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Evaluation of Small-Scale Gasification for CHP for Wood from Salvage Logging in the Czech Republic

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Abstract: This study focused on small gasification units for combined heat and power generation (CHP) up to 200 kW of electric power, which can use wood from salvage logging, and assessed the current feasibility of running commercially available units in the conditions of the Czech Republic. In total, the technical and economic parameters of 21 gasification units from ten major international producers were compiled. One of the most important parameters assessed was the net calorific value, which in the analysed samples of spruce wood was determined at 18.37 MJ kg^{-1} on a dry basis. This complies to the requirements for fuel quality for these units. The economic profitability was determined for three investment variants with electric power of 10, 100, and 200 kW$_{el}$ in an operating mode of constant power at 20 and 30 wt.% input moisture level of the wood. Economic analysis showed that smaller alternatives with an output of 10 and 100 kW$_{el}$ produce economic losses. On the other hand, the 200-kW$_{el}$ alternative produced operating profit and positive cash flow at both fuel moisture levels in the first year of operation. The evaluation of individual alternatives using dynamic investment evaluation methods also showed that only the alternative with an output of 200 kW$_{el}$ with both fuel moistures was able to produce a positive net present value.

Keywords: spruce; gasifier; salvage logging; bark beetle; net present value; internal rate of return

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1. Introduction

Within the framework of the National Plan of the Czech Republic in the field of energy and climate, a European target was adopted for the level of 32% of renewable energy sources (RES) by 2030 expressed as the share in gross final energy consumption [1]. In the area of reducing greenhouse gas emissions, a Europe-wide target of a 43% reduction in greenhouse gas emissions [2] has been set at RES levels compared to 2005 in the EU Emissions Trading System (EU ETS) sectors and by 30% outside EU ETS sectors [3]. The Czech Republic's goal is a 30% reduction in total greenhouse gas emissions by 2030 compared to 2005, which corresponds to a reduction in emissions of 44 million tonnes of CO_{2eq} [4].

In the field of energy security, the National Plan is based mainly on the objectives and policies contained in the approved State Energy Concept of the Czech Republic [5]. The main goals include increasing the diversification of the energy mix, maintaining self-sufficiency in electricity production, ensuring sufficient development of energy infrastructure and decreasing import dependence [2]. However, in the case of import dependence, there is a high probability of a gradual increase due to a decrease in the use of domestic brown and black coal and the related increase in imported energy commodities [6,7]. One method to prevent an increase in import dependence is to use gasification technologies for domestic raw materials [8].

The technology of production and use of wood gas has long been known [9]. Currently, offered wood biomass gasification technologies produce electricity and heat directly from biomass [8,10]. Thanks to the gasification technology, significantly more energy can be used from the supplied wood than by conventional combustion [11,12]. The advantage of the gasification process over conventional combustion systems with respect to the environment is that it enables better regulation of greenhouse gas emissions [13] compared to combustion of solid biofuels [14] or waste biomass [15,16]. The disadvantages are mostly related to the high initial capital costs, as stated by Skanderová et al. [16], and also to insufficient standardization of gasification units.

The advantages of using gaseous fuels generated from biomass over solid fuels are significant [17,18]. Especially in the dynamics of combustion process, exothermic combustion reactions occur more effectively in the diffusion regions, which leads to more efficient use of energy from gaseous fuels and reduced emissions in flue gases [19]. Undoubtedly, the increased ease of use of gaseous fuels can lead to wider adoption compared to solid fuels. The main advantage of solid biomass gasification is that it is almost environmentally neutral with regard to greenhouse gases when comparing the Global Emission Model for Integrated Systems (GEMIS) factors to a combined heat and power plant fired by, e.g., natural gas [2].

To ensure gasification process quality, the recommended net calorific value of wood fuels for small gasification units is around 17 MJ kg^{-1}. The moisture level requirement is at or below 10 wt.% In the raw samples, the net calorific value of the wood tends to be around 15 MJ kg^{-1} at a moisture content around 20 wt.% [20,21].

For small gasification units up to 200 kW_{el}, which require the lowest possible ash content in the fuel, most manufacturers state the amount of ash up to a maximum of 1% by weight. This parameter does not pose any problem for clean wood chips, because the ash content of wood is well below 1 wt.% [22,23].

Since the fuels used in gasification technologies are natural and renewable raw materials, such as wood, it is possible to use regionally available resources, which is an important step in locally self-sustainable energy transformation [24,25]. In addition to forest wood, short-rotation plantations are other possible sources of fuel, which can also be implemented in agroforestry systems [22,26]. In addition, a large amount of dry biogenic industrial residues can be used [27,28].

The most suitable source of raw material for gasification technologies is calamity wood biomass, for which there is often no use [29,30]. In the years 2018–2019, extreme climatic conditions in the Czech Republic led to extensive damage to spruce stands by subcortical insects, especially in the areas of Moravia and Silesia and subsequently in the areas of the Vysočina Region and the Šumava Region [31]. Even today, the volume of salvage logging is high [32]. For example, in 2018 in the Czech Republic, salvage logging reached a record value of 23.01 million m^3. The share of salvage logging thus represented 90% of the total volume of logging, which was 25.69 million m^3 [33]. Considering that about 10% of aboveground biomass is stored in branches and smallwood [34] and only about 60% of it is recovered, even in clear-cut areas [35], hundreds of thousands of m^3 of material suitable only for energy use can be assumed to be available in the Czech Republic annually. Among other options, gasification technologies are a method for the efficient use of this material.

In order to successfully assess the sustainability of a biomass gasification unit, a technical and economic study must be carried out while identifying possible variables hindering success. Cardoso et al. [36] carried out a technical and economic analysis of a biomass gasification power plant dealing with mixtures of forestry residues for electricity generation in Portugal. The results showed the feasibility of the project in the selected region under current market conditions. For Canada, the economic feasibility of biomass gasification for energy production was evaluated, where it was determined that the cost of electricity production has decreased significantly with increasing power plant capacity [37]. In a feasibility study of a forest biomass gasification plant in the Republic of Korea, the results showed that the investment can be financially attractive if the owners are entitled to additional income from the sale of heat [38]. In an article by Rentizelas et al. [39], two technologies for energy conversion from biomass were compared: the organic Rankine cycle (ORC) and gasification. Technological and economic comparisons have shown that gasification has provided a higher financial return, mainly due to higher electric efficiency.

Gasification units are being developed in Central and Southern Europe, and in Northern European countries such as Norway and Sweden, but these units are mostly the exception. In Norway, energy prices are relatively low, so gasification-based combined heat and power production (CHP) is too expensive compared to other energy sources [40]. Thus, gasification projects do not focus on the production of heat and electricity but on other uses of generator gas, such as the production of gaseous and liquid biofuels [41].

The overall economic balance of gasification technologies in the Czech Republic is going to be influenced by the price decision of the Energy Regulatory Office [1], which stipulates financial support for renewable energy sources. Depending on the non-repayable investment aid received, the operating aid is then accordingly reduced.

In 2019, 20.7 million m^3 of harvested spruce wood damaged by bark beetle was recorded in the Czech Republic. This represents an increase compared to 2018 by more than 70%, when approximately 12 million m^3 was harvested (2017—5.34 million m^3). It was practically exclusively wood-infested with European spruce bark beetle (*Ips typographus*), which is usually accompanied by glossy bark beetle (*Pityogenes chalcographus*), and in northern and central Moravia and Silesia, but locally it is often infested elsewhere (central Bohemia), also involving the northern bark beetle (*Ips duplicatus*). Bark beetles in 2019 occurred in calamity numbers on spruce stands practically in the whole territory of the Czech Republic. The bark-beetle-damaged wood amounted to an alarming 15.9 m^3 ha^{-1} of spruce stands, which is about eighty times the neutral state value of 0.20 m^3 ha^{-1} [42]. From a long-term point of view, the total amount of bark-beetle-damaged wood in 2019 was the highest in the recorded history of the Czech Republic [43]. The wood damaged by bark beetles is not immediately of worse quality as a fuel, however it can be more quickly decomposed by the action of fungi [44] and it might not be suitable for all purposes. One of the ways to utilize this wood biomass may be local gasification units.

The aim of this study was, therefore, to assess the use of wood damaged by bark beetle in the form of spruce chips using gasification technologies in the Czech Republic. The article assessed the current feasibility of applying gasification technology for wood material in the Czech Republic in terms of economic feasibility in small-scale gasification units.

2. Materials and Methods

2.1. Study Location and Materials

In all current gasification units with an electric output of up to 200 kW_{el}, fuel in the form of wood chips or pellets is required [45]. For this reason, the fuel considered for the gasification units in this study were wood chips from bark-beetle-damaged spruce. To assess the suitability of this material for gasification units, the average quality parameters of bark-beetle-damaged spruce were determined. The determined qualitative parameters were then compared with the technical requirements of current gasification units up to 200 kW_{el}.

Samples of spruce in the form of 0.5 m logs were taken from the Pardubice region of the Czech Republic in 2020, where this material was harvested as bark-beetle-damaged wood. In 2019, a total of 0.62 million m^3 of this wood was harvested from this locality. Samples coming from the area were divided into 4 age categories: up-to-6-months-old, one-year-old, 18-months-old, and older. In each category, 6 wood log samples were obtained, i.e., 24 wood log samples in total.

2.2. Material Analysis

The fuel parameters determined were moisture, ash, the contents of the main elements, as well as gross and net calorific values. To assess the properties of raw materials for the gasification process, combustion calorimetry was the most useful method in monitoring the quality of bark-beetle-damaged wood for fuel purposes [46]. The initial moisture content in each log was found using 3 wood core samples dried at 105 °C until constant weight in a laboratory oven. For other analyses, separate batches were taken from each log, and analytical samples were produced using a Retsch SM100 laboratory cutting mill (Retsch GmBh, Haan, Germany). Further analyses were performed on these, and their results were converted to a dry basis and to the average original moisture content of the wood chips.

The moisture and ash content in the analytical samples were found using an automatic thermogravimetric furnace LECO TGA701 (LECO Corporation, St. Joseph, MI, USA) according to ISO 18134-3:2015 [47] and ISO 18122:2015 [48], respectively. They were dried at 105 °C until constant weight and then incinerated at 550 °C until constant weight. The contents of the main elements (C, H, N) were determined by combustion analysis at 950 °C in a LECO CHN628+S analyser (LECO Corporation, St. Joseph, MI, USA). Oxygen was determined as a difference from 100% in combustible matter and all values converted to dry state of the fuel according to ISO 16993:2016 [49]. The gross calorific value was found by combustion calorimetry in an isoperibol calorimeter LECO AC600 (LECO Corporation, St. Joseph, MI, USA) by combusting 1-g pellets. The conversions for the formation of sulphuric and nitric acid were not performed. The net calorific value was calculated according to ISO 1928:2020 [50]. For each sample, all analyses were performed in at least 3 repetitions. The values reported are averages across age categories and across all samples. Average values from all samples were used for subsequent calculations.

2.3. Acquisition of Data

The first step before deciding on investing in gasification technology is the calculation of input–output balances, which depend on multiple assumptions, e.g.,:

- Availability of input material at all times in an appropriate quality for the gasification unit.
- Sufficient utilization of heat (especially with regard to the financial return on investment).
- Smaller units can be used especially in places where an additional source of electricity is needed or as a backup source.
- For larger units, it is essential to ensure sustainable and continuous operation.
- Environmental benefits.
- Financial incentives.

To determine the capital costs of gasification units, producers, who had had demonstrated more than ten units sold were contacted. A total of ten major companies supplied information including unit costs. These companies were Burkhardt GmbH (Mühlhausen, Germany), CMD SPA (Atella, Italy), ESPE S.r.l. (Grantorto, Italy), Fröling (Grieskirchen, Austria), GLOCK ÖKOenergie GmbH (Griffen, Austria), Holzenergie Wegscheid GmbH (Sonnen, Germany), LiPRO Energy GmbH & Co. KG. (Wardenburg, Germany), RESET S.r.l. (Rieti, Italy), Spanner Re2 GmbH (Bayerbach, Germany), and Volter Oy (Tupos, Finland). In total, they offered 21 small-scale gasification unit models in a range of electric power from 10 kW_{el} to 200 kW_{el}.

The reported costs were related to the respective nominal electric and heat outputs of individual models. The costs of biomass cogeneration should correspond to the average costs reported by the International Renewable Energy Agency [51] for the “Gasifier—Cogeneration” technology. Their report states a range of costs for biomass gasification with cogeneration lying between EUR 5500 and EUR 6500 per installed 1 kW. For this study, the calculations were based on the costs reported by manufacturers. The initial cost for equipment with an electric output of up to 30 kW_{el} corresponded to EUR 5500 per installed 1 kW_{el}. The cost of equipment with an electric output between 30 kW_{el} and 200 kW_{el} corresponded to EUR 5000 per 1 kW_{el} installed. These costs represent the price for the gasification technology with cogeneration with no other equipment that is not directly part of the gasification process.

Operating costs were again based on average numbers reported by manufacturers. Spare parts and maintenance of the gasification equipment cost an average of 1.00 EUR h^{-1}.

Material consumption is one of the important parameters for the evaluation of gasification units. To calculate the approximate material consumption, Equation (1) was used, into which the required values P_{el} a η_{el} are inserted:

$$m_p = \frac{P_{el} \cdot 100}{q_n \cdot \eta_{el}} \quad (1)$$

where:

- m_p mass flow of fuel into the gasifier (kg s^{-1});
- P_{el} nominal electric power (W);
- q_n net calorific value of the fuel (J kg^{-1});
- η_{e1} electric efficiency of the gasifier (%).

2.4. Economic Analysis

The economic analyses assess the economic efficiency of investment of a new gasification unit with combined heat and power generation in three alternative variants.

The three considered alternatives would use a gasifier with an electric output of 10, 100, and 200 kW_{el}, respectively, in the operating mode of constant output. The produced electricity not used in the operation of the technology could be supplied to the grid at the market price of 62.31 EUR MWh^{-1} as of 7 April 2021 [52]. The produced heat would be used to dry the input material to the required moisture level of 10 wt.% and the rest without loss for sale to third parties for the price of natural gas at 0.06 EUR kWh^{-1} [53] for end customers in the Czech Republic. Natural gas was chosen as an alternative fuel because of its important role in heat supply.

The assessment of the viability of individual alternatives was performed by the evaluation of dynamic indexes, such as the net present value (NPV), the discounted payback period (DPP), the internal rate of return (IRR), and the profitability index (PI) [54,55]. The economic and financial analysis assessed investment and operating costs, financial resources, depreciation, project revenues for supplied heat, electricity, products, etc.

Economic analyses were performed for a period of 15 years, typical in the energy sector in the Czech Republic, with the first year of investment in 2021. Only costs defined as integral for electricity and heat production were included in the economic analyses: consumables, depreciation, personnel costs, services, and financial costs.

For consumables, fuel costs, technological water consumption, the cost of removing solid residue, and energy consumed were considered. The main component of variable costs were fuel costs. The price of wood chips in their original state, 0.013 EUR kWh^{-1}, was provided by the company, at which the study was conducted. The company based the price on the costs incurred by the company during processing and storing the material into a suitable form for drying and subsequent gasification. Other variable costs were water, technological materials, etc. Charges for CO_2, NO_X, and PM emissions were not considered since the 10 kW_{el} variant was below the legal liability limit. In the case of the 100 and 200 kW_{el} variants, only charges for NO_X and PM emissions could apply; however, these would depend on the emissions of each particular co-generation unit and would not be a significant cost item.

Depreciation was included in the project in the form of tax depreciation according to the legislation of the Czech Republic, i.e., in the form of a share in capital expenditures in each year. The residual value of the investment was zero at the end of the period, although the service life of the asset was expected to be longer. The investment costs of individual alternatives include only the costs of the assessed project alternative, i.e., they do not include land prices or costs incurred before the investment.

Personnel costs were calculated from the expected number of employees and the expected average monthly earnings, i.e., EUR 1154 for a full-time employee. The 10 and 100 kW_{el} alternatives were considered to need 0.5 of extra full-time employee time. The 200 kW_{el} alternative would need an extra full-time employee. Social, health insurance and other contributions were calculated according to valid legislation as a share of gross wages of employees (in the Czech Republic 34% and 5% of gross wages of employees).

The costs of repairs and maintenance of new technology were determined on the basis of data from the manufacturers. In the economic analysis, they were included in the cost of services. Financial expenses included property insurance costs, and interest rates on loans used to carry out the investment project (5% p.a.). Property insurance costs were determined as a share of the value of fixed assets (1% of the purchase price of the alternative).

The prices of fuels, energy, and other cost components were used in constant prices at the level of the first year of implementation. The constant prices for costs and revenues were used to avoid the effects of price volatility on the market with woodchips and power. The future state of the markets cannot be easily predicted, and using constant prices provided the ability to assess the feasibility of an investment without the noise in the data that nominal prices would provide. The revenues were considered to be sales of heat, electricity for own consumption, electricity supplied to the grid, and sale of products (dry wood chips). Revenues were calculated at constant prices excluding VAT and other indirect taxes. The income tax rate valid in the Czech Republic at the time of the study was used, which was −21%. The time value of money used was 2.5%, which is typical for the assessment of investment plans in the Czech energy sector.

3. Results and Discussion

3.1. Spruce Wood Properties and Gasifier Parameters

The average composition and calorific values of the spruce samples are listed in Table 1, including general requirements for small-scale gasification units. The amount of ash corresponded to other sources of fuel wood [22,23]. This was also due to the fact that bark-beetle-damaged wood tends to be almost free of bark, which is often a source of increased mineral pollution [56,57] and a source of problems during combustion [58,59]. The nitrogen content was low, which is typical for wood biomass [23]. The problem with nitrogen concentration can occur during combustion processes by the formation of prompt NO_x concentrations in flue gases [11,60].

Table 1. Composition and calorific values of spruce samples.

Sample/Moisture Level	Water Content (wt.%)	Ash (wt.%)	Carbon (wt.%)	Hydrogen (wt.%)	Nitrogen (wt.%)	Oxygen (wt.%)	Gross Calorific Value (MJ kg^{-1})	Net Calorific Value (MJ kg^{-1})
Recommended	<10							>17
Spruce o.s.	17.46 (±4.6)	0.26 (±3.22)	42.61 (±0.01)	4.97 (±0.07)	0.13 (±0.97)	34.57 (±0.15)	16.68 (±0.12)	15.17 (±0.12)
Spruce d.b.	0.00	0.32	51.63	6.02	0.16	41.88		18.37
Spruce W20	20.00	0.26	41.30	4.82	0.12	29.95		14.70
Spruce W30	30.00	0.22	36.14	4.21	0.11	25.11		12.86

Numbers in parenthesis express standard deviation, o.s.—original sample; d.b.—dry basis

Table 2 shows variability between different age groups of the wood logs. There were differences mainly in the water and ash content. The average moisture content was 17.46 wt.% for all categories. However, apart from some time after large calamities, very old wood would not be on the market. In logs that were less than one year after felling, the moisture content was close to 20 wt.% This is quite close to the results of Manzone [61] who reported a decrease in water content from 45–60 wt.% to 18 wt.% after 180 days of storage over the spring and summer in Italy in three deciduous tree species stored in uncovered piles and under roofs, albeit as split logs rather than roundwood. In a German study [62], fresh wood chips dried from 48.9 wt.% to 30.6 wt.% over one summer. Cremer et al. [63] reported that wood chips of Norway spruce (*Picea abies* L.) had a moisture content of 34.7 wt.% This relatively low moisture content was caused by several months of standing of dead trees before being felled and chipped. In general, dead wood can be expected to have lower water content than healthy trees [64]. Drying during storage is affected by storage organization as well as the environmental conditions [61,65]. In some areas, it is justified to partially cover the wood from the effects of weather on the final moisture in the wood, while in others it may be counterproductive [65]. It is also important to note that debarking of wood also contributes to the acceleration of drying [65], while bark-beetle-damaged wood often has only a residual bark or is completely without bark. Since the moisture of raw woodchip fuel is going to change depending on the location, storage organization, climatic conditions, etc. and 20 and 30 wt.% starting moisture contents were chosen for the economic evaluation, as these should be achievable after a six-month storage.

Table 2. Variability of spruce wood parameters between age categories.

	Initial State	**Dry State**	**Relative Difference from Dry State Average of All Samples**					
Age Category	**Water Content (wt.%)**	**Ash (wt.% d.b.)**	**Carbon (%)**	**Hydrogen (%)**	**Nitrogen (%)**	**Oxygen (%)**	**Gross Calorific Value (%)**	**Net Calorific Value (%)**
<6 months	19.0	0.31	−0.12	−0.29	+0.94	−0.22	−0.48	−0.49
RSD (%)	22.9	4.00	0.26	1.06	12.55	0.84	0.56	0.53
6–12 months	19.5	0.35	+0.13	+0.19	+5.07	−0.13	+0.18	+0.18
RSD (%)	11.9	13.66	0.59	0.60	4.57	0.83	0.93	0.98
12–18 months	16.8	0.33	+0.15	−0.02	−2.98	−0.06	+0.36	+0.39
RSD (%)	8.4	8.37	0.82	0.45	9.98	0.96	0.95	1.03
18–24 months	14.6	0.28	−0.17	+0.12	−3.03	+0.41	−0.07	−0.08
RSD (%)	17.4	5.26	0.28	0.43	24.32	0.32	0.41	0.44

Water content values are shown in absolute numbers in the initial state. Ash content shows absolute values in dry state. Other values show relative difference in percent compared to the average of all samples in dry state. RSD is the relative standard deviation of absolute values for each parameter.

There were some differences in ash content. These could be caused by a small degree of decay in some samples, different growth conditions, and, to some extent, by measurement error. However, these differences would have little to no effect on their suitability for gasification. Manzone [61] also found that the ash content did not change significantly regardless of the storage method. Finally, there were no significantly high differences in carbon content and calorific values, which suggests that there was no significant decomposition that would prevent the fuel from being used.

The technical and economic evaluation of gasification units for the conditions of the Czech Republic was based on data reported by manufacturers. The nominal parameters of all investigated gasification units are listed in Table 3.

Table 3. Technical and economic parameters of gasification units.

Company	Electric Power P_{el} (kW_{el})	Thermal Power P_{th} (kW_{th})	Investment Costs (EUR)	Operating Costs (EUR a^{-1})
1.	50	110	250,000	9593
	165	260	480,000	22,272
	180	270	550,000	23,926
2.	20	40	110,000	6286
3.	49	110	245,000	9483
4.	49	107	245,000	7586
5.	65	130	325,000	12,297
	133	250	665,000	20,493
6.	18	44	99,000	6470
	50	110	250,000	10,233
7.	30	70	165,000	7881
	50	110	250,000	10,233
8.	35	66	175,000	7940
	50	93	250,000	9593
	60	112	300,000	10,696
	100	187	500,000	15,106
9.	9	25	49,500	5749
	30	73	165,000	8373
	45	108.5	225,000	10,248
	68	123	340,000	13,121
10.	40	100	200,000	8830

Based on the nominal performance parameters, a correlation between electric and thermal outputs was performed (Figure 1). These were interpolated by regression Equation (2).

$$P_{th} = -0.0043P_{el}^2 + 2.2874P_{el} + 2.8595 \quad R^2 = 0.9833 \tag{2}$$

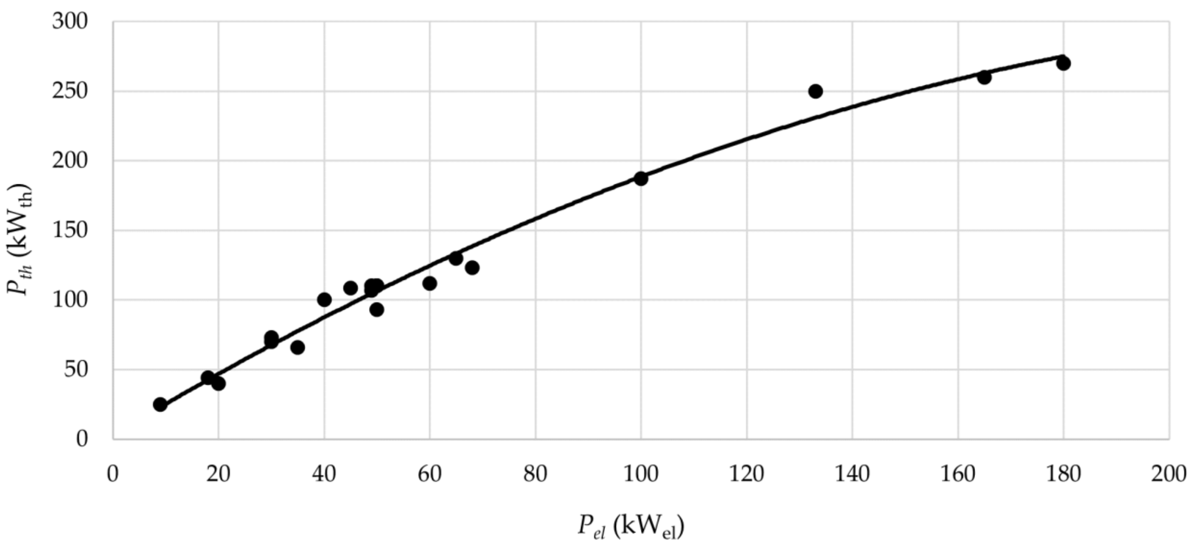

Figure 1. Dependence relation between electric and thermal output of small gasification units up to 200 kW_{el}.

The fuel consumption rates for the hypothetical variants were based on the nominal electric and thermal efficiencies supplied for the individual gasification units. A total of 21 units with an electric output from 10 to 200 kW_{el} were assessed. The values of electric (η_{el}) and thermal (η_{th}) efficiency were obtained as the arithmetic mean of the reported values by manufacturers. The stated electric efficiency of these units was around 30%, while the thermal efficiency was around 55% with an overall efficiency of 85%. The resulting wood chip consumption is calculated in Table 4.

Table 4. Wood chip consumption rates for chosen variants of electric power and input material moisture.

P_{el}	P_{th}	P_{total}	m_p (20 wt.%)	m_p (30 wt.%)
kW_{el}	kW_{th}	kW	kg h^{-1}	kg h^{-1}
10	25	35	8.16	9.33
100	189	289	81.65	93.31
200	625	825	163.29	186.63

The optimum fuel moisture for the gasification process itself is around 10 wt.% [8,13]. Therefore, in order for the raw material to be adjusted to the required moisture level, an increased amount of material must be fed into a drying unit to compensate for the energy consumed for drying. Therefore, using woodchips with excessive moisture content resulted in increasing the operational costs of the plant and decreasing its heat output, thus decreasing the revenues for heat and power generation. The graphical dependence of the fuel consumption rate on the electric output from cogeneration at 20 and 30 wt.% fuel moisture is shown in Figure 2. The difference in consumption of material of different moisture increased with the electric output of the unit.

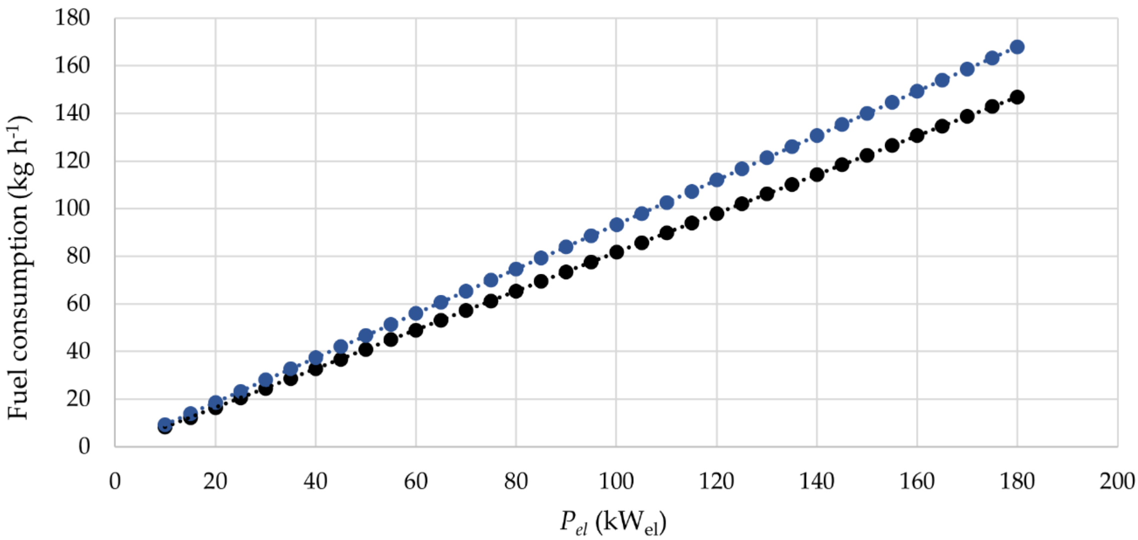

Figure 2. Dependence of material consumption on the electric output of a wood chip unit with a moisture content of 20% (black) and 30% (blue) by weight.

3.2. Economic Analysis

Capital costs for the gasification technology in individual alternatives, including costs for a container in which the units would be stored, and dryers for drying the input material from its original moisture to the fuel requirement are listed in Table 5. These expenditures were included in the operating costs via tax depreciation, which depends on the amount of capital expenditures and the classification of assets into depreciation groups, which depends on the expected useful life of the given cost element. Depreciation of the gasification units themselves did not increase linearly depending on the output, but for very small units with an output of up to 30 kW_{el}, based on market research, they were around 6000 EUR kW_{el}^{-1}, whereas, above this limit, they were at around 5000 EUR kW_{el}^{-1}. Our findings that units with smaller outputs are more capital intensive per kW_{el} installed corresponds with the findings of Cardoso et al. [36], who reported capital expenditures of 3390 EUR kW_{el}^{-1} for an 11-MW gasification unit in Portugal.

Decreasing capital expenditures related to increasing output based on the economy of scale for gasification units were reported also by Upadhyay et al. [37]. On the other hand, Colantoni et al. [55] considered even lower capital expenditures for the purchase of gasification technology similar to the mid-tier technology assessed in this study. They reported approximately 3000 EUR kW_{el}^{-1} capital expenses for a 100-kW_{el} gasification unit, albeit this was based on data from 2016.

Table 5. Investment costs for gasification technology in EUR.

	Years of Amortization	Variant 10 kW_{el}	100 kW_{el}	200 kW_{el}
Gasification unit	10	60,000	500,000	1,000,000
Container	6	3846	3846	3846
Drying unit	10	9615	57,692	115,385
Total		73,400	73,461	561,538

In addition to capital expenditures and the resulting depreciation, fuel costs were an important part of costs (Table 6). Fuel costs depend on the price of wood chips as well as their moisture, which affects the consumption. The lower fuel costs for fuel with higher moisture were caused by the lower energy content in the fuel, i.e., wood chips with higher moisture had a lower unit price per unit weight. This effect was partially counterbalanced by the increased consumption of the higher-moisture wood chips. The price of the fuel is essential for the viability of small gasification units. These are typically devices with a fixed bed and are dependent on high-quality fuel. This is in contrast to gasifiers with a fluidised bed, which can deal with a wide variety of waste organic materials [7]. Personnel costs also play a significant role, including statutory social and health benefits, which grew between the 100- and 200-kW_{el} variants. A gasifier with an output of 200 kW_{el} would need a full-time operator. Also important were the costs of services, which included maintenance and anticipated repairs of the gasification units. According to the market research, these would be dependent on the rated electric output (Table 3).

Table 6. Operating costs of individual variants of electric output and wood chip moisture in EUR.

	10 kW_{el}		100 kW_{el}		200 kW_{el}	
	20 wt.%	30 wt.%	20 wt.%	30 wt.%	20 wt.%	30 wt.%
Fuel costs	3074	2690	30,725	26,884	61,449	53,769
Water consumption	5	5	38	38	77	77
Ash disposal	29	25	290	250	580	500
Service costs	5750	5750	10,000	10,000	15,000	15,000
Personnel costs	6923	6923	6923	6923	13,846	13,846
Social and health security	2354	2354	2354	2354	4708	4708
Social funds	346	346	346	346	692	692
Amortization	4925	4925	35,135	35,135	69,846	69,846
Interest	3673	3673	28,077	28,077	55,962	55,962
Insurance	735	385	5615	3846	11,192	3846
Total costs	27,814	27,076	119,501	113,855	233,348	218,249

The nominal electric output and quality of the supplied fuel influenced not only the costs but also the revenues from heat and electricity in all alternatives, as listed in Table 7. In the model variants, utilizing the entire amount of heat produced was considered in a local heat distribution system. The heat distribution system, however, was not included in the project cash flow. All the electricity produced would be sold at market prices on the commodity exchange. As can be seen, the higher moisture fuel reduced both the heat supply and the electricity supply to the grid. About a 15% revenue decrease was caused by a 10% increase in fuel humidity in the 10 kW_{el} alternative, composed of a 22%

drop in revenues for heat distribution and a slight 2% decrease in revenues for electricity generation. In contrast, in the 200 kW_{el} alternative, a 10% increase in fuel moisture caused a 10% drop in heat sales, while electricity sales decreased by less than 1% (less than 8% on average).

Table 7. Revenue items from heat and electricity in individual variants.

Revenue Item	Unit	10 kW_{el} 20 wt.%	10 kW_{el} 30 wt.%	100 kW_{el} 20 wt.%	100 kW_{el} 30 wt.%	200 kW_{el} 20 wt.%	200 kW_{el} 30 wt.%
Heat	kWh	153,200	119,771	1,137,808	870,000	4,376,340	3,930,000
Heat price	EUR kWh^{-1}	0.0614	0.0614	0.0614	0.0614	0.0614	0.0614
Electricity to the grid	kWh	78,830	77,994	790,645	783,950	1,584,409	1,573,250
Electricity price	EUR kWh^{-1}	0.0623	0.0623	0.0623	0.0623	0.0623	0.0623
Revenues from heat	EUR	9410	7357	69,888	53,438	268,808	241,393
Revenues from electricity	EUR	4912	4860	49,265	48,848	98,724	98,029
Total revenues	EUR	14,322	12,217	119,153	102,309	367,533	339,469

The increase in costs and decrease in sales had an effect on the cash flow of individual alternatives, which is shown in Table 8. From the table it can be seen that smaller alternatives, with 10 and 100 kW_{el} power were not viable under the given conditions and produced losses. Assuming selling all heat and electricity on the market, only the 200-kW_{el} alternative was viable, which in the first year of operation produced an operating profit and a positive cash flow, both gross and net, at both fuel moistures. Therefore, the only meaningful variant to consider the return on investment was the 200-kW_{el} alternative, for which the payback period with fuel at 20 wt.% moisture was calculated between 10 and 11 years (Figure 3). Cardoso et al. [36] reported a longer payback period of more than 23 years for their gasification power plant, though one needs to consider the fact that the plant assessed had an installed electric output of 11 MW_{el} and that they used a higher discount rate (8.18%). The evaluation of individual alternatives using dynamic methods also showed that only the alternatives with 200-kW_{el} power output with both fuel moistures were able to produce a positive net present value (Table 9). Souza et al. [54] and Cardoso et al. [36] showed economic viability for larger units above 1 MW_{el} assuming co-generation from forest residual biomass when replacing natural gas. The economic feasibility of 50 MW_{el} units was studied by Upadhyay et al. (2012) [37], who found the total cost per unit of electricity produced was significantly reduced when the capacity of the unit increased thanks to economies of scale.

Table 8. Cash flow items of individual variants in the first year of operation in EUR.

Cash Flow Item	10 kW_{el} 20 wt.%	10 kW_{el} 30 wt.%	100 kW_{el} 20 wt.%	100 kW_{el} 30 wt.%	200 kW_{el} 20 wt.%	200 kW_{el} 30 wt.%
Revenues	14,322	12,217	119,153	102,309	367,533	339,469
Costs	−19,215	−18,478	−56,289	−50,644	−107,540	−92,442
EBITDA	−4894	−6261	62,863	51,666	259,993	247,027
Amortization	−4925	−4925	−35,135	−35,135	−69,846	−69,846
EBIT	−9819	−11,186	27,729	16,531	190,147	177,181
Interest	−3673	−3673	−28,077	−28,077	−55,962	−55,962
EBT	−13,492	−14,859	−348	−11,546	134,185	121,220
Income tax	0	0	0	0	−25,495	−23,032
Net profit	−13,492	−14,859	−348	−11,546	108,690	98,188
Amortization	4925	4925	35,135	35,135	69,846	69,846
Cash flow	−8567	−9934	34,786	23,589	178,536	168,034
Credit installment	−4897	−4897	−37,436	−37,436	−74,615	−74,615
Net cash flow	−13,464	−14,832	−2649	−13,847	103,921	93,419

EBITDA—earnings before interest, taxes, depreciation, and amortization; EBIT—earnings before interest and taxes; EBT—earnings before taxes.

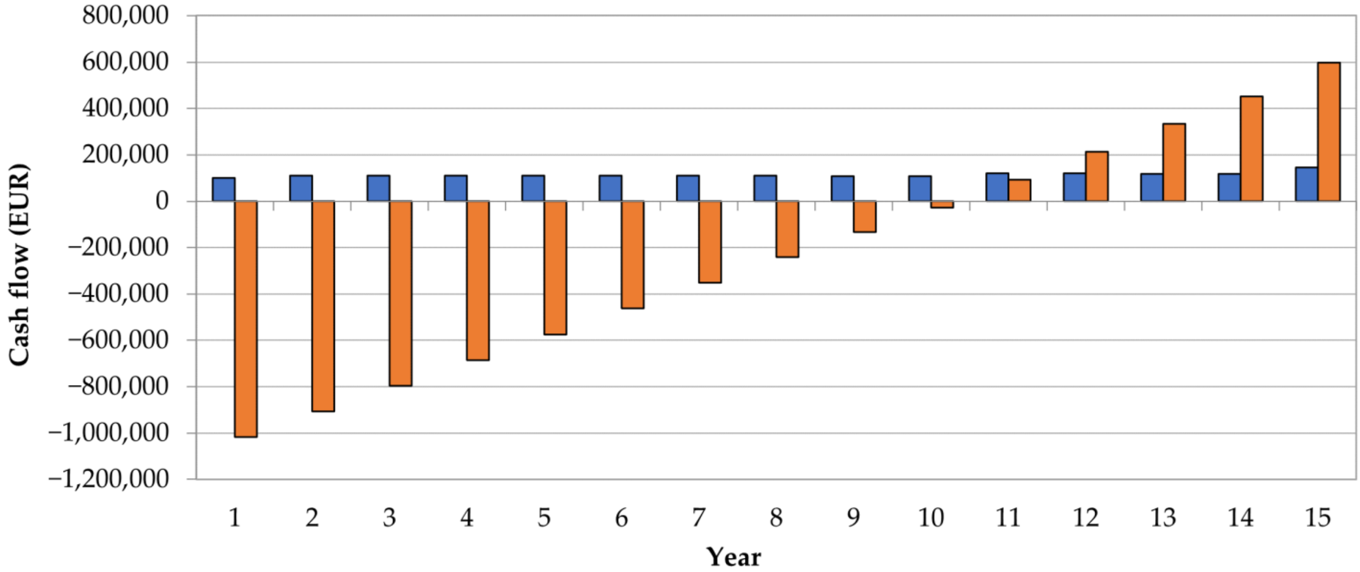

Figure 3. Discounted cash flow (blue) and cumulative discounted cash flow (orange) in 15 years after investment in the 200-kW$_{el}$ variant.

Table 9. Dynamic investment indexes.

		10 kW$_{el}$		100 kW$_{el}$		200 kW$_{el}$	
		20 wt.%	**30 wt.%**	**20 wt.%**	**30 wt.%**	**20 wt.%**	**30 wt.%**
Net present value	EUR	−216,786	−233,718	−455,044	−585,967	596,866	466,832
Profitability index	INX	−1.95	−2.18	0.19	−0.04	1.53	1.42
Internal rate of return	%	0.00	0.00	0.00	0.00	7.68	6.85

According to the profitability index, in the projected period of 15 years, at a fuel moisture of 20%, the investor will see approximately EUR 1.53 for each Euro invested. With 30 wt.% moisture, it would be EUR 0.11 less. The internal rate of return showed that the 20 wt.% moisture alternatives could withstand a higher rate of loss of money value than the 30 wt.% moisture (Table 9). The internal rate of return was positive and was above the discount rate only for the 200 kW$_{el}$ alternative. Compared to Cardoso et al. [36], these figures were considerably lower. However, the gasification units observed by these authors had considerably greater outputs. Colantoni et al. [55], on the other hand, considered similar units in terms of output and found an even greater profitability, which was caused by both the electricity and the heat price being approximately 33% higher in their case.

An increased economic attractiveness has generally been shown also in the case where there was the option of selling heat and receiving subsidies for renewable energy sources [38,55]. Colantoni et al. [55] showed that the likelihood of economic feasibility for small gasifiers is dependent on the use of credits for renewable energy, i.e., a 66% chance of positive NPV for a 13.6-kW$_{el}$ unit and a 90% chance of positive NPV for a 136-kW$_{el}$ unit.

4. Conclusions

As the results suggest, bark-beetle-damaged wood from salvage logging is a suitable raw material that meets the quality requirements for small gasifiers. The economic analysis then showed, for gasification technologies up to 200 kW$_{el,}$ that this material with a moisture content of up to 30 wt.% might be able to produce profit and a positive net present value.

In the current economic situation, small gasifiers with no more than 100 kW$_{el}$ of output cannot compete with current energy sources in the Czech Republic. A greater possibility of employing these technologies is in countries where the price of energy is much higher and where there are more effective support schemes for RES. This work showed the conditions under which it is viable to operate small gasifiers in the Czech Republic. The analysis was based on several initial assumptions, such as the dependence of investment price and operating costs on power output obtained from manufacturers, average wages, expected electric and thermal efficiency of the equipment, unchanging prices of commodities, etc. The economic analysis assessed the economic efficiency of invested funds into a new gasifier with combined heat and power generation, where units of 10 and 100 kW_{el} produce losses under current conditions. On the other hand, a unit with an electric output of 200 kW_{el} would be able to produce an operating profit under unchanging conditions.

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