactor walls, which in turn can be oriented at any angle. Particle movement is forced by gravity or mechanically, for example, using a screw feeder.

Particle flow through the reactor is unidirectional without backmixing. Heat transfer occurs primarily through convection between gas and solid in directly heated reactors. Indirectly heated convection reactors also exist. Scientists (Bergman et al., 2005) estimate that the heat transfer coefficient between gas and biomass is high and in the range of 200 W·$(m^2K)^{-1}$. In some types of directly heated convection torifiers.

Fluidized bed reactor. Inert gas is blown through bed of granular solids acting as a heat transfer medium in this type of device, so that solids behave like a fluid. The constantly mixing hot solid particles intensely heat incoming new biomass fuel (Basu, 2006). Well-mixed biomass particles are torrefactioned with uniform temperature distribution. Maintaining wood chips in fluidized state requires air stream with an appropriate flow adapted to particle size. In this type of reactor, particle size is crucial. Particles that are too large do not flow through air stream, while those that are too small easily coagulate with water and lose their fluidization ability.

Hydrothermal reactor. During whole process, feedstock is heated in high-pressure water, eliminating need for drying. The dominant heat transfer mode in hydrothermal reactor is flow between hot water (fluid) and solid. The energy required to increase pressure and move large volume of biomass through pressure barrier creates significant practical difficulties in this type of reactor (Hoekman et al., 2011).

Microwave reactor. Biomass is heated using microwaves in microwave reactor, which are electromagnetic radiation with power of 100-300 MW. Generating microwaves requires large amount of electrical energy (Budarin, 2011). Microwave energy is directly transferred to the water molecules present in the biomass in this type of reactor. Polar molecules rotate at the same frequency as the microwaves. The accumulation of energy by the water causes rotational vibrations of its molecules, which causes friction. The energy is dissipated and transferred to other biomass molecules as result of friction and strong vibration damping. This process resulting in increase in temperature of raw material (Kappe et al., 2012; von Hippel, 1995). The microwave reactor can handle large amounts of biomass particles. The torrefaction process is relatively fast, and the reactor temperature is easy to control.

Flow reactor. Ground biomass particles are entrained in high-velocity (50-80 m·s^{-1}) hot gas stream. The charging time is less than 100 seconds, significantly increasing the reactor's throughput (Crnogaca, 2017; Gray and Seijo, 2013). Rapid heating and short material residence time reduce char production at expense of increased volatile matter during heating without oxygen. The key features of this type of reactor are its high mass and heat transfer coefficients, as well as absence of any moving parts in the reactor. This technique allows for precise product monitoring, and the process is characterized by low energy consumption (Batidzirai et al., 2013; Crnogaca, 2017; Mayor and Williams, 2011).

Rotary drum reactor. Devices of this type utilize rotational motion for intensifying the process, so it is responsible for material movement and mixing of fuel particles. Torrefied biomass is contained in inert gaseous medium. Heat is transferred from warmer reactor wall to biomass particles through conduction and convection. The advantage of this type of reactor is that the heating medium does not have to be oxygen-free (all post-process gases, including exhaust gases and all types of waste heat, are permitted), and the volatile substances released in the process are not diluted, allowing them to be combusted in supplement the reactor's thermal requirements. Process is controlled by thermal energy flow transferred from reactor wall to biomass particles in this type of reactor's design.

Screw reactor. Rotating screw agitates and moves biomass through reactor to enhance heat transfer while simultaneously moving biomass along its path. Hot outer wall indirectly heats biomass, thereby avoiding direct contact with oxygen-containing heating medium.

Belt reactor. Biomass is transported through heated reactor using belt conveyor. This method ensures that all biomass particles have same residence time. Advantages of this approach include good temperature control and ability to torrefywide range of biomass sizes within the reactor. (Dhungana, 2011). Maximum capacity of this type of reactor is approximately 5 $t \cdot h^{-1}$.

6. SOLID BIOFUELS

6.1. Raw material for the production of solid biofuels

Pellets are most often made from woody biomass. Plant materials, such as straw, grasses, and energy crops, also play a significant role in the production of solid fuels (pellets, briquettes).

For commercial energy sector, the most useful types of biomass (species) are those that have large annual growth rates and can be used at various levels of processing – as wood chips or refined fuels in the form of briquettes or pellets (Figure 6.1). In European Union countries, the most popular energy crops that can be used in pressure agglomeration are willow (*Slaix* L.), poplar (*Populus* L.), black locust (*Robinia pseudoacacia* L.), multiflora rose (*Rosa multiphlora Thunb.*), giant miscanthus (*Miscanthus sinensis giganteus*), Virginia mallow (*Sida hermaphrodita Rusby* L.), prairie spartina (*Spartina pectinata*), Jerusalem artichoke (*Helianthus tuberosus*), and Sakhalin knotweed (*Reynoutria sachalinensis*). In addition to the energy crops mentioned above, straw from various cereal species, as well as shredded waste from the timber industry and forest logging residues in the form of shredded branches, tree crowns, and undersized pieces of wood, are also used in pressure agglomeration for briquette and pellet production.

Figure 6.1. Energy biomass: a) energy willow plantation, b) Jerusalem artichoke plantation, c) logging residues on the forest surface (instsani.pl, 2016; kalendarzrolnikow.pl, 2017)

Willow, poplar, and black locust. These are woody species cultivated in plantations in multi-year rotations. Depending on the type of cultivation and rotation length, they can take on shrubby or tree-like forms. Willows are typically harvested in one-, two-, and three-year rotations. They usually have a shrubby form. Depending on the habitat and age, they reach heights of up to 6 m and diameters of up to approximately 80 mm. Willow yields on class III-V soils with sufficient moisture are 10-15 tons of dry matter. Poplars are harvested in two-, three-, or four- to six-year rotations. In longer rotations, they develop into trees exceeding 10 m in height and with trunk diameters exceeding 10 cm. Production efficiency in poplar plantations is 8-12 tons of dry matter per hectare. Black locust is species widely distributed in southern Europe (e.g., Hungary). It is also popular energy species in Poland. It is recommended for cultivation on devastated land and wasteland. The purpose of production is to produce energy wood in chunks. In plantation production, the highest yields are achieved in 5-year harvest cycles. To obtain chunk wood, it is recommended to produce it in 15-20-year cycles, where trees can grow up to 25 meters in height (Frączek, 2010; Lisowski et al., 2010).

Multiflora rose, giant miscanthus, Virginia mallow, prairie spartina, Jerusalem artichoke, and Sakhalin knotweed. These are popular energy crops, with shrubby or herbaceous forms and more or less woody stems. Multiflora rose has woody shoots that can reach up to 4 meters in length, and the shrubs can reach 2.5 meters in height. It has low climatic and soil requirements. It can be grown on class V and VI soils. Under favorable habitat and climatic conditions, yields can reach 10-15 tons of dry matter per hectare. Giant miscanthus is a perennial herbaceous plant that reaches heights of up to 2.5 meters in Central Europe. It does not require fertile soils; energy crops can be established on class V and VI soils. Depending on the site conditions, miscanthus yields can reach 10-30 tons of dry matter per hectare, and in richer and wetter soils, they can be approximately 20-30% higher. Virginia mallow is a perennial plant producing stems 5-30 mm in diameter and up to 4 m high. Like other energy crops, it does not require good and fertile soils. It can be grown in class V soils and can yield up to 18 tons of dry matter per hectare. Prairie spartina is a herbaceous plant growing in large, loose tussocks and can grow up to 2 m tall. It adapts well to a variety of soil conditions; energy crops can be established on impoverished and acidic class V and VI soils. Spartina yields reach 10-20 tons of dry matter per hectare. Jerusalem artichoke is a plant with a fertile soil type. Its above-ground part resembles the common sunflower. Its stem height can reach up to 4 meters with a diameter of approximately 30 mm. It has average soil requirements; plantations can be established in medium-firm, well-ventilated, and moist soils. The yield is 10-20 tons of dry matter per hectare. Sakhalin knotweed is a perennial whose highly branching stems can reach over 3 meters in height. It is an expansive and highly invasive plant, making it not recommended for energy plantations. It reaches full yield in the third year of cultivation, reaching 15-30 tons of dry matter per hectare (Frączek, 2010; Lisowski et al., 2010).

Forest logging residues are generated during timber harvesting in maintenance cuts and during final felling. In younger stands, these may be whole trees of small diameter. In older stands, logging residues include treetops, branches with leaves and needles, and undersized pieces of roundwood produced during delimbing and cutting into specific lengths. Logging residues contain wood, bark, leaves, needles, and organic and mineral pollutants that accumulate in them upon contact with forest soil. They are a byproduct of primary timber harvesting activities. Depending on the habitat and dominant species, approximately 15-17% of logging residues are harvested per hectare, relative to the volume of harvested wood.

All the types of biomasses intended for energy purposes described above, after prior preparation (mainly reducing the moisture content and crushing to the appropriate particle size), can be used to produce solid fuels in the form of briquettes or pellets.

Figure 6.2. Wood biomass in the form of chips (a), sawdust (b), sawmill waste for further processing (c) (Penny, 2015)

The main raw material for pellet production in production plants is waste from the wood industry in the form of shavings, chips, and sawdust, or larger pieces processed into this form (Figure 6.2). Depending on the country and applicable legal regulations, the shredding of entire tree trunks was also permitted to maintain production continuity. Current legislation prohibits this use of trees.

Both hardwood and softwood are suitable for pellet production, with the share typically accounting for around 70%. This use of softwood is primarily due to the dominance of these species in the forests of the V4 countries and in the wood processing industry.

Because lignin in wood plays a crucial role in binding particles together during agglomeration, pellet production involves mixing materials from various tree species and energy crops to maintain a uniform lignin content in the input material. This is because hardwood species, such as beech, have a lower lignin content than softwoods, such as the popular spruce. Therefore, it's crucial to ensure the waste mixture is as uniform as possible.

6.2. Biomass densification and conditioning technologies

Depending on the material processing method, there are several agglomeration methods, i.e. sintering, two-stage granulation and pressure agglomeration.

Sintering, also known as fritting, is primarily used for materials in powder or granular form. This process involves the use of high temperatures to initially melt the material, but does not allow it to burn or completely melt (Dobrzański and Matula, 2012).

Two-stage granulation is a method of forming loose particles into larger, regular grains in two subsequent technological stages (Zielińska and Pomorski, 2020). The first stage involves lightly granulating the bulk material, which involves merging the smallest particles into larger, yet still brittle and unstable particles. This process is often performed at relatively low pressure or using a small amount of a binding liquid, such as water or special solutions (Feliks et al., 2018). The goal of two-stage granulation is to obtain so-called pregranulates, i.e., preformed agglomerates that are still suitable for further processing. In the next step, the preformed agglomerates are re-compacted, hardened, and stabilized. This is done at higher pressure, higher temperature, with the addition of binders, and by additional drying or heating. The second stage results in durable, hard, and mechanically strong granules with specific functional properties, such as appropriate size, specific and bulk density, and abrasion resistance (Gara, 2015).

The final and most popular method of densification is pressure agglomeration. It involves subjecting the material to very high compressive forces. Appropriate doses of material are placed in chambers of appropriate shape and size (Bembenek et al., 2012). The high forces exerted by the pressure of a moving piston or pressure rollers cause compaction and shape fixation. This process produces pellets or briquettes. Depending on the production method, the resulting material is cut with a special knife or removed from the compression chamber. The simplicity of this process makes it a very attractive way to improve the properties of materials and utilize waste (Frączek et al., 2011; Yaman et al., 2001).

The most common industrial pressure agglomeration technologies for plant biomass are pelletizing and briquetting. In both processes, the final product is typically a cylinder of a specific diameter and length, based on which the resulting agglomerate is classified as a pellet or briquette. The difference between these two forms of agglomerate is primarily related to their size and the pressures required to produce them. A general diagram of pelletizing (pressure agglomeration) is shown in Figure 6.3.

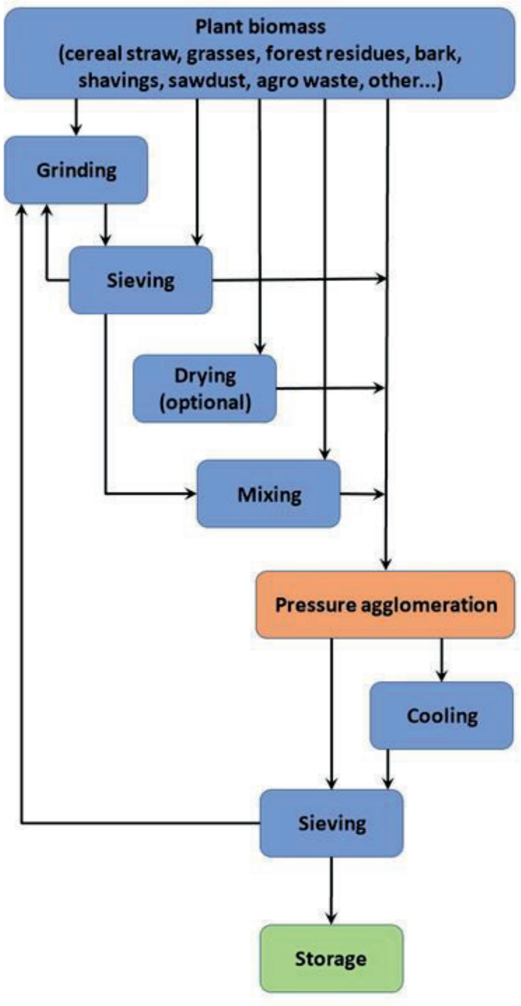


Figure 6.3. General scheme of pressure agglomeration

In pellet production technology, there are several important parameters that influence compaction efficiency. These include compaction pressure, process (die) temperature, die hole diameter (pellet diameter), and material moisture content.

Compaction pressure is one of the most important parameters in the agglomeration process. Too low a pressure does not ensure adequate compaction, leading to the formation of loose, unstable agglomerates that are highly susceptible to crumbling (Skonecki and Laskowski, 2010) or in extreme cases, the material fails to bond and disintegrates. Higher pressure brings the material particles closer together, which in turn allows for the formation of stronger intermolecular bonds (Mudryk and Wróbel, 2012). This leads to increased density and mechanical strength of the resulting pellets. However, excessive pressure can also lead to excessive particle crushing, which in turn causes structural changes, clumping, or cracking of the finished agglomerates (Kulig et al., 2013). Excessive pressure can also push moisture out of the particles, resulting in local drying and disruption of the moisture balance necessary for permanent particle bonding.

The die heating temperature and the temperature at which the material is processed within the die are crucial to the agglomeration process. Heating the die plasticizes the material, which facilitates its formation and reduces process resistance. In the case of lignocellulosic biomass, higher temperatures activate polysaccharides, such as lignin, which act as a natural binder (Domian and Jemielity, 2006). Lignin, under appropriate temperature and humidity conditions, becomes more plastic, enabling better bonding of material particles and the creation of more durable agglomerates. At higher temperatures, water is more active, moves more quickly between particles and penetrates surfaces more effectively, creating stronger bonds. This makes the agglomeration process faster and more effective, and the final product is more cohesive. However, excessively high temperatures can lead to, for example, partial caramelization of sugars or thermal degradation of certain nutrients, which reduces product quality (Niedziółka and Szpryngiel, 2013). For most raw materials, such as sawdust, straw, and dried plants, the optimal agglomeration temperature range is 70–130°C. It has been determined that within this temperature range, lignin is sufficiently activated without the risk of burning the material, which allows for high-quality pellets with optimal energy consumption.

The die orifice diameter in the pressure agglomeration process is crucial for achieving the proper shape and size of the agglomerates. Orifices are a design element of the die that define the space in which the material is formed under the action of force. A smaller die and plunger diameter results in higher pressure exerted on a given surface area of the material (Skonecki et al., 2013). However, too small a diameter can also cause excessive material compaction or problems with its even distribution within the die, leading to agglomerates of uneven density and reduced durability. A larger die diameter, on the other hand, allows for the production of larger agglomerates but also requires greater force to achieve a comparable unit pressure. A diameter that is too large risks insufficient compaction of the material throughout the agglomerate, particularly at its edges, which can result in weaker cohesion or increased porosity of the final product. Therefore, selecting the appropriate die and plunger sizes is crucial to ensuring the proper agglomerate quality while maintaining the energy efficiency of the process (Skonecki and Laskowski, 2012).

Moisture affects the material's ability to form stable agglomerates. In the densification process of lignocellulosic material, moisture acts as a binder (Skonecki et al., 2017). Water causes the lignin contained in the raw material to become more plastic, thus facilitating the bonding of particles into a stable structure. With the appropriate moisture level, the particles of the bonded materials densify better and maintain cohesion, allowing for the formation of agglomerates with stable shape and adequate mechanical strength (Fiszer, 2009; Hejft and Obidziński, 2012). Too little moisture can cause agglomerates to crumble or form unevenly, and can also lead to the material burning during the agglomeration process at higher temperatures. Burnt material becomes brittle, with a glassy, slippery surface, and possible discoloration due to the burning of lighter substances. Excessive water, on the other hand, leads to a too soft, sticky mass that can stick to the pressing elements or deform during the agglomeration process (Hebda and Złobecki, 2011).

During the pressure agglomeration process, a situation may arise where the material is not amenable to bonding. This depends on the material from which the agglomerate is formed. In such a case, it will be necessary to add a binder to the substance being bonded. Its purpose is to improve the agglomerate's properties, such as cohesion, durability, and sometimes even strength. This procedure is essential when working with materials relatively low in lignin, one of whose functions is to impart viscosity (Poszytek and Lenart, 2006). The use of binders in the biomass agglomeration process not only contributes to increasing the mechanical strength of the obtained pellets by strengthening the connections between the material particles, but also improves the process of their formation (Zawiślak and Sobczak, 2007). The addition of binders positively impacts the operation of technological equipment, reducing wear and tear on their working components and lowering energy demand. Granulates produced with binders are characterized by greater durability during transport and storage, as well as a reduced ability to absorb moisture from the environment. Properly selected additives can help reduce emissions of undesirable compounds, such as sulfur and carbon oxides, which are produced during combustion. The use of binders can also positively impact the efficiency of the biomass combustion process (Kulig et al., 2023). Natural plant-based binders, such as corn starch, molasses, or additional lignin, are most commonly used. They are readily available, relatively inexpensive, and environmentally safe. Synthetic or mineral additives, such as resin or lime, are also sometimes used, but they are rarely used in pellets used for energy purposes, as they can impair combustion properties, increase ash content, or increase the amount of pollutants released during the combustion process (Kajda-Szcześniak, 2011).

6.3. Production of pellets from torrefied biomass

By using pressure agglomeration of torrefied biomass, a number of advantages can be achieved in terms of transport and storage compared to the intermediate product, which can be produced from biomass and torrefied woodchips. The energy density per unit volume of torrefied biomass chips (in $GJ \cdot m^{-3}$) is approximately the same as that of the starting material (pure woodchips). Compaction into pellets increases the energy density by 4 to 8 times (Cremers et al., 2015; Koppejan et al., 2025, 2012). This significantly reduces transportation and storage costs. The pellets produced can be transported pneumatically or mechanically to boilers and are less susceptible to degradation and moisture absorption compared to wood chips or powdered fuels.

Pellet production from torrefied biomass (so-called black pellets) can be accomplished using two methods (Figure 6.4). In the first method, the biomass is torrefied, then ground, and then pressure agglomerated to produce appropriately sized pellets. In the second method, pellets are first made from the crushed biomass and then torrefied. In both technologies, the volatile substances released during torrefication are used as supplementary fuel. They are burned and used to produce heat for drying the material and/or for torrefication.

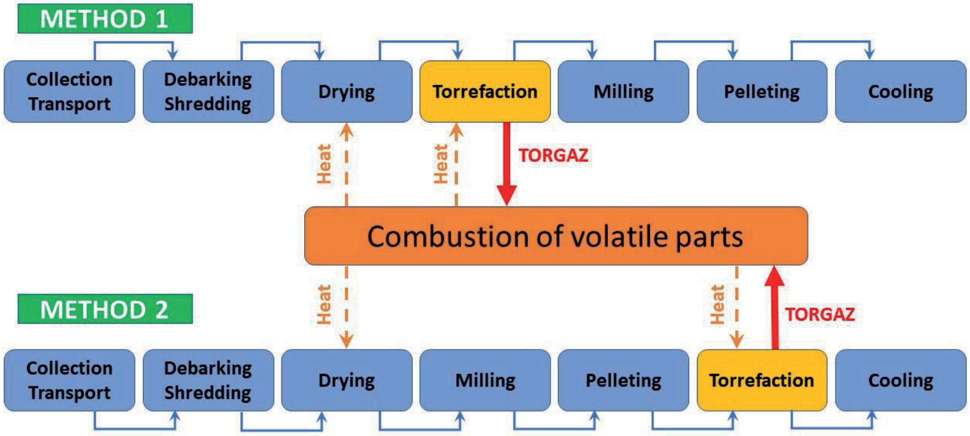


Figure 6.4. Methods of producing torrefied pellets (black pellets) (Kumar et al., 2017)

Depending on the technology adopted, different process requirements apply. In the second method, agglomeration prior to torrefaction, ensuring uniformity of the pellets at the reactor inlet increases the overall process efficiency. However, the physical strength of the torrefied pellets decreases compared to pellets produced using the first method.

Accurate information on the energy demand needed for production can be obtained by the energy and mass balance of both methods (Cremers et al., 2015; Koppejan et al., 2025, 2012). In torrefied pellet production, the energy demand increases compared to non-torrefied pellet production. This demand is also higher in the second torrefaction process of the finished pellets compared to the first torrefaction process of biomass. The results shown in Table 6.1 were obtained based on research conducted at the University of Minnesota's Natural Resources Research Institute (NRRI). These studies also showed that producing black pellets using the second torrefaction process produces a product that, after crushing, has a higher bulk density and better hydrophobicity compared to the uncrushed material. The crushing process produces coarse-grained particles that can be a good fuel product on their own or serve as a supplement in preparing whitewood for the production of conventional pellets with increased energy value (Fosnacht et al., 2018).

Torrefied biomass is more difficult to compress into compact pellets than raw biomass. The drying process and the torrefaction process remove free water and partially bound water. Furthermore, during torrefaction, OH groups are replaced by unsaturated nonpolar groups, which causes a significant loss of water adsorption capacity in the torrefied material. This loss of water hinders the efficient agglomeration of the torrefied material; the particles do not bond together. Adding water (up to approximately 15% moisture) to the torrefied biomass and increasing the agglomeration temperature reduces the compaction and friction energy, resulting in higher-quality pellets (Stelte et. al., 2012).

Table 6.1. Process and energy requirements in various technologies for the production of non-torrefied (white pellets) and torrefied (black pellets) pellets (Koppejan et al., 2012; Kumar et al., 2017; Saffron, 2020)

White pellets	Black pellets	
	Method 1 (Biomass torrefaction)	Method 2 (Pellet torrefaction)
No mechanical, chemical, or mineral impurities Ensuring the required moisture content (12-15%) and fineness	High amounts of energy and/or use of binders to densify torrefied biomass into strong and durable pellets	Creating strong pellets and maintaining their consistency both during and after torrefaction. It's important to ensure the right conditions for torrefaction of pellets as efficiently as wood chips.
Energy demand 1873 MJ·t^{-1}	Energy demand 3300 MJ·t^{-1}	Energy demand 2939 MJ·t^{-1}

Energy consumption in the pelletization process is higher per tonne of torrefied biomass (approximately 80–210 kWh·t^{-1}) compared to e.g. wood pellets (50–60 kWh·t^{-1}) (Koppejan et al., 2012; Stelte et al., 2012). This depends on the type of biomass, moisture content and particle size, the type of grinding device (mill), and the diameter of the holes in the die. Preparing durable and strong pellets therefore requires optimizing process conditions during both torrefaction and pelletization. Torrefaction and pressure agglomeration companies add various binders, such as glycerin, paraffin, molasses, lignin, flour, and bioplastics, to achieve better fuel quality.

However, the low hydrophobicity of the torrefaction and the resulting pellets makes the fuel less susceptible to degradation (rotting), self-heating, and moisture absorption.

6.4. Pellet quality

The popularity of using solid biofuels in the form of pellets or briquettes in individual heating systems is growing each year. The market has developed significantly, with customers seeking fuel with high calorific value, yet clean and durable. In turn, producers supply fuel made from various types of raw materials (most often woody biomass and energy crops), striving to maximize profits while minimizing production costs.

When purchasing pellets, it's worth checking whether the manufacturer refers to any certification system. This allows you to verify whether a given entity is certified and to what extent.

One of the key reasons for the company's success is its reputation as a provider of high-quality products and services. In today's competitive market, maintaining this position requires constant striving for quality improvement and finding increasingly effective ways to meet consumer needs.

Therefore, the most important tool influencing the solid biofuels market is quality standards. These standards facilitate trade in biofuels through mutual understanding between buyers and sellers, as well as between sellers and manufacturers of boilers in which these fuels are to be combusted.

With the growing production of solid biofuels, a significant issue arises regarding their quality and assessment methods. The quality standards being introduced aim to ensure a uniform level of fuel quality, as well as the efficiency of heating equipment, transportation, and storage. Furthermore, these standards contribute to compliance with applicable regulations and increased safety for all market participants, while defining their responsibilities and obligations. Furthermore, they support the harmonization of individual elements of the supply chain by defining quality indicators and acceptable values (Wróbel and Mudryk, 2010). These standards also provide consumers with essential information about product characteristics, which not only ensures customer satisfaction but also contributes to the popularization of biomass fuels. A summary of the standards and requirements for solid biofuels is presented in Table 6.2.

Table 6.2. Standards specifying the parameters and quality of biofuels from biomass

Standard No.	Title
EN ISO 16559:2022	Solid biofuels — Vocabulary
EN ISO 18134-1:2023	Solid biofuels — Determination of moisture content. Part 1: Reference method
EN ISO 18134-2:2024	Solid biofuels — Determination of moisture content. Part 2: Simplified method
EN ISO 18134-3:2023	Solid biofuels — Determination of moisture content. Part 3: Moisture in general analysis sample
EN ISO 18122:2023	Solid biofuels — Determination of ash content
EN ISO 18135:2017	Solid biofuels — Sampling
EN ISO 14780:2017	Solid biofuels — Sample preparation
EN ISO 18125:2017	Solid biofuels — Determination of calorific value
EN ISO 17225-1:2021	Solid biofuels — Fuel specifications and classes. Part 1: General requirements
EN ISO 17225-2:2021	Solid biofuels — Fuel specifications and classes. Part 2: Graded wood pellets
EN ISO 17225-3:2021	Solid biofuels — Fuel specifications and classes - Part 3: Graded wood briquettes
EN ISO 17225-4:2021	Solid biofuels — Fuel specifications and grades - Part 4: Wood chip grades
EN ISO 17225-5:2021	Solid biofuels — Fuel specifications and classes - Part 5: Graded firewood
EN ISO 17828:2025	Solid biofuels — Determination of bulk density
EN ISO 16948:2015	Solid biofuels — Determination of total content of carbon, hydrogen and nitrogen

Standard No.	Title
EN ISO 16995:2015	Solid biofuels - Determination of the water soluble chloride, sodium and potassium content
EN ISO 18123:2023	Solid biofuels — Determination of volatile matter

Table 6.2 (continued). Standards specifying the parameters and quality of biofuels from biomass

Standard No.	Title
EN ISO 17827-1:2024	Solid biofuels — Determination of particle size distribution for uncompressed fuels. Part 1: Oscillating screen method using sieves with apertures of 3,15 mm and above
EN ISO 17827-2:2024	Solid biofuels — Determination of particle size distribution for uncompressed fuels. Part 2: Vibrating screen method using sieves with apertures of 3,15 mm and below
EN ISO 17831-1:2025	Solid biofuels — Determination of mechanical durability of pellets and briquettes. Part 1: Pellets
EN ISO 17831-2:2025	Solid biofuels — Determination of mechanical durability of pellets and briquettes. Part 2: Briquettes
EN 15234-1:2011	Solid biofuels - Fuel quality assurance - Part 1: General requirements
EN ISO 16994:2016	Solid biofuels — Determination of total content of sulfur and chlorine
EN ISO 16967:2015	Solid biofuels — Determination of major elements — Al, Ca, Fe, Mg, P, K, Si, Na and Ti
EN ISO 16993:2016	Solid biofuels — Conversion of analytical results from one basis to another
EN ISO 16968:2015	Solid biofuels — Determination of minor elements

The two basic criteria for assessing the quality of solid biofuels are their composition and chemical-energetic characteristics, as well as their physical and mechanical properties.

Taking the above criteria into account, there are many parameters that significantly influence the quality of biofuels and produce specific effects on combustion processes, transport, and the entire logistics associated with them. These parameters were specified by Hahn (Hahn, 2004) and Mudryk and Wróbel (Mudryk and Wróbel, 2010; Wróbel and Mudryk, 2010) and summarized in Table 6.3.

Regarding the quality of pellets, the most important factors determining its quality are moisture, durability and dust content.

Moisture content, which should be 5-10%, directly impacts calorific value. In the case of pellets, there are no significant differences in moisture content, as it is impossible to granulate material with moisture content above 15%.

For consumers, the mechanical durability of pellets is crucial. Pellets with low durability tend to be damaged during transport and storage, resulting in increased dust formation and the shrinkage and fragmentation of individual pellets. Durability depends on many material and process factors, such as the particle size of the input material, the type of material and its lignin content, and the temperature and pressure of compaction. Durability is also significantly influenced by the humidity of the material and the environment in which the pellets are stored.

Table 6.3. Biofuel parameters and their effects (Hahn, 2004; Mudryk and Wróbel, 2010; Wróbel and Mudryk, 2010)

Parameter	Produced effect
Water content	Increase causes decrease in storage capacity, lower calorific value, losses, and spontaneous combustion
Calorific value	Determines way how fuel is used and determines design work, e.g. of heating boilers, installations in heating plants, etc.
Cl	HCl, dioxin/furan emissions, equipment corrosion
N	NO_x, emissions of HCN and N_2O
S	Emissions of NO_x
K	Causes corrosion of equipment and adversely reduces the ash melting point
Mg, Ca, P	These increase the melting point of the ash, which is a beneficial phenomenon, and increase the retention of pollutants in the ash, which limits the possibilities of its use
Heavy metals	These cause pollutant emissions and limit the possibilities of using ash
Ash content	Increase in ash content increases particulate matter emissions and increases ash disposal costs
Fungal spores	Health hazards when handling fuel
Bulk density	Affects the costs of transportation and storage
Specific density	Influences the dynamics of the combustion process and affects the accumulated amount of energy
Granulometric composition	Influences the flowability of the fuel, the course of the drying process, influences the formation of so-called "bridges", and influences the formation of dust
Share of dust	Increase in content affects the bulk density, increases losses during transport and storage, causes dusting, and affects health upon contact and inhalation
Durability	High durability minimizes losses, changes in quality and fuel breakdown during handling and transportation

A significant factor influencing pellet quality is dust content. Dust is generated during production and transport. Dust generated during production is typically removed by the manufacturer, while dust generated later, i.e., during transport and storage, is largely dependent on durability. Dust impedes pellet movement in the screw feeders that transport it from storage to the boiler. High dust content makes the fuel non-homogeneous. The smaller the installation, the more sensitive it is to the presence of dust. Generally speaking, dust content should not exceed 8%, but this value is difficult to estimate and adhere to due to the uneven distribution of dust in the fuel.

Three European countries have developed their own standards to determine pellet quality: Austria ŐNORM M7315 (*ÖNORM M 7315*, 1984), Sweden SS 187120 (*SS 187120*, 1998), and Germany DIN 51731 (*DIN 51731*, 1993) and DIN plus. However, the Technical Committee (TC 335) of the European Committee for Standardization (CEN) has developed the European standard EN 14961 (*EN 14961-1, 2011*), which organizes analyses and establishes control parameters for all types of biofuels, including pellets. In 2014, this standard was withdrawn and replaced by EN ISO 17225-1 (*ISO 17225-1, 2021*), which is currently the applicable standard specifying general requirements for biofuels, and EN ISO 17225-2 (*ISO 17225-2, 2021*), which specifies requirements for wood pellets. Thermally treated pellets (e.g., torrefaction pellets) are not included in this document; their requirements are specified in EN ISO 17225-8 (*ISO 17225-8, 2023*). Requirements for pellets produced from biomass by thermal processing are summarized in Table 6.4.

Table 6.4. Specifications for sorted compacted biomass fuels produced by thermal processing of chemically untreated woody biomass (Table 1, EN ISO 17225-8:2023. Solid biofuels – Fuel specifications and classes – Part 8: Graded thermally treated and densified biomass fuels for commercial and industrial use)

Properties	Unit	TW1	TW2
NORMATIVE			
Origin and source		Forest, plantation and other primary wood Chemically untreated wood by-products and residues	
Form	-	Pellets or briquettes	
Diameter (D) and length (L) of the pellet	mm	D06, 6 ±1 D08, 8 ±1 3,15≤L≤40	D06, 6 ±1 D08, 8 ±1 3,15≤L≤40
Humidity (M)	%wt., wet state	M08 ≤8	M08 ≤8
Ash (A)	g/MJ, dry state	A0.6 ≤0.6	A1.6 ≤1.6
Mechanical durability (DU)	%wt., wet state	DU97.5 ≥97.5	DU97.5 ≥97.5
Amount of fines, F, determined for pellets and briquettes of shape 9 ISO 5370	% wt., original state	F2.0 ≤2.0 (value should be specified)	F4.0 ≤4.0 (value should be specified)
Amount of fine particles below 0.5 mm, F0.5, determined for pellets and briquettes of shape 9	% wt. original state	value should be specified	value should be specified
Additives	% wt. original state	≤4 value should be specified	≤5 value should be specified
Bulk density, BD, determined for pellets and briquettes of shape 9	kg/m^3 original state	BD650 ≤ 650	BD600 ≤ 600

Properties	Unit	TW1	TW2
NORMATIVE			
Calorific value, Q , ISO 18125	MJ/m^3 original state	Q20 ≤ 20 (value should be specified)	Q19 ≤ 19 (value should be specified)
Nitrogen, N_{MJ} ISO 16948	g/MJ, dry state	N0.26 ≤ 0,26	N0.53 ≤ 0.53
Sulphur, S_{MJ}, ISO 16994	g/MJ, dry state	S0.03 ≤ 0.03	S0.05 ≤ 0.05
Chlorine, CI_{MJ}, ISO 16994	g/MJ, dry state	Cl0.03 ≤ 0.03	Cl0.03 ≤ 0.05
Arsenic, As_{MJ}, ISO 16968	g/MJ, dry state	As0.05 ≤ 0.05	As0.11 ≤ 0.11
Cadmium, Cd_{MJ}, ISO 16968	g/MJ, dry state	Cd0.03 ≤ 0.03	Cd0.05 ≤ 0.05
Chrome. Cr_{MJ}, ISO 16968	g/MJ, dry state	Cr0.53 ≤ 0.53	Cr0.79 ≤ 0.79
Copper, Cu_{MJ}, ISO 16968	g/MJ, dry state	Cu0.53 ≤ 0.53	Cu0.05 ≤ 1.05
Lead. Pb_{MJ}, ISO 16968	g/MJ, dry state	Pb0.53 ≤ 0.53	Pb0.05 ≤ 1.05
Mercury, Hg_{MJ}. ISO 16968	g/MJ, dry state	Hg0.005 ≤ 0.005	Hg0.005 ≤ 0.005
Nickel. $Ní_{MJ}$, ISO 16968	g/MJ, dry state	Ni0.53 ≤ 0.53	Ni0.53 ≤ 0.53
Zinc. ZnMJ. ISO 16968	g/MJ, dry state	Zn5.26 ≤ 5.26	Zn5.26 ≤ 5.26
Bound carbon, C_f	% wt., dry state	value should be specified	value should be specified

The introduction of standards specifying pellet quality requirements means for end users, especially owners of homes heated with pellets, that every type of wood pellet introduced and sold must meet specific quality standards. Pellets will have to meet class A1 requirements if used in heating appliances of classes 3, 4, and 5 and/or meeting ecodesign requirements, or class A2 requirements if used in heating appliances with emissions below class 3 as defined in the EN305-5 standard. Thanks to these regulations, users will be assured that the biofuel they are purchasing is of the highest quality, and therefore efficient in combustion and safe for health and the environment.

The introduced quality requirements for wood pellet burners can bring both benefits and challenges. The introduction of mandatory certification of wood pellet quality by obtaining a quality certificate or submitting test results reports from an accredited laboratory at specified intervals will improve the availability of selected, top-quality biofuel. This, in turn, will translate into more efficient combustion and fewer boiler operating issues. However, there is a risk of wood pellet price increases, which could be caused not only by a decline in the availability of the desired pellet quality on the market, but also by speculation that this selected biofuel will be in short supply.

7. SUMMARY

The practical use of suitable biomass and other raw materials for energy purposes is associated with relatively large fluctuations in its quality. The growth phase primarily influences chemical properties. The processing phase is primarily important for the physical properties of the manufactured products. Technical specifications for ensuring fuel quality address fuel issues only. To ensure the efficient use of solid fuels, it is also crucial to consider the relationship between the fuel and the processing device—for combustion, gasification, or pyrolysis.

Using biomass for energy purposes (electricity and heat production) is considered more environmentally friendly than burning fossil fuels. This primarily involves reducing pollutant emissions compared to burning fossil fuels. This method of biomass use also enables the utilization of residues and waste from forestry and agricultural production. Biomass can be used to produce many forms of energy, from heat for heating to fuel for motor vehicles.

Biomass as an energy source for direct use or processing into fuels with increased energy density (e.g., torrefaction, pelleting, briquetting) is relatively inexpensive, readily available, and widely available. Its resources are the largest of all alternative energy sources. It can be used and produced without major technological investments, and importantly, it is an ecological, reproducible, and cultivable resource.

From an economic perspective, the use of biomass for energy purposes stimulates economic growth and creates new jobs in its production and in its utilization from forests (especially in rural areas). Energy crops allow for the development of wasteland and the remediation of industrial areas. This increases countries' energy security by decentralizing energy production and reducing dependence on imported fuels such as oil and gas. Biomass resources are relatively evenly distributed, especially compared to other fossil fuels, which often require long-distance transportation and are susceptible to global geopolitical conditions.

Biomass resources and the solid fuels produced from them can be stored and used as needed, and their transport and storage do not entail such environmental threats as the transport or storage of crude oil or natural gas.

Biomass, as a renewable energy source, also has its drawbacks, both environmental and socioeconomic. It can emit pollutants, requires proper storage, and is considered a competitor to food production. Combustion of biomass, especially if improperly used, can result in emissions of particulate matter, nitrogen oxides, and sulfur, which negatively impact air quality. From an economic perspective, a significant drawback is the low density of the raw material, which complicates its transport and storage, and the wide range of moisture content, which hinders its preparation for energy use. To maintain its good energy properties (low moisture content, high calorific value) and prevent mold growth, biomass must be properly dried and stored. This can be counteracted by using torrefaction and pressure agglomeration technologies. Intensive cultivation of energy crops for energy purposes can lead to reduced biodiversity and negative impacts on ecosystems. The situation is similar in forestry. Forest breeders point out that the intensive extraction of logging residues from forest areas and their removal from the forest leads to the removal of mineral substances needed for the future young generation of the forest and the impoverishment of habitats.

In summary, biomass has its advantages and disadvantages, and its use requires a sustainable approach that takes into account ecological, economic and social aspects.

REFERENCES

Acharjee, T.C., Coronella, C.J., Vasquez, V.R., 2011. Effect of thermal pretreatment on equilibrium moisture content of lignocellulosic biomass. Bioresource Technology 102, 4849–4854. https://doi.org/10.1016/j.biortech.2011.01.018

Act of the Czech Republic, 2012. Act on Air Protection. Promulgated on 13. 6. 2012, effective date 1. 9. 2012, amount 69/2012.

Agrárminisztérium, 2025. Adatbázisok linkjei - Erdészet [WWW Document]. foldalap.am.gov.hu. URL https://foldalap.am.gov.hu/Adatbazisok_linkjei___Erdeszet_news_305 (accessed 11.20.25).

Agrárminisztérium, 2024. Magyarország erdeivel kapcsolatos adatok [WWW Document]. foldalap.am.gov.hu. URL https://foldalap.am.gov.hu/Magyarorszag_erdeivel_kapcsolatos_adatok_news_513 (accessed 6.6.25).

Alauddin, Z.A.B.Z., Lahijani, P., Mohammadi, M., Mohamed, A.R., 2010. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review. Renewable and Sustainable Energy Reviews 14, 2852–2862. https://doi.org/10.1016/j.rser.2010.07.026

Alpár T., Csóka L., Németh G., 2011. Faipari melléktermékek hasznosítása és a CO2-kibocsátás, in: Faipar.hu. Presented at the Magyar Asztalos és Faipar Konferencia, Nyugat-magyarországi Egyetem.

AMM INVESTMENT, 2025. Kotły na biomasę [WWW Document]. AMM INVESTMENT Sp. z o.o. URL https://www.amminvestments.pl/fu/piece-na-pellet/ (accessed 6.26.25).

Aniszewska, M., Gendek, A., 2014. Comparison of heat of combustion and calorific value of the cones and wood of selected forest trees species. Forest Research Papers 75, 231–236. https://doi.org/10.2478/frp-2014-0022

Aniszewska, M., Gendek, A., Hýsek, Š., Malaťák, J., Velebil, J., Tamelová, B., 2020. Changes in the Composition and Surface Properties of Torrefied Conifer Cones. Materials 13, 5660. https://doi.org/10.3390/ma13245660

Aniszewska, M., Gendek, A., Tamelová, B., Malaťák, J., Velebil, J., Krilek, J., Čabalová, I., Výbohová, E., Bubeníková, T., 2025. Changes in the physical, mechanical, chemical and energy parameters of coffee husk pellets during short-term storage. Fuel 386, 134191. https://doi.org/10.1016/j.fuel.2024.134191

Anukam, A., Mamphweli, S., Reddy, P., Okoh, O., Meyer, E., 2015. An Investigation into the Impact of Reaction Temperature on Various Parameters during Torrefaction of Sugarcane Bagasse Relevant to Gasification. Journal of Chemistry 2015, 235163. https://doi.org/10.1155/2015/235163

ARGUS, 2024. European wood pellet consumption falls in 2023 [WWW Document]. Market: Biomass. URL https://www.argusmedia.com/en/news-and-insights/latest-market-news/2580542-european-wood-pellet-consumption-falls-in-2023 (accessed 7.30.25).

Asikainen, A., Ranta, T., Laitila, J., 2001. Large-Scale Forest Fuel Procurement, in: Pelkonen, P., Hakkila, P., Karjalainen, T., Schlamadinger, B. (Eds.), Woody Biomass as an Energy Source – Challenges in Europe, Proceedings 39. European Forest Institute, Joensuu, Finland, pp. 73–78.

Bajpai, P., 2016. Structure of Lignocellulosic Biomass, in: Bajpai, P. (Ed.), Pretreatment of Lignocellulosic Biomass for Biofuel Production. Springer, Singapore, pp. 7–12. https://doi.org/10.1007/978-981-10-0687-6_2

Basu, P., 2006. Combustion and Gasification in Fluidized Beds. CRC Press, Boca Raton. https://doi.org/10.1201/9781420005158

Batidzirai, B., Mignot, A.P.R., Schakel, W.B., Junginger, H.M., Faaij, A.P.C., 2013. Biomass torrefaction technology: Techno-economic status and future prospects. Energy 62, 196–214. https://doi.org/10.1016/j.energy.2013.09.035

Bembenek, M., Gara, P., Hryniewicz, M., 2012. Metoda doboru elementów formujących prasy walcowej do kawałkowania materiału drobnoziarnistego. Chemik 66, 485–492.

Bergman, P.C.A., Boersma, A.R., Zwart, R.W.R., Kiel, J.H.A., 2005. Torrefaction for biomass co-firing in existing coal-fired power stations “BIOCOAL” (Renewable Energy in the Netherlands No. ECN-C-05-013). Energy Research Centre of the Netherlands (ECN), Petten, Netherlands.

Bioenergy Europe, 2025. Pellets 2024. Bioenergy Europe Statistical Raport [WWW Document]. Bioenergy Europe. URL https://bioenergyeurope.org/pellet-report/ (accessed 7.22.25).

Bíró, B., 2011. Biomassza hasznosítás - digitális tankönyvtár. Edutus Főiskola, Eduweb Multimédia Zrt.

Boonstra, M.J., van Acker, J., Kegel, E., Stevens, M., 2007. Optimisation of a two-stage heat treatment process: durability aspects. Wood Sci Technol 41, 31–57. https://doi.org/10.1007/s00226-006-0087-4

Börcsök, Z., Pásztory, Z., 2021. The role of lignin in wood working processes using elevated temperatures: an abbreviated literature survey. Eur. J. Wood Prod. 79, 511–526. https://doi.org/10.1007/s00107-020-01637-3

Bradna, J., Malaťák, J., Hájek, D., 2016. The properties of wheat straw combustion and use of fly ash as a soil amendment. Agronomy Research 14, 1257–1265.

Brandt, A., Gräsvik, J., Hallett, J.P., Welton, T., 2013. Deconstruction of lignocellulosic biomass with ionic liquids. Green Chem. 15, 550–583. https://doi.org/10.1039/C2GC36364J

Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T., 2008. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel 87, 844–856. https://doi.org/10.1016/j.fuel.2007.05.041

Bufka, A., Blechová-Tourková, J., Veverková, J., Modlík, M., 2024. Obnovitelné zdroje energie v letech 2022 a 2023. Oddělení analýz a datové podpory koncepcí. Ministerstvo průmyslu a obchodu ČR, Praha, Czech Republic.

Bufka, A., Veverková, J., Modlík, M., Blechová-Tourková, J., 2022. Obnovitelné zdroje energie v roce 2021. Oddělení analýz a datové podpory koncepcí. Ministerstvo průmyslu a obchodu ČR, Praha, Czech Republic.

Čabalová, I., Bubeníková, T., Kučerová, V., Krilek, J., Jablonský, M., Hönig, V., 2021. Technológia a technika spracovania drevnej a rastlinnej biomasy. Technická univerzita vo Zvolene, Zvolen, Slovakia.

Čabalová, I., Kačík, F., Lagaňa, R., Výbohová, E., Bubeníková, T., Čaňová, I., Ďurkovič, J., 2018. Effect of thermal treatment on the chemical, physical, and mechanical properties of pedunculate oak (*Quercus robur* L.) wood. BioResources 13, 157–170.

Čabalová, I., Zachar, M., Kačík, F., Tribulová, T., 2019. Impact of thermal loading on selected chemical and morphological properties of spruce ThermoWood. BioResources 14, 387–400.

Cai, J., He, Y., Yu, X., Banks, S.W., Yang, Y., Zhang, X., Yu, Y., Liu, R., Bridgwater, A.V., 2017. Review of physicochemical properties and analytical characterization of lignocellulosic biomass. Renewable and Sustainable Energy Reviews 76, 309–322. https://doi.org/10.1016/j.rser.2017.03.072

Carroll, J., Finnan, J., 2013. Emissions and efficiencies from the combustion of agricultural feedstock pellets using a small scale tilting grate boiler. Biosystems Engineering 115, 50–55. https://doi.org/10.1016/j.biosystemseng.2013.01.009

Čermák, M., Malaťáková, J., Malaťák, J., Aniszewska, M., Gendek, A., 2024. Regional wood chip quality parameters decomposition and price linkage with impact on Polish energy sustainability: Time frequency analysis between 2013 and 2019. Heliyon 10, e33322. https://doi.org/10.1016/j.heliyon.2024.e33322

Čermák, M., Malaťáková, J., Malaťák, J., Krepl, V., Aniszewska, M., Gendek, A., 2022. Analysis of the price relationship between coal and wood chip for the Czech Republic. Sylwan 166, 733–750.

Cha, J.S., Park, S.H., Jung, S.-C., Ryu, C., Jeon, J.-K., Shin, M.-C., Park, Y.-K., 2016. Production and utilization of biochar: A review. Journal of Industrial and Engineering Chemistry 40, 1–15. https://doi.org/10.1016/j.jiec.2016.06.002

Channiwala, S.A., Parikh, P.P., 2002. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 81, 1051–1063. https://doi.org/10.1016/S0016-2361(01)00131-4

Chen, W.-H., Lin, B.-J., Lin, Y.-Y., Chu, Y.-S., Ubando, A.T., Show, P.L., Ong, H.C., Chang, J.-S., Ho, S.-H., Culaba, A.B., Pétrissans, A., Pétrissans, M., 2021. Progress in biomass torrefaction: Principles, applications and challenges. Progress in Energy and Combustion Science 82, 100887. https://doi.org/10.1016/j.pecs.2020.100887

Chen, W.-H., Peng, J., Bi, X.T., 2015. A state-of-the-art review of biomass torrefaction, densification and applications. Renewable and Sustainable Energy Reviews 44, 847–866. https://doi.org/10.1016/j.rser.2014.12.039

Cremers, M., Koppejan, J., Middelkamp, J., Witkamp, J., Sokhansanj, S., Melin, S., Madrali, S., 2015. Status overview of torrefaction technologies – A review of the commercialisation status of biomass torrefaction (No. IEA Bioenergy: Task 32: Biomass Combustion and Cofiring). IEA Bioenergy, Enschede.

Crnogaca, B., 2017. Torrefaction as a process for biomass conversion into biocoal. Tehnika 72, 323–327. https://doi.org/10.5937/tehnika1703323C

ČSÚ, 2025a. Lesnictví - 2024 [WWW Document]. Kód: 100004-25. URL https://csu.gov.cz/produkty/lesnictvi-2024 (accessed 7.22.25).

ČSÚ, 2025b. Obnova lesů po kalamitách dále pokračovala [WWW Document]. Kód: 101000-25. URL https://csu.gov.cz/produkty/obnova-lesu-po-kalamitach-dale-pokracovala (accessed 7.22.25).

DGLP, 2024. Raport o stanie lasów w Polsce 2023. Ośrodek Rozwojowo-Wdrożeniowy Lasów Państwowych w Bedoniu, Warszawa.

Dhungana, A., 2011. Torrefaction of biomass (Master thesis). Dalhousie University, Halifax, Nova Scotia.

DIN 51731:1993-05 - Prüfung fester Brennstoffe; Holzbriketts; Anforderungen und Prüfung, 1993. . Deutsches Institut für Normung, Berlin.

Dobrzański, L.A., Matula, G., 2012. Podstawy metalurgii proszków i materiały spiekane, ISBN 978-83-63553-12-8, Open Acces Library. International OCSCO World Press, Gliwice.

Domian, E., Jemielity, M., 2006. Wpływ warunków aglomeracji w złożu fluidalnym na gęstość i porowatość granulatów. Inżynieria Rolnicza 2, 263–268.

Dz.U. 2025 poz. 618, 2025. Rozporządzenie Ministra Klimatu i Środowiska z dnia 8 maja 2025 r. w sprawie wymagań jakościowych dla biomasy pozyskanej z drzew i krzewów wprowadzanej do obrotu lub obejmowanej procedurą celną dopuszczenia do obrotu w postaci brykietu lub peletu. Rządowe Centrum Legislacji, Warszawa, Polska.

ECA, 2023. Sprawozdanie specjalne 29/2023: Unijne wsparcie na rzecz zrównoważonych biopaliw w transporcie (www No. 29/2023). European Court of Auditors, EU, Brussels.

ECO-PRIUS, 2025. Zbiorniki na pellet, silosy na pellet o konstrukcji szkieletowej [WWW Document]. ECO-PRIUS Heizung und Klima Technologien. URL https://ecoprius.pl/pl/zbiorniki-na-pellet.html (accessed 7.23.25).

Elbersen, B.S., Staritsky, I.G., Hengeveld, G.M., Schelhaas, M.J., Naeff, H.S.D., Böttcher, H., 2012. Atlas of EU biomass potentials: spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources (No. 3.3), IEE 08653 S12.529 241. Alterra / IIASA.

EMI Maszyny, 2025. MŁYN BIJAKOWY STELLA HMX 60 [WWW Document]. www.maszynydodrewna.com. URL https://www.maszynydodrewna.com/machine-catalog/briquetting-shredders/5910-mlyn-bijakowy-stella-hmx-60 (accessed 7.23.25).

EN 303-5:2022+A1:2023 Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking, 2022. . European Committee for Standardization, Brussels.

Esteves, B.M., Pereira, H.M., 2009. Wood modification by heat treatment: A review. BioResources 4, 370–404.

European Commission, 2025. National energy and climate plans for 2021-2030 [WWW Document]. EU countries' 10-year national energy and climate plans for 2021-2030. URL https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en (accessed 7.30.25).

European Commission, 2019. Going climate-neutral by 2050: A strategic long term vision for a prosperous, modern, competitive and climate neutral EU economy, Environment policy and protection of the environment. Publications Office of the European Union, Luxemburg, Belgium.

European Commission, 2015. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL

COMMITTEE AND THE COMMITTEE OF THE REGIONS. Closing the loop - An EU action plan for the Circular Economy (Document 52015DC0614; COM/2015/0614 final). Publications Office of the European Union, Luxemburg, Belgium.

European Commission, 2014. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Towards a circular economy: A zero waste programme for Europe (Document 52014DC0398R(01); COM/2014/0398 final/2). Publications Office of the European Union, Luxemburg, Belgium.

European Union, 2018a. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, Official Journal L 328, 21.12.2018, p. 82–209.

European Union, 2018b. Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012 (Text with EEA relevance.), OJ L 334, 31.12.2018, p. 1–93.

European Union, 2012. 2012/601/EU: Decision of the European Parliament of 10 May 2012 on the closure of the accounts of the European Agency for the Management of Operational Cooperation at the External Borders of the Member States of the European Union for the financial year 2010, OJ L 286, 17.10.2012, p. 297–297.

European Union, 2010. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control), Official Journal L 334, 17.12.2010, p. 17–119.

Eurostat, 2025. Eurostat [WWW Document]. The home of high-quality statistics and data on Europe. URL https://ec.europa.eu/eurostat/web/main/home (accessed 7.22.25).

Feliks, J., Klojzy-Karczmarczyk, B., Wiencek, M., 2018. Granulating coal sludge and their mixtures to improve transport properties. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi Polskiej Akademii Nauk 104, 173–188. https://doi.org/10.24425/124368

Fengel, D., Wegener, G. (Eds.), 1983. Wood: chemistry, ultrastructure, reactions, Reprint 2011 edition. ed. De Gruyter, Berlin/Boston.

Fiszer, A., 2009. Influence of straw humidity and temperature of briquetting processon the quality of agglomerate. Journal of Research and Applications in Agricultural Engineering 54, 68–70.

Flach, B., Bolla, S., 2022. European Union: Wood Pellets Annual (No. E42022- 0049), Biofuels, Wood Products. United States Department of Agriculture, Foregin Agricultural Service, European Union.

Flizikowski, J., Mroziński, A., 2016. Inżynieria aglomeracji biomasy. Grafpol Agnieszka Blichacz-Krupińska, Bydgoszcz.

Fosnacht, D.R., Hagen, T.S., Young, M., Carden, K., Kiesel, R.F., 2018. Use of Improved Densification Conditions for Producing High Fuel Content Products from Biomass Processed by Torrefaction, Hydrothermal Carbonization, and Various Densification Methodologies. Final Report (No. NRRI/TR-2018/09). University of Minnesota Duluth, Duluth, Minnesota.

Frączek, J. (Ed.), 2010. Produkcja biomasy na cele energetyczne. DRUKROL S.C., Kraków.

Frączek, J., Mudryk, K., Wróbel, M., 2011. Wybrane właściwości fizyczno-mechaniczne topinambu (*Helianthus tuberosus* L.). Inżynieria Rolnicza 15, 29–36.

Fromm, J., Rockel, B., Lautner, S., Windeisen, E., Wanner, G., 2003. Lignin distribution in wood cell walls determined by TEM and backscattered SEM techniques. Journal of Structural Biology 143, 77–84. https://doi.org/10.1016/S1047-8477(03)00119-9

Gałęzia, T., 2016. Economic methods for the utilisation of logging residues. Forest Research Papers 77, 50–55. https://doi.org/10.1515/frp-2016-0006

Gara, P., 2015. Badania procesu dwustopniowej granulacji drobnoziarnistych odpadów. Przemysł Chemiczny T. 94, nr 9, 1509–1511. https://doi.org/10.15199/62.2015.9.11

GEMCO Energy, 2025. How does a wood pellet machine work? [WWW Document]. GEMCO Energy Machinery Co, Ltd. URL https://www.pellet-making.com/blog/how-does-a-pellet-mill-work.html (accessed 6.26.25).

Gendek, A., Aniszewska, M., Malaťák, J., Velebil, J., 2018a. Evaluation of selected physical and mechanical properties of briquettes produced from cones of three coniferous tree species. Biomass and Bioenergy 117, 173–179. https://doi.org/10.1016/j.biombioe.2018.07.025

Gendek, A., Malaťák, J., Velebil, J., 2018b. Effect of harvest method and composition of wood chips on their caloric value and ash content. Sylwan 162, 248–257. https://doi.org/10.26202/sylwan.2017125

Gendek, A., Nurek, T., 2016. Variability of energy woodchips and their economic effects. Folia Forestalia Polonica, Series A 58, 62–71. https://doi.org/10.1515/ffp-2016-0007

Gendek, A., Wężyk, P., Moskalik, T., 2018c. Share and accuracy of estimation of logging residues in the total volume of harvested timber. Sylwan 162, 679–687. https://doi.org/10.26202/sylwan.2018050

Gendek, A., Więsik, J., 2015. Rębarki (Rozdział 7), in: Więsik, J. (Ed.), Urządzenia techniczne w produkcji leśnej. Tom 2: Maszyny i urządzenia do pozyskiwania i transportowania drewna. Wydawnictwo SGGW, Warszawa, pp. 321–351.

Gendek, A., Zychowicz, W., 2015. Analysis of wood chippings fractions utilized for energy purposes. Annals of Warsaw University of Life Sciences - SGGW, Agriculture 65, 79–91.

Ghaffariyan, M., Andonovski, V., Brown, M., 2011. Application of slash-bundler for collecting harvest restudies in Eucalyptus plantation. Forest Science (Sofia) 1–2, 83–89.

Główny Urząd Statystyczny, 2024. Rocznik Statystyczny Leśnictwa 2024. Urząd Statystyczny w Białymstoku, Podlaski Ośrodek Badań Regionalnych, Warszawa, Białystok, Polska.

Goh, C.S., Junginger, M., Cocchi, M., Marchal, D., Thrän, D., Hennig, C., Heinimö, J., Nikolaisen, L., Schouwenberg, P.-P., Bradley, D., Hess, R., Jacobson, J., Ovard, L., Deutmeyer, M., 2013. Wood pellet market and trade: a global perspective. Biofuels, Bioproducts and Biorefining 7, 24–42. https://doi.org/10.1002/bbb.1366

Gołuchowska, B., Sławiński, J., Markowski, G., 2015. Biomass utilization as a renevable energy source in Polish power industry - current status and perspectives. J. Ecol. Eng. 16, 143–154. https://doi.org/10.12911/22998993/2948

Gray, R.W., Seijo, F., 2013. Forest Sustainability: Bioenergy Breaks and Barriers [WWW Document]. Biomass Magazine. URL https://biomassmagazine.com//articles/forest-sustainability-bioenergy-breaks-and-barriers-8949 (accessed 6.26.25).

Greenhalf, C.E., Nowakowski, D.J., Harms, A.B., Titiloye, J.O., Bridgwater, A.V., 2013. A comparative study of straw, perennial grasses and hardwoods in terms of fast pyrolysis products. Fuel 108, 216–230. https://doi.org/10.1016/j.fuel.2013.01.075

Hahn, B., 2004. Existing Guidelines and Quality Assurance for Fuel Pellets—Pellets for Europe Project. UMBERA, Umweltorientierte Betriebsberatungs, Forschungsund Entsorgungs-Gesellschaft m.b.H, Austria.

Hakkila, P., 1991. Hakkuupoistuman latvusmassa., Folia Forestalia. Metsäntutkimuslaitos. Institutum Forestale Fenniae, Helsinki.

Hakkila, P., 1989. Utilization of Residual Forest Biomass, Springer Series in Wood Science. Springer-Verlag, Berlin Heidelberg.

He, X., Lau, A.K., Sokhansanj, S., Lim, C.J., Bi, X.T., Melin, S., Keddy, T., 2013. Moisture sorption isotherms and drying characteristics of aspen (*Populus tremuloides*). Biomass and Bioenergy 57, 161–167. https://doi.org/10.1016/j.biombioe.2013.07.007

Hebda, T., Złobecki, A., 2011. Wpływ wilgotności słomy na trwałość kinetyczną brykietów. Inżynieria Rolnicza 6, 45–52.

Hejft, R., Obidziński, S., 2012. The pressure agglomeration of the plant materials - the technological and technical innovations. Part 1. Journal of Research and Applications in Agricultural Engineering 57, 63–65.

Higman, C., van der Burgt, M., 2003. Gasification. Gulf Professional Publishing, Burlington. https://doi.org/10.1016/B978-0-7506-7707-3.X5000-1

Hoefnagels, R., Resch, G., Junginger, M., Faaij, A., 2014. International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union. Applied Energy 131, 139–157. https://doi.org/10.1016/j.apenergy.2014.05.065

Hoekman, S.K., Broch, A., Robbins, C., 2011. Hydrothermal Carbonization (HTC) of Lignocellulosic Biomass. Energy Fuels 25, 1802–1810. https://doi.org/10.1021/ef101745n

Hudák, M., 2022. Slovenské lesy drvia na štiepku kvôli dotáciám [WWW Document]. Aktuality.sk. URL https://www.aktuality.sk/clanok/6AAbYyW/slovenske-lesy-drvia-na-stiepku-kvoli-dotaciam/ (accessed 12.4.24).

Hussain, M., Ali, O., Raza, N., Zabiri, H., Ahmed, A., Ali, I., 2023. Recent advances in dynamic modeling and control studies of biomass gasification for production of hydrogen rich syngas. RSC Adv. 13, 23796–23811. https://doi.org/10.1039/D3RA01219K

Hydrogaz, 2024. Kotły na biomasę - typy i rodzaje oraz jak działają [WWW Document]. hydrogaz.eu. URL https://hydrogaz.eu/kotly-na-biomase-typy-i-rodzaje-oraz-jak-dzialaja/ (accessed 6.26.25).

IEA, 2025. IEA – International Energy Agency [WWW Document]. IEA. URL https://www.iea.org (accessed 7.22.25).

IndexBox, 2025a. Wood Pellets - Poland - 2007-2020 [WWW Document]. INDEXBOX www.indexbox.iowww. URL https://app.indexbox.io/report/1693/616/ (accessed 7.30.25).

IndexBox, 2025b. Hungary - Wood Pellets - Market Analysis, Forecast, Size, Trends and Insights [WWW Document]. Production of Wood Pellets in Hungary. URL https://www.indexbox.io /search/production-wood-pellets-hungary/ (accessed 7.30.25).

IndexBox, 2024. Slovakia - Solid Biofuels - Market Analysis, Forecast, Size, Trends and Insights [WWW Document]. INDEXBOX www.indexbox.io. URL https://www.indexbox.io/store/slovakia-solid-biofuels-market-analysis-forecast-size-trends-and-insights/ (accessed 12.4.24).

instsani.pl, 2017. Magazyny zewnętrzne podziemne. Technik urządzeń i systemów energetyki odnawialnej. URL https://instsani.pl/technik-urzadzen-i-systemow-energetyki-odnawialnej/vademecum-energetyki-odnawialnej/biomasa/magazynowanie-biomasy/magazyny-peletu/magazyny-zewnetrzne-podziemne/ (accessed 7.23.25).

instsani.pl, 2016. Rośliny energetyczne, uprawa. Vademecum energetyki odnawialnej. URL https://instsani.pl/technik-urzadzen-i-systemow-energetyki-odnawialnej/vademecum-energetyki-odnawialnej/biomasa/rosliny-energetyczne-uprawa/ (accessed 7.23.25).

Ippolito, J.A., Laird, D.A., Busscher, W.J., 2012. Environmental Benefits of Biochar. Journal of Environmental Quality 41, 967–972. https://doi.org/10.2134/jeq2012.0151

ISO 1928:2009 - Solid mineral fuels — Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value, 1st ed, 2009. , Solid mineral fuels. International Organization for Standardization, Geneva, Switzerland.

ISO 17225-2:2021 - Solid biofuels -- Fuel specifications and classes -- Part 2: Graded wood pellets, 2021. . International Organization for Standardization, Geneva, Switzerland.

ISO 18123:2023 Solid biofuels — Determination of volatile matter, 2nd ed, 2023. . International Organization for Standardization, Geneva, Switzerland.

Jablonski, K., Chlebowski, K., 2012. Struktura czasu roboczego i wydajności pracy podczas pakietowania pozostałości zrębowych pakieciarką John Deere 1490E. Nauka Przyroda Technologie 06, 1–10.

Jankowiak, R., Szewczyk, G., Bilański, P., Jazłowiecka, D., Harabin, B., Linnakoski, R., 2021. Blue-stain fungi isolated from freshly felled Scots pine logs in Poland, including Leptographium sosnaicola sp. nov. Forest Pathology 51, e12672. https://doi.org/10.1111/efp.12672

Jeníček, L., Malaťák, J., Velebil, J., Neškudla, M., 2025. Pyrolyzed Agro-Food By-Products: A Sustainable Alternative to Coal. Materials 18, 1495. https://doi.org/10.3390/ma18071495

Jenkins, B.M., Baxter, L.L., Miles, T.R., Miles, T.R., 1998. Combustion properties of biomass. Fuel Processing Technology 54, 17–46. https://doi.org/10.1016/S0378-3820(97)00059-3

Jha, S., Okolie, J.A., Nanda, S., Dalai, A.K., 2022. A Review of Biomass Resources and Thermochemical Conversion Technologies. Chemical Engineering & Technology 45, 791–799. https://doi.org/10.1002/ceat.202100503

Jílková, L., Gál, L., 2018. Přehled zplyňovacích technologií použitelných v regionálním měřítku. Paliva 10, 1–16. https://doi.org/10.35933/paliva.2018.01.01

Jodlowski, K., 2004. Technologia i technika pozyskiwania drewna na cele energetyczne. Postępy Techniki w Leśnictwie 87, 17–24.

Juszczak, M., 2016. Comparison of CO and NOx concentrations from a 20 kW boiler for periodic and constant wood pellet supply. Environment Protection Engineering 42. https://doi.org/10.5277/epe160308

Juszczak, M., 2014. Concentrations of carbon monoxide and nitrogen oxides from a 15 kW heating boiler supplied periodically with a mixture of sunflower husk and wood pellets. Environment Protection Engineering 40, 65–74. https://doi.org/10.5277/epe140205

Kajda-Szcześniak, M., 2011. Wybrane lepiszcza zastosowane w procesie brykietowania biomasy. Ochrona Powietrza i Problemy Odpadów 45, 129–134.

kalendarzrolnikow.pl, 2017. Wierzba energetyczna urośnie nawet na nieużytkach [WWW Document]. Przyrodnicze abc. URL https://www.kalendarzrolnikow.pl/472/wierzba-energetyczna-urosnie-nawet-na-nieuzytkach (accessed 7.23.25).

Kambo, H.S., Dutta, A., 2015. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renewable and Sustainable Energy Reviews 45, 359–378. https://doi.org/10.1016/j.rser.2015.01.050

Kappe, C.O., Stadler, A., Dallinger, D., 2012. Microwaves in Organic and Medicinal Chemistry, 2nd Edition. ed. Vch Pub, Weinheim.

Kędziora-Urbanowicz, A., 2025. Dynamika rozwoju polskiej branży pelletu drzewnego [WWW Document]. Kominki.org. URL https://www.kominki.org/artykul/6995,dynamika-rozwoju-polskiej-branzy-pelletu-drzewnego (accessed 6.13.25).

KMEC Engineering, 2024. Biomass Pellet Fuel Market Across Hungary [WWW Document]. KMEC Pellet Plant. URL https://www.biomasspelletplant.com/news/pellet-market-hungary.html?utm_source=chatgpt.com (accessed 7.30.25).

Kopczyński, M., Zuwała, J., 2013. Biomasa toryfikowana - nowe paliwo dla energetyki. Chemik 67, 540–551.

Koppejan, J., Cremers, M., Middelkamp, J., Witkamp, J., Sokhansanj, S., Melin, S., Madrali, S., 2025. Two Page Summary – Status overview of torrefaction technologies. A review on the status of the commercialisation of biomass torrefaction (No. IEA Bioenergy: Task 32: 2015), Summary Series. IEA Bioenergy, Enschede.

Koppejan, J., Sokhansanj, S., Melin, S., Madrali, S., 2012. Status overview of torrefaction technologies (No. IEA Bioenergy Task 32 report). IEA Bioenergy, Enschede.

Krajewski, A., Witomski, P., 2016. Ochrona drewna - surowca i materiału, II. ed. Wydawnictwo SGGW, Warszawa, Polska.

Krilek, J., Gendek, A., Aniszewska, M., Szewczyk, G., Ťavodová, M., Spinelli, R., Kováč, J., Malaťák, J., Kormanek, M., Mancel, V., Kuvik, T., 2024. Research of Chipper Knives with a Modified Cutting Edge for the Production of Dimensionally Uniform Wood Chips. BioResources 19, 3653–3667.

Krilek, J., Kováč, J., 2013. Energetická náročnosť sekacích strojov. Technická Univerzita vo Zvolene, Zvolen, Slovakia.

Kuglarz, M., Alvarado-Morales, M., Dąbkowska, K., Angelidaki, I., 2018. Integrated production of cellulosic bioethanol and succinic acid from rapeseed straw after dilute-acid pretreatment. Bioresource Technology 265, 191–199. https://doi.org/10.1016/j.biortech.2018.05.099

Kulig, R., Różyło, R., Łysiak, G., Hyła, P., 2023. Zastosowanie procesu aglomeracji ciśnieniowej do zagospodarowania wytłoków jabłkowych. Przemysł Spożywczy 77, 27–31. https://doi.org/10.15199/65.2023.8.4

Kulig, R., Skonecki, S., Gawłowski, S., Zdybel, A., Łysiak, G., 2013. The effect of pressure on efficiency of chosen soft wood sawdust. Acta Scientiarum Polonorum. Technica Agraria 12, 31–40.

Kumar, L., Koukoulas, A.A., Mani, S., Satyavolu, J., 2017. Integrating Torrefaction in the Wood Pellet Industry: A Critical Review. Energy Fuels 31, 37–54. https://doi.org/10.1021/acs.energyfuels.6b02803

La Meccanica, 2025. Pellet press classification [WWW Document]. La Meccanica. Technology & Experience at your Service. URL https://www.lameccanica.it/pl/news/press-review-animal-feed/pellet-press-classification (accessed 7.23.25).

Lenartowska, A., 2025. Biomasa na świecie - śladami projektów biomasowych. URL https://magazynbiomasa.pl/sladami-projektow-biomasowych/ (accessed 7.22.25).

Lenartowska, A., 2024. UE pozostaje największym na świecie producentem i konsumentem pelletu. Wnioski z raportu Bioenergy Europe - Magazyn Biomasa [WWW Document]. magazynbiomasa.pl. URL https://magazynbiomasa.pl/ue-pozostaje-najwiekszym-na-swiecie-producentem-i-konsumentem-pelletu-wnioski-z-raportu-bioenergy-europe/ (accessed 6.27.25).

Leuschner, C., Ellenberg, H., 2017. Ecology of Central European Non-Forest Vegetation: Coastal to Alpine, Natural to Man-Made Habitats: Vegetation Ecology of Central Europe, Volume II, Ecology of Central European Non-Forest Vegetation: Coastal to Alpine, Natural to Man-Made Habitats. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-43048-5

Lisowski, A., Chlebowski, J., Klonowski, J., Nowakowski, T., Strużyk, A., Sypuła, M., 2010. Technologie zbioru roślin energetycznych (Technologies of energy crops harvesting). Wydawnictwo SGGW, Warszawa.

Liu, Q., Wang, S., Zheng, Y., Luo, Z., Cen, K., 2008. Mechanism study of wood lignin pyrolysis by using TG–FTIR analysis. Journal of Analytical and Applied Pyrolysis 82, 170–177. https://doi.org/10.1016/j.jaap.2008.03.007

Makwana, J., Dhass, A.D., Ramana, P.V., Sapariya, D., Patel, D., 2023. An analysis of waste/biomass gasification producing hydrogen-rich syngas: A review. International Journal of Thermofluids 20, 100492. https://doi.org/10.1016/j.ijft.2023.100492

Malaťák, J., Gendek, A., Aniszewska, M., Velebil, J., 2020. Emissions from combustion of renewable solid biofuels from coniferous tree cones. Fuel 276, 118001. https://doi.org/10.1016/j.fuel.2020.118001

Malat'ak, J., Jevič, P., Vaculík, P., 2010. Účinné využití tuhých biopaliv v malých spalovacích zařízeních s ohledem na snižování emisí znečišťujících látek. Powerprint, Praha, Czech Republic.

Malat'ak, J., Vaculík, P., 2008. Biomasa pro výrobu energie. Česká zemědělská univerzita v Praze, Praha.

Malaťák, J., Velebil, J., Bradna, J., Kučera, M., Gendek, A., Aniszewska, M., Ivanova, T.A., 2024. Comparative Experimental Assessment of Pollutant Emission Behavior in Combustion of Untreated and Thermally Treated Solid Biofuels from Spruce Chips and Rapeseed Straw. Atmosphere 15, 452. https://doi.org/10.3390/atmos15040452

Malat'ak, J., Velebil, J., Jankovský, M., Tamelová, B., Malaťáková, J., Passian, L., 2020. Aplikace zplyňovacích technologií při energetickém využití jehličnatých dřevin z kůrovcové a kalamitní těžby. Lesy České republiky, s. p., Hradec Králové.

Malaťák, J., Velebil, J., Malaťáková, J., Passian, L., Bradna, J., Tamelová, B., Gendek, A., Aniszewska, M., 2022. Reducing Emissions from Combustion of Grape Residues in Mixtures with Herbaceous Biomass. Materials 15, 7288. https://doi.org/10.3390/ma15207288

Malaťáková, J., Jankovský, M., Malaťák, J., Velebil, J., Tamelová, B., Gendek, A., Aniszewska, M., 2021. Evaluation of Small-Scale Gasification for CHP for Wood from Salvage Logging in the Czech Republic. Forests 12, 1448. https://doi.org/10.3390/f12111448

MARD, 2021. Forestry. Area of the forest land fund. [WWW Document]. Ministry of Agriculture and Rural Development of the Slovak Republic. URL https://www.mpsr.sk/en/index.php?navID=30 (accessed 6.13.25).

Mayor, J.R., Williams, A., 2011. Residence Time Influence on the Fast Pyrolysis of Loblolly Pine Biomass. Journal of Energy Resources Technology 132, 041801. https://doi.org/10.1115/1.4003004

McIlveen-Wright, D.R., Huang, Y., Rezvani, S., Mondol, J.D., Redpath, D., Anderson, M., Hewitt, N.J., Williams, B.C., 2011. A Techno-economic assessment of the reduction of carbon dioxide emissions through the use of biomass co-combustion. Fuel 90, 11–18. https://doi.org/10.1016/j.fuel.2010.08.022

MEKH, 2022. MEKH Energiastatisztika 2021 [WWW Document]. FATÁJ (fataj.hu). URL https://fataj.hu/2022/11/mekh-energiastatisztika-2021/ (accessed 6.6.25).

Meyer, S., Glaser, B., Quicker, P., 2011. Technical, Economical, and Climate-Related Aspects of Biochar Production Technologies: A Literature Review. Environ. Sci. Technol. 45, 9473–9483. https://doi.org/10.1021/es201792c

Ministerstvo zemědělství, 2024. Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2023. Ministerstvo zemědělství, Praha, Czech Republic.

Ministerstvo zemědělství, 2023. Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2022. Ministerstvo zemědělství, Praha, Czech Republic.

Ministerstvo zemědělství, 2022. Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2021. Ministerstvo zemědělství, Praha, Czech Republic.

Ministerstvo zemědělství, 2021. Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2020. Ministerstvo zemědělství, Praha, Czech Republic.

Ministerstvo zemědělství, 2016. Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2015. Ministerstvo zemědělství, Praha, Czech Republic.

Ministerstvo zemědělství, 2011. Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2010. Ministerstvo zemědělství, Praha, Czech Republic.

MKiŚ, 2019. Krajowy plan na rzecz energii i klimatu na lata 2021-2030. Założenia i cele oraz polityki i działania [Poland's National Energy and Climate Plan for the years 2021-2030 (NECP PL)]. Ministerstwo Aktywów Państwowych, Warszawa, Polska.

Mlonka-Mędrala, A., Magdziarz, A., Gajek, M., Nowińska, K., Nowak, W., 2020. Alkali metals association in biomass and their impact on ash melting behaviour. Fuel 261, 116421. https://doi.org/10.1016/j.fuel.2019.116421

Moon, T.A., Druckenmiller, M.L., Thoman, R.L., 2024. NOAA Arctic Report Card 2024: Executive Summary, NOAA technical report OAR ARC. United States. National Oceanic and Atmospheric Administration. Office of Oceanic and Atmospheric Research, Boulder, CO, USA.

Mora-Pale, M., Meli, L., Doherty, T.V., Linhardt, R.J., Dordick, J.S., 2011. Room temperature ionic liquids as emerging solvents for the pretreatment of lignocellulosic biomass. Biotechnology and Bioengineering 108, 1229–1245. https://doi.org/10.1002/bit.23108

Moravčík, M. (Ed.), 2024. ZELENÁ SPRÁVA. Správa o lesnom hospodárstve v Slovenskej republike za rok 2023. Ministerstvo pôdohospodárstva a rozvoja vidieka Slovenskej republiky, Národné lesnícke centrum, Bratislava.

Moskalik, T., 2013. Techniczne, technologiczne i organizacyjne uwarunkowania pozyskania i transportu drewna energetycznego (Technical, technological and organizational conditions for the harvesting and transportation of energy wood), in: Gołos, P., Kaliszewski, A. (Eds.), Biomasa leśna na cele energetyczne. Instytut Badawczy Leśnictwa, Sękocin Stary, pp. 107–118.

Moskalik, T., 2004. Model maszynowego pozyskiwania drewna w zrównoważonym leśnictwie polskim. Wydawnictwo SGGW, Warszawa.

Moskalik, T., Gendek, A., 2019. Production of Chips from Logging Residues and Their Quality for Energy: A Review of European Literature. Forests 10, 262. https://doi.org/10.3390/f10030262

Moskalik, T., Nowacka, W., Sadowski, J., Zastocki, D., 2014. Energochłonność procesu balotowania pozostałości pozrębowych. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej 16, 77–85.

Moskalik, T., Sadowski, J., Zastocki, D., 2016. Some technological and economic aspects of logging residues bundling. Sylwan 160, 31–39.

MPO ČR, 2024. Vnitrostátní plán České republiky v oblasti energetiky a klimatu. Ministerstvo průmyslu a obchodu, Praha, Czech Republic.

Mudryk, K., Wróbel, M., 2012. Wpływ stopnia rozdrobnienia i ciśnienia aglomeracji na wybrane parametry jakościowe brykietu ze słonecznika wierzbolistnego. Autobusy : technika, eksploatacja, systemy transportowe 13, 166–169.

Mudryk, K., Wróbel, M., 2010. Produkcja biopaliw stałych. Maszyny i urządzenia, in: Frączek, J. (Ed.), Przetwarzanie Biomasy Na Cele Energetyczne. DRUKPOL S.C., Kraków, pp. 175–205.

Nagadowski, M., 2008. Analiza strat jakościowych i wartościowych w surowcu drzewnym w wyniku szkód huraganowych na przykładzie Nadleśnictwa Mircze (RDLP w Lublinie). Sylwan 152, 46–52.

NFC, 2025. Informacie o lesoch [WWW Document]. Národné lesnícke centrum | National Forest Centre. URL https://web.nlcsk.org/ (accessed 10.21.25).

Niedziółka, I., Szpryngiel, M., 2013. Wpływ temperatury na gęstość i trwałość brykietów wytworzonych w brykieciarce ślimakowej. Inżynieria Rolnicza 3, 301–310.

Nielsen, H.P., Frandsen, F.J., Dam-Johansen, K., Baxter, L.L., 2000. The implications of chlorine-associated corrosion on the operation of biomass-fired boilers. Progress in Energy and Combustion Science 26, 283–298. https://doi.org/10.1016/S0360-1285(00)00003-4

Nimitpaitoon, T., Boonrod, S., Punyaporn, P., 2023. The effect of storage conditions on the characteristics of various types of biomass. International Journal of Advanced and Applied Sciences 10, 130–139. https://doi.org/10.21833/ijaas.2023.05.016

Obroučka, K., 2001. Termické odstraňování a energetické využívání odpadů. VŠB - Technická univerzita Ostrava, Ostrava.

Ochodek, T., Najser, J., 2014. Zplyňování biomasy I. VŠB – Technická univerzita Ostrava, Ostrava.

ÖNORM M 7315:1984 - Auflagerkonstruktionen liegender ortsfester Druckbehälter; Ausführung und Berechnung, 1984. . Austrian Standards International, Wien, Austria.

Oravec, M., Slamka, M., 2014. Produkcia a využívanie drevnej biomasy na Slovensku. SIEA - Slovenská inovačná a energetická agentúra, Praha, Czech Republic.

Pappné Vancsó, J., 2010. A biomassza, mint lehetséges energiaforrás hasznosítási lehetőségei, különös tekintettel Magyarországra (Doktori értekezés). Eötvös Loránd Tudományegyetem, Budapest.

Paramonova, K., Ivanova, T.A., Muntean, A., Passian, L., Malaťák, J., Hutla, P., Ribintev, I., 2025. Assessment of Quality and Combustion Characteristics of Briquettes Derived from Giant Hogweed Biomass. Agronomy 15, 2213. https://doi.org/10.3390/agronomy15092213

Penny, 2015. Odpady drzewne. Penny Dobroszyce. URL https://penny.pl/porady/odpady-drzewne/ (accessed 7.23.25).

Peters, J.F., Iribarren, D., Dufour, J., 2015. Biomass Pyrolysis for Biochar or Energy Applications? A Life Cycle Assessment. Environ. Sci. Technol. 49, 5195–5202. https://doi.org/10.1021/es5060786

Phanphanich, M., Mani, S., 2011. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. Bioresource Technology 102, 1246–1253. https://doi.org/10.1016/j.biortech.2010.08.028

Pinter, G., Nemeth, K., Kis-Simon, T., 2009. A szőlővenyige és a fanyesedék biomassza-erőművi beszállításának elemzése. GAZDÁLKODÁS: Scientific Journal on Agricultural Economics 53, 357–363. https://doi.org/10.22004/ag.econ.92491

Pohořelý, M., Jeremiáš, M., Kameníková, P., Skoblia, S., Svoboda, K., Punčochář, M., 2012. Biomass Gasification. Chemické listy 106, 264–274.

POLEXIM, 2008. Peleciarki z matrycą pierścieniową: seria MZLH [WWW Document]. POLEXIM Import Export. URL http://www.polexim-online.pl/?prod=102 (accessed 6.26.25).

Porter, B., 1995. Badania jakości technicznej surowca drzewnego oraz sposobów jego pozyskania w drzewostanach objętych klęskami żywiolowymi. Las Polski 4–6.

Postrzednik, S., 2014. Wartość opałowa jako parametr przydatności energetycznej biomasy [Net calorific value as a parameter of a biomass energy usefulness]. Energetyka 10, 573–579.

Postrzednik, S., 2011. Analiza parametrów wpływających na energetyczną przydatność paliw [Analysis of parameters influencing the energetic usefulness of fuels]. Energetyka 7, 395–398.

Poszytek, K., Lenart, A., 2006. Wlaściwosci sorpcyjne modelowych odżywek sproszkowanych. Żywność Nauka Technologia Jakość 13, 128–135.

Ranalli, P. (Ed.), 2007. Improvement of Crop Plants for Industrial End Uses, 1st ed. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-1-4020-5486-0

Regulation (EU) 2018/1999 of the European Parlament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council, 2018. . Official Journal of the European Union, Brussels.

Ren, X., Sun, R., Meng, X., Vorobiev, N., Schiemann, M., Levendis, Y.A., 2017. Carbon, sulfur and nitrogen oxide emissions from combustion of pulverized raw and torrefied biomass. Fuel 188, 310–323. https://doi.org/10.1016/j.fuel.2016.10.017

Rénes, J., 2008. Fás szárú energiaültetvények a gyakorlatban II. Bio energia 3, 16–18.

Roder, H., 2012. Pöyry Management Consulting: Biomass imports to Europe and global availability, IEA - 2n Workshop - Cofiring biomass with coal. Pöyry Management Consulting (Deutschland) GmbH, Freising.

Rokni, E., Ren, X., Panahi, A., Levendis, Y.A., 2018. Emissions of SO2, NOx, CO2, and HCl from Co-firing of coals with raw and torrefied biomass fuels. Fuel 211, 363–374. https://doi.org/10.1016/j.fuel.2017.09.049

Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B.S., Brosowski, A., Thrän, D., 2019. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energy Strategy Reviews 26, 100379. https://doi.org/10.1016/j.esr.2019.100379

Rumpf, J., Horváth, Major, T., Szakálosné Mátyás, K., 2016. Erdőhasználat. Mezőgazda Kiadó, Budapest.

Rybín, M., 1985. Spalování paliv a hořlavých odpadů v ohništích průmyslových kotlů - Miroslav Rybín (1985, Státní nakladatelství technické literatury). Redakce báňské a strojírenské literatury, Praha.

Saffron, C. (Ed.), 2020. Achieving carbon negative bioenergy systems from plant materials. Burleigh Dodds Science Publishing, London. https://doi.org/10.1201/9781003047612

Sahu, S.G., Sarkar, P., Chakraborty, N., Adak, A.K., 2010. Thermogravimetric assessment of combustion characteristics of blends of a coal with different biomass chars. Fuel Processing Technology 91, 369–378. https://doi.org/10.1016/j.fuproc.2009.12.001

Sazima, M., Kmoníček, V., Schneller, J., 1989. Teplo. SNTL, Praha, Czech Republic.

Scarlat, N., Dallemand, J.-F., Banja, M., 2013. Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. Renewable and Sustainable Energy Reviews 18, 595–606. https://doi.org/10.1016/j.rser.2012.10.040

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Banja, M., Motola, V., 2015. 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 51, 969–985. https://doi.org/10.1016/j.rser.2015.06.062

Scelsi, E., Angelini, A., Pastore, C., 2021. Deep Eutectic Solvents for the Valorisation of Lignocellulosic Biomasses towards Fine Chemicals. Biomass 1, 29–59. https://doi.org/10.3390/biomass1010003

Schipfer, F., Kranzl, L., 2019. Techno-economic evaluation of biomass-to-end-use chains based on densified bioenergy carriers (dBECs). Applied Energy 239, 715–724. https://doi.org/10.1016/j.apenergy.2019.01.219

Schut, M., Slingerland, M., Locke, A., 2010. Biofuel developments in Mozambique. Update and analysis of policy, potential and reality. Energy Policy, Special Section on Carbon Emissions and Carbon Management in Cities with Regular Papers 38, 5151–5165. https://doi.org/10.1016/j.enpol.2010.04.048

Sermyagina, E., Saari, J., Kaikko, J., Vakkilainen, E., 2016. Integration of torrefaction and CHP plant: Operational and economic analysis. Applied Energy 183, 88–99. https://doi.org/10.1016/j.apenergy.2016.08.151

Sermyagina, E., Saari, J., Zakeri, B., Kaikko, J., Vakkilainen, E., 2015. Effect of heat integration method and torrefaction temperature on the performance of an integrated CHP-torrefaction plant. Applied Energy 149, 24–34. https://doi.org/10.1016/j.apenergy.2015.03.102

Sharma, H.B., Sarmah, A.K., Dubey, B., 2020. Hydrothermal carbonization of renewable waste biomass for solid biofuel production: A discussion on process mechanism, the influence of process parameters, environmental performance and fuel properties of hydrochar. Renewable and Sustainable Energy Reviews 123, 109761. https://doi.org/10.1016/j.rser.2020.109761

Singh Chouhan, A.P., Sarma, A., 2013. Critical Analysis of Process Parameters for Bio-oil Production via Pyrolysis of Biomass: A Review. Recent Patents on Engineering 7, 98–114. https://doi.org/10.2174/18722121113079990005

Skonecki, S., Kulig, R., Łysiak, G., Różyło, R., Wójcik, M., 2017. Wpływ wilgotności materiału i nacisku tłoka na parametry zagęszczania i wytrzymałość aglomeratu ślazowca pensylwańskiego (*Sida hermaphrodita*). Acta Agrophysica 24, 329–339.

Skonecki, S., Laskowski, J., 2012. Wpływ średnicy komory i wilgotności słomy pszennej na parametry zagęszczania. Acta Agrophysica 19, 415–424.

Skonecki, S., Laskowski, J., 2010. Wpływ wielkości cząstek rozdrobnionej pszenicy na parametry procesu zagęszczania. Inżynieria Rolnicza 14, 185–191.

Skonecki, S., Laskowski, J., Kulig, R., Lysiak, G., 2013. Wpływ wilgotności materiału i średnicy komory na parametry zagęszczania miskanta olbrzymiego. Acta Agrophysica 20, 185–194.

Spokas, K.A., 2010. Review of the stability of biochar in soils: predictability of O:C molar ratios. Carbon Management 1, 289–303. https://doi.org/10.4155/cmt.10.32

SS 187120 - Biofuels and peat - Fuel pellets, 1st ed, 1998. . Svenska institutet för standarder, SIS, Stockholm.

Starfelt, F., Tomas Aparicio, E., Li, H., Dotzauer, E., 2015. Integration of torrefaction in CHP plants – A case study. Energy Conversion and Management 90, 427–435. https://doi.org/10.1016/j.enconman.2014.11.019

Stelte, W., Sanadi, A.R., Shang, L., Holm, J.K., Ahrenfeldt, J., Henriksen, U.B., 2012. Recent developments in biomass pelletization – A review. BioRes 7, 4451–4490. https://doi.org/10.15376/biores.7.3.4451-4490

Šupa, 2020. Drevoštiepka: ekologický a cenovo výhodný spôsob vykurovania [WWW Document]. Šupa Technika. Šupa.sk. URL https://www.supa.sk/blog/drevostiepka-ekologicky-a-cenovo-vyhodny-sposob-vykurovania-n66 (accessed 12.4.24).

Sutton, D., Kelleher, B., Ross, J.R.H., 2001. Review of literature on catalysts for biomass gasification. Fuel Processing Technology 73, 155–173. https://doi.org/10.1016/S0378-3820(01)00208-9

Szalay, D., 2018. Energetikai célú dendromassza termesztés és hasznosítás lehetséges szerepe a lignocellulóz biohajtóanyag üzemek alapanyag ellátásában (Doktori értekezés). Soproni Egyetem, Sopron.

Szewczyk, G., Jankowiak, R., Mitka, B., Bożek, P., Bilański, P., Kulak, D., Barycza, A., Kunys, G., 2020. Development of blue stain in mechanically harvested Scots pine (*Pinus sylvestris*) logs during storage. Can. J. For. Res. 50, 42–50. https://doi.org/10.1139/cjfr-2019-0112

Szilágyi, Z., 2022. A biomassza felhasználása energiatermelésre. Energiagazdálkodás 63, 44–47.

Tezer, Ö., Karabağ, N., Öngen, A., Çolpan, C.Ö., Ayol, A., 2022. Biomass gasification for sustainable energy production: A review. International Journal of Hydrogen Energy, Green Hydrogen For Global Decarbonization 47, 15419–15433. https://doi.org/10.1016/j.ijhydene.2022.02.158

Thengane, S.K., Kung, K.S., Gomez-Barea, A., Ghoniem, A.F., 2022. Advances in biomass torrefaction: Parameters, models, reactors, applications, deployment, and market. Progress in Energy and Combustion Science 93, 101040. https://doi.org/10.1016/j.pecs.2022.101040

ThermoStahl, W., 2017. Silosy na pellet. Thermostahl. Ogrzewanie - Klimatyzacja. URL https://thermostahl.pl/silosy-na-pellet-5-100-ton-tel-22-758-40-96/ (accessed 7.23.25).

Tolnayová, M., 2004. Štátne lesy chcú byť strategickým výrobcom biomasy [WWW Document]. HNonline.sk. URL https://hnonline.sk/dennik/podniky-a-trhy/10286-statne-lesy-chcu-byt-strategickym-vyrobcom-biomasy (accessed 12.4.24).

Tomaszewski, K., 2020. The Polish road to the new European Green Deal – challenges and threats to the national energy policy. Polityka Energetyczna 23, 5–18. https://doi.org/10.33223/epj/123411

Tripathi, M., Sahu, J.N., Ganesan, P., 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable and Sustainable Energy Reviews 55, 467–481. https://doi.org/10.1016/j.rser.2015.10.122

Trnobranský, K., 1996. Energetické využití dřevních odpadů spalováním a zplyňováním. Topenářství a instalace 2, 51.

Tumuluru, J.S., Sokhansanj, S., Hess, J.R., Wright, C.T., Boardman, R.D., 2011. A review on biomass torrefaction process and product properties for energy applications. Industrial Biotechnology 7, 384–401. https://doi.org/10.1089/ind.2011.7.384

Tunklová, B., Jeníček, L., Malaťák, J., Neškudla, M., Velebil, J., Hnilička, F., 2022. Properties of Biochar Derived from Tea Waste as an Alternative Fuel and Its Effect on Phytotoxicity of Seed Germination for Soil Applications. Materials 15, 8709. https://doi.org/10.3390/ma15248709

UNFCCC, 2016. Paris Agreement on climate change [WWW Document]. Consilium. URL https://www.consilium.europa.eu/en/policies/paris-agreement-climate/ (accessed 12.16.24).

US EPA, 2013. U.S. Environmental Protection Agency [WWW Document]. URL https://www.epa.gov/home (accessed 7.22.25).

Valenzuela, J.L., 2015. Final Evaluation Project URU/10/G31 "Electricity Production from Biomass in Uruguay" (PROBIO) (No. URU/10/G31). Triple Desarrollo Consultores SpA, Montevideo, Uruguay.

van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J., 2011. Biomass upgrading by torrefaction for the production of biofuels: A review. Biomass and Bioenergy 35, 3748–3762. https://doi.org/10.1016/j.biombioe.2011.06.023

Vares, V., Kask, Ü., Muiste, P., Pihu, T., Soosaar, S., 2005. Manual for biofuel users. Tallinn University of Technology Press, Tallinn.

Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G., 2010. An overview of the chemical composition of biomass. Fuel 89, 913–933. https://doi.org/10.1016/j.fuel.2009.10.022

Viessmann PL, 2023. Systemy magazynowania i dostawy peletów [WWW Document]. Magazynowanie peletu w zbiornikach, magazynach i pojemnikach materiałowych. URL https://www.viessmann.pl/pl/wiedza/technologia-i-systemy/kotly-na-pelet/dostawa-i-magazynowanie-peletu.html (accessed 7.23.25).

von Hippel, A.R., 1995. Dielectrics and Waves. Artech House Publishers, Boston, London.

Wang, S., Dai, G., Yang, H., Luo, Z., 2017. Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review. Progress in Energy and Combustion Science 62, 33–86. https://doi.org/10.1016/j.pecs.2017.05.004

Wang, S., Lin, H., Zhang, L., Dai, G., Zhao, Y., Wang, X., Ru, B., 2016. Structural Characterization and Pyrolysis Behavior of Cellulose and Hemicellulose Isolated from Softwood Pinus armandii Franch. Energy Fuels 30, 5721–5728. https://doi.org/10.1021/acs.energyfuels.6b00650

Wannapeera, J., Fungtammasan, B., Worasuwannarak, N., 2011. Effects of temperature and holding time during torrefaction on the pyrolysis behaviors of woody biomass. Journal of Analytical and Applied Pyrolysis 92, 99–105. https://doi.org/10.1016/j.jaap.2011.04.010

Weber, K., Quicker, P., 2018. Properties of biochar. Fuel 217, 240–261. https://doi.org/10.1016/j.fuel.2017.12.054

Werle, S., 2021. Termiczne przetwarzanie biomasy odpadowej jako element gospodarki obiegu zamkniętego, 1st ed. Wydawnictwo Politechniki Śląskiej, Gliwice.

Werle, S., 2014a. Multi-criterial analysis of the gasification process of municipal sewage sludge. Wydawnictwo Politechniki Śląskiej, Gliwice.

Werle, S., 2014b. Impact of feedstock properties and operating conditions on sewage sludge gasification in a fixed bed gasifier. Waste Manag Res 32, 954–960. https://doi.org/10.1177/0734242X14535654

Werle, S., Ksiądz, A., Szwedo, I., 2011. Badania eksperymentalne podstawowych właściwości palnych komunalnych osadów ściekowych [Experimental studies of basic properties of combustible municipal sewage sludge]. Gaz, Woda i Technika Sanitarna 11, 447–450.

Werle, S., Sobek, S., Kaczor, Z., 2019a. Biomass pyrolysis – the prediction of the process behaviour based on the chemical structure of fuel. Journal of International Scientific Publications: Materials, Methods and Technologies (Online) 13, 128–135.

Werle, S., Sobek, S., Kaczor, Z., Ziółkowski, Ł., Buliński, Z., Dudziak, M., 2019b. Experimental and numerical analysis of the biomass innovativ solar pyrolysis process. E3S Web Conf. 137, 01004. https://doi.org/10.1051/e3sconf/201913701004

Werle, S., Wilk, R., 2013. Ograniczenie emisji tlenków azotu poprzez zintegrowanie układu: reaktor zgazowania - kocioł węglowy. Proceedings of ECOpole 7, 751–756. https://doi.org/10.2429/proc.2013.7(2)098

Więcek, R., 2024. Rynek pelletów 2023 [WWW Document]. KominkiPro. URL https://kominkipro.ihz.pl/rynek-pelletow-2023/ (accessed 7.22.25).

Wierzbicki, M., Majcher, J., Sołtys, J., Sołtys, M., 2023. Znaczenie biomasy w gospodarce i energetyce w krajach UE. PolitykaRolna.eu. URL https://politykarolna.eu/2023/09/19/znaczenie-biomasy-w-gospodarce-i-energetyce-w-krajach-ue/ (accessed 7.22.25).

Wikipedia, 2025. Énergie en Hongrie. Wikipédia.

Wilk, M., Magdziarz, A., Kalemba, I., Gara, P., 2016. Carbonisation of wood residue into charcoal during low temperature process. Renewable Energy 85, 507–513. https://doi.org/10.1016/j.renene.2015.06.072

WJK Invest, 2014. Zrębki drzewne w liczbach [WWW Document]. wjk-invest.pl. URL http://www.wjk-invest.pl/zrebkowanie-biomasy/przydatne-informacje/zrebki-drzewne-w-liczbach (accessed 7.22.25).

Wróbel, M., Mudryk, K., 2010. Jakość biopaliw stałych, in: Frączek, J. (Ed.), Przetwarzanie Biomasy Na Cele Energetyczne. DRUKPOL S.C., Kraków, pp. 207–221.

Yaman, S., SahanŞahan, M., Haykiri-Açma, H., Şeşen, K., Küçükbayrak, S., 2001. Fuel briquettes from biomass–lignite blends. Fuel Processing Technology 72, 1–8. https://doi.org/10.1016/S0378-3820(01)00170-9

Ye, J., Li, D., Sun, Y., Wang, G., Yuan, Z., Zhen, F., Wang, Y., 2013. Improved biogas production from rice straw by co-digestion with kitchen waste and pig manure. Waste Management 33, 2653–2658. https://doi.org/10.1016/j.wasman.2013.05.014

Zajączkowski, S., 2013. Prognozy pozyskania drewna w Polsce w perspektywie 20 lat oraz możliwości ich wykorzystania do szacowania zasobów drewna na cele energetyczne, in: Gołos, P., Kaliszewski, A. (Eds.), Biomasa leśna na cele energetyczne. Instytut Badawczy Leśnictwa, Sękocin Stary, pp. 21–32.

Zajonc, O., Raclavská, H., Juchelková, D., Volfová, M., 2011. Energetic properties of compost. Inzynieria Mineralna 12, 77–88.

Zakzeski, J., Bruijnincx, P.C.A., Jongerius, A.L., Weckhuysen, B.M., 2010. The Catalytic Valorization of Lignin for the Production of Renewable Chemicals. Chem. Rev. 110, 3552–3599. https://doi.org/10.1021/cr900354u

Zawiślak, K., Sobczak, P., 2007. Zmiany wybranych właściwości fizycznych granulatu uzyskanego z dodatkiem różnych substancji wiążących. Inżynieria Rolnicza 5, 437–444.

Zielińska, A., Pomorski, A., 2020. Granulowanie drobnych frakcji odpadu wydobywczego z gnejsu metodą ciśnieniową. Górnictwo odkrywkowe LXI, 35–40.

Zuwała, J., Hrycko, P., 2005. Analiza efektów energetycznych i ekologicznych procesu współspalania węgla i biomasy w kotle pyłowym OP-230. Polityka Energetyczna 8, 405–420.

Zuwała, J., Topolnicka, T., Głód, K., Kopczyński, M., 2010. Zastosowanie technik sprzężonych TGA-MS oraz micro-GC do analizy przebiegu procesów termicznego rozkładu mieszanek węgla i biomasy. Przemysł Chemiczny 89, 812–816.

Abstract

The multi-author monograph "Energy Utilization of Agglomerated Logging Residues" describes the possibilities of processing and using plant biomass for energy purposes. It covers forest biomass in the form of logging residues from planned and unplanned tree felling. The authors also discuss other plants used as ecological biofuels for producing energy carriers. The monograph aims to provide both scientific and practical guidance in identifying the possibilities for processing and utilizing such biomass.

The efficient use of this biomass type for energy purposes poses numerous challenges stemming from the significant variation in its physical, chemical, and qualitative characteristics, such as calorific value, moisture content, mineral contamination, particle and agglomerate size resulting from extraction and pre-processing processes. These challenges are currently being addressed scientifically and practically worldwide. One way to eliminate or significantly reduce these limitations is to use torrefaction to convert plant biomass into energy-efficient, renewable fuel.

This monograph is in the form of review and comparative study. It presents current situation and challenges related to harvesting and processing methods of by-product biomass, primarily from forests, in four Visegrad Group countries (Poland, Czech Republic, Slovakia, and Hungary) in comparison with similar systems in other European and global countries. The methodology is based on broad review of available source materials. In the case of the Visegrad Group (V4) countries, the primary sources of information include scientific texts, European Commission documents, national legal documents, and publications by national forest managers and government bodies responsible for agricultural and forest management.

This monograph provides basic information about forest biomass in the V4 countries. It describes also the pellet market and the legal framework in the mentioned countries for the use of solid biofuels. Development trends are outlined, highlighting challenges and barriers to the use of these fuels. The discussion of biofuel properties focuses primarily on elemental analysis, water and ash content, heat of combustion and calorific value. Biomass harvesting and shredding technologies are described, along with machinery and equipment used in subsequent technological operations. Machines for material preparation, pellet production, and storage, as well as combustion devices, are described in detail. Combustion, pyrolysis, and gasification processes are also described. Authors also address legal standards that characterize and define parameters of pellet quality as biofuels.

The book is addressed to both scientists and technology producers, users and other readers involved in biomass processing, the production of refined fuels, and the production of combustion devices.

The monograph is co-financed by the Governments of the Czechia, Hungary, Poland and Slovakia through Visegrad Grants from International Visegrad Fund. The mission of the fund is to advance ideas for sustainable regional cooperation in Central Europe. Project ID 22420094, title „Logging Residue Torrefaction and Pressure Agglomeration as a Method to Conserve Fossil Fuels”.

Streszczenie

Wieloautorska monografia pt. „Energy utilization of agglomerated logging residues" opisuje możliwości przetworzenia i energetycznego wykorzystania biomasy roślinnej. Dotyczy biomasy leśnej w postaci pozostałości zrębowych po planowych jak i nieplanowych cięciach drzew w lasach. Autorzy, nawiązują również innych roślin wykorzystywanych jako ekologiczne biopaliwa do produkcji nośników energii. Monografia ma naukowo i praktycznie pomóc we wskazaniu możliwości przetwarzania oraz zagospodarowywania takiej biomasy.

Efektywne, energetyczne wykorzystanie tego rodzaju biomasy niesie za sobą wiele problemów wynikających ze znacznego zróżnicowania jej cech fizycznych, chemicznych czy jakościowych, takich jak np. wartość opałowa, zawartość wilgoci, zanieczyszczenie cząstkami mineralnymi, wielkość cząstek i aglomeratu jakie zostały uzyskane w wyniku procesów pozyskania i wstępnego przerobu. Są to wyzwania, które aktualnie próbuje się naukowo i praktycznie rozwiązywać na całym świecie. Jednym ze sposobów na wyeliminowanie lub znaczne zmniejszenie wspomnianych ograniczeń jest zastosowanie procesu toryfikacji jako sposobu przetwarzania biomasy roślinnej na wydajne energetycznie paliwo odnawialne.

Monografia ma charakter przeglądowy i porównawczy. Przedstawia aktualną sytuację i problemy związane z pozyskiwaniem i przetwarzaniem ubocznej biomasy głównie leśnej w czterech krajach Grupy Wyszehradzkiej (Polska, Czechy, Słowacja Węgry) na tle funkcjonowania podobnych systemów w innych krajach Europy i świata. Metodologia pracy oparta została na szerokim przeglądzie dostępnych materiałów źródłowych. W przypadku krajów Grupy Wyszehradzkiej (V4), głównymi źródłami informacji są teksty naukowe, dokumenty Komisji Europejskiej, krajowe dokumenty prawne, opracowania wydawane przez krajowych zarządców terenów leśnych oraz organy władzy, odpowiadające za gospodarkę rolniczą i leśną.

Monografia zawiera podstawowe informacje dotyczące biomasy leśnej w krajach V4. Opisano rynek pelletu i ramy prawne dotyczące stosowania biopaliw stałych. Podane zostały kierunki rozwoju ze wskazaniem wyzwań i barier stosowania tych paliw. Omawiając właściwości biopaliw, skupiono się na głównie na analizie elementarnej, zawartości wody, popiołu oraz cieple spalania i wartości opałowej. Opisano technologie pozyskiwania i rozdrabniania biomasy oraz maszyny i urządzenia wykorzystywane w kolejnych operacjach technologicznych. Scharakteryzowane zostały maszyny do przygotowania materiału, produkcji i magazynowania pelletu oraz kotły do spalania. Szeroko i szczegółowo opisano procesy spalania, pirolizy oraz zgazowania materiału. Autorzy odnoszą się również norm prawnych charakteryzujących i wyznaczających wartości parametrów określających jakość pelletu jako biopaliwa.

Książka skierowana jest zarówno do naukowców, jak również do praktyków zajmujących się przetwarzaniem biomasy, produkcją paliw uszlachetnionych czy produkcją kotłów do spalania.

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