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Techno-Economic and Environmental Assessment of Power Supply Chain by Using Waste Biomass Gasification in Iceland

Sahar Safarian[1] · Runar Unnthorsson[1] · Christiaan Richter[1]

Abstract

In this paper, technical, economic and environmental assessments are carried out for power supply chain by using timber and wood waste (T&WW) gasification in Iceland. The Icelandic municipalities were clustered into 35 subgroups based on various number of households/ inhabitants. Different expenses were taken into consideration, like capital, installation engineering, operation and maintenance costs and the interest rate of the investment. Regarding revenues, they come from the electricity sale and the fee paid by the Icelandic municipalities for waste collection and disposal. The economic feasibility was conducted based on the economic indicators of net present value (NPV) and discounted payback period (DPP), bringing together three different scenarios, with interest rates of 8% for Scenario 1, 10% for Scenario 2 and 13% for Scenario 3. The environmental analysis was also performed relied on the environmental impacts of global warming (GWP), acidification (AP) and eutrophication (EP) potentials. The results show that changing the interest rate does not have significant impact on NPV and DPP for all studied scenarios. NPV is positive for the municipalities with more than 150 inhabitants or for a gasification plant with the capability to generate greater than 45 kW. Moreover, electricity generation based on T&WW gasification would lead to a GWP of 13 $tonCO_{2eq}$ (Subgroup 1) to 469 $tonCO_{2eq}$ (Subgroup 35), AP of 173.6 $tonSO_{2eq}$ (Subgroup 1) to 6187.2 $tonSO_{2eq}$ (Subgroup 35) and EP potential of 331.9 $tonNO_{3eq}$ (Subgroup 1) to 11,827.7 $tonNO_{3eq}$ (Subgroup 35), yearly.

Keywords Waste biomass gasification · Techno-economic analysis · Environmental assessment · Power supply chain · Waste to energy

Introduction

Waste is a major problem that causes not only serious economic losses, but also significant environmental impacts. Better living standards, tourist streams and economic growth accelerate the waste generation in Iceland. Improper management of wastes has led to increased public concerns about health and environmental impacts. The total amount of municipal solid waste (MSW) in Iceland in 2010 has been estimated to 76 ± 6 thousand ton, based on data available from Sorpa, the waste management company in the Capital area. In other words, the annual amount of MSW per capita has been estimated to 222–257 kg (Sundberg et al. 2010). The amount of MSW produced in 2030 is estimated

to approximately 100 ± 7 thousand ton. Generally 60% of this amount is organic material which 43, 41 and 16% of that are paper mixed, timber and wood and garden wastes, respectively (Safarian et al. 2020b; Sundberg et al. 2010).

Landfilling and incineration have been the only methods of disposal of solid wastes in Iceland, while most landfill sites have been open dumping areas, which pose serious environmental and social threats. An incinerator in Skutulsfjörður caused carcinogenic and toxic chemicals to be found in meat and milk (Halldorsson et al. 2010). Soil and incinerator-emissions measurements at several sites, including Kirkjubaejarklaustur, reveal emissions 85 times above the EU limit (Niðurstöður úr mælingum á díoxí, í jarðvegi 2011). These problems resulted in the shuttering of several incinerators and the withdrawal of Icelandic meat and milk products (Halldorsson et al. 2010; Safarian and Unnthorsson 2018).

All these problems demonstrated the need to find more responsible alternatives than conventional incineration and landfilling (Mohapatra 2013; Omari et al. 2014). The method

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must be environmentally friendly, low cost and energy efficient and must reduce land use and emissions. These advantages are all found in modern gasification technology. Gasification is an attractive alternative that has recently gained considerable attention, as it disposes of solid waste without landfilling or incineration problems (Brunner et al. 2004; Porteous 2005).

Unlike the relatively uncontrolled combustion occurring in incineration, gasification is a partial oxidation at elevated temperature (600–1700 °C) that converts organic components to a Synthesis Gas (syngas), consisting mainly of CO, H_2, small amount of CH_4, minor quantities of different hydrocarbons (tars), inorganic impurities (H_2S, HCl, NH_3, HCN, HF, alkalis) and particulates (Ofori-Boateng et al. 2013; Safarian et al. 2019d; Samadi et al. 2019). Air, O2, steam, CO_2 or a mixture of all these can be used as an agent in the gasifier. Air gasification produces a syngas with small lower heating value (LHV) among 4–6 MJ/Nm^3, while oxygen gasification produces a syngas with a medium LHV in the range of 10–20 MJ/Nm^3 (Leckner 2015).

Beneficially, MSW gasification can be applied for small/medium scales that leads to dramatic reduction of some pollutants emission as furans, dioxins, and NOx and the possibility of the utilization of the syngas in high efficiency thermal devices like internal combustion engine and gas turbines (Luz et al. 2015). Hence, waste gasification can be installed as a reliable energy supply technology for places which are far from the central energy networks and require district heat and power systems (Safarian et al. 2019a, 2019c, 2020c).

In this paper, we will explore the potential of timber and wood waste (T&WW) gasification for energy production in small communities in Iceland (T&WW is the most existing biomass feedstock in this country). In this way, a comprehensive techno-economic and environmental assessment of T&WW gasification facilities integrated with electricity generation unit will be directed to propose a sustainable waste to power system adapted with conditions in Iceland.

Material and methods

Case study description

Iceland is one of the biggest islands in Europe, 103,000 m^2 in area. The population of Iceland is only about 300,000 (2.9 per m^2). Iceland is therefore one of the most sparsely populated countries in the world. The entire country is divided into regional municipalities that have self-determination and responsibility regarding their own affairs. More than 60% of the population lives in the capital city area. There are 72 municipalities in Iceland that their population varies from 43 inhabitants in the smallest ones, to more than 126,000 in the biggest. About 55% of Icelandic municipalities have lower

than 1000 residents and 70% of them occupies lower than 2000 populations. In these kinds of regions where wide grid is not feasible, small-scale gasification integrated with power generation offers a viable option for meeting the electricity needs of the local population (Safarian and Unnthorsson 2018).

In order to have a wide evaluation of the economic feasibility of the installation of gasification facilities for all disparate Icelandic zones, we established 35 subgroups based on various number of households/inhabitants (Table 1). In each subgroup, the study was conducted over hypothetical cases, according to the number of households as each household includes 5 persons.

Organic waste produced from industries, household and services sectors is a valuable source for biofuels production in Iceland. In this way, the Icelandic Environment Agency sets up a national plan to decrease the amount of organic wastes which are landfilled or incinerated for years. The main categories of organic waste that can be used as input feedstock into gasifier are timber and wood waste, garden waste, and paper mixed waste. Safarian et al. (2019a, b, c, d) (Safarian et al. 2019c) showed that among the different gasification systems based on various wastes in Iceland, timber and wood waste is the most beneficial from the performance and availability perspectives.

Timber waste is generally defined as unpainted and painted timber and is produced from construction/demolition work, packaging waste and pallets. The total amount of timber waste in Iceland in 2010 has been estimated to

Table 1 The considered subgroups with the number of household and population

Subgroups	Household	Persons	Subgroups	Household	Persons
1	10	50	19	190	950
2	20	100	20	200	1000
3	30	150	21	210	1050
4	40	200	22	220	1100
5	50	250	23	230	1150
6	60	300	24	240	1200
7	70	350	25	250	1250
8	80	400	26	260	1300
9	90	450	27	270	1350
10	100	500	28	280	1400
11	110	550	29	290	1450
12	120	600	30	300	1500
13	130	650	31	310	1550
14	140	700	32	320	1600
15	150	750	33	330	1650
16	160	800	34	340	1700
17	170	850	35	350	1750
18	180	900			

around 37 ± 11 thousand ton and it has been projected to reach approximately 49 ± 15 thousand ton in 2030. Wood waste is also available from forestry, and it has been estimated to nearly 8260 ton/year. Totally, timber and wood waste mainly consist of softwood, with a composition of 45% cellulose, 22% hemicellulose and 28% lignin as well as extractives, acids, salts and minerals. Hence, all produced T&WW can be considered as potential for syngas production (Sundberg et al. 2010).

Process Description

The studied system in this paper includes all the process steps from resources to the end product (Fig. 1).

Timber and wood waste is the significant resource entering to the system, and liquid fuel and electricity are also the accessory inputs. The proximate and elemental analyses of T&WW are shown in Table 2.

Diesel fuel is used in trucks for transportation, and electricity is applied for driving force and heat generation over the process. The electricity production in Iceland is derived from geothermal and hydropower that makes Iceland's main source of clean energy. T&WW is transferred from the waste fields to pretreatment part that is next to gasification and electricity generation unit. The gasification process consists of drying, pyrolysis, combustion and gasification (Safarianbana et al. 2019). Drying occurs at a temperature 100–150 °C. Typically, the moisture in biomass is among 5–35% that it is reduced to lower 5% during drying. Pyrolysis occurs in the range of 200–700 °C; in this step, biomass is heated in the absence of oxygen then its volatile components are vaporized. The volatile vapour consists mainly of H_2, CO, CO_2, CH_4, hydrocarbon gases, tar and steam. Finally, combustion turns up in 700–1500 °C and gasification occurs between 800 and 1100 °C. In this work, the down draft reactors are considered that operate at atmospheric pressure, to gasify T&WW and air is used as the gasification agent, resulting in CO_2 and H_2O, which subsequently undergo reduction upon contact with the char produced from pyrolysis. Reduction yields combustible gases as H_2, CO, and CH_4 through a series of reactions (Safarian et al. 2019d). Then the produced syngas enters in internal combustion engine that is modelled as a combustion chamber followed by a gas turbine. The combination of these two modules represents the behaviour of a combustion engine where the reaction with air occurs (Safarian and Bararzadeh 2012; Safarian et al. 2013). The input values and key assumptions are shown in Table 3, we also used from our waste biomass gasification simulation model developed by ASPEN Plus (Safarian et al. 2020a) to have the main values of the downdraft gasifier characteristics, operational parameters and the flue gas composition which are listed in Table 3.

Techno-Economic Assessment

All prices are expressed in K€ (kilo-euro). In the economic assessment, three scenarios are considered based on different interest rates: 8% in Scenario 1, 10% in Scenario 2 and 13% in Scenario 3. A computer program has been developed to investigate these scenarios for all subgroups shown in Table 1. The model is able to evaluate the economic performance of each one. Cash flow analysis, total cost, Net Present Value (NPV) and Discounted Payback Period (DPP) are standardized financial indicators to assess the profitability of projects. A project is an economically attractive while it has the lowest DPP and the NPV higher than zero. NPV
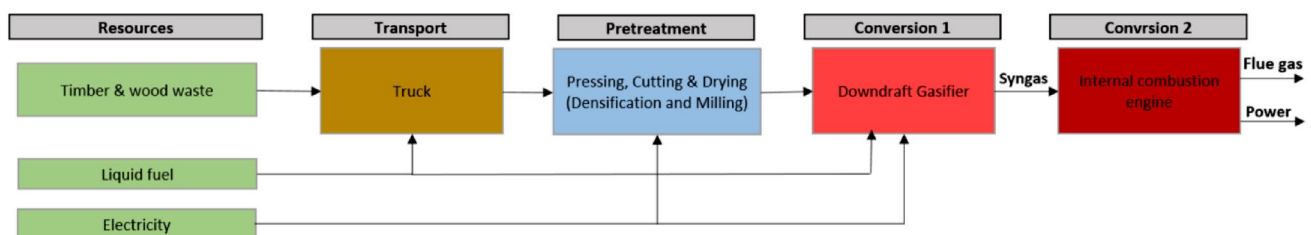
Table 2 Ultimate and proximate analyses of timber and wood waste (Freeman et al.)

Parameters	Value (%)
Proximate analysis (wt%)	
Moisture	5.01
Volatile matter (VM)	93.06
Fixed carbon (FC)	6.38
Ash	0.56
Ultimate analysis (wt%—dry basis)	
C	56.8
H	7.28
N	0.18
Cl	0.82
S	0.07
O	34.29

Fig. 1 System boundaries, technologies, energy and material streams

Table 3 Input values, assumptions, gasifier characteristics, operational parameters and flue gas composition

Step	Unit	Amount	Comment
Transport			
Distance	km	100	Distance from fields to energy conversion plants
Diesel fuel	L/km. $ton_{T\&WW}$	0.06	
Preparation			
Electricity for pressing & cutting	kWh/ $ton_{T\&WW}$	5.48	
Conversion 1			
Type of gasifier			Downdraft fixed bed (autothermal)
Gasification agent			air
Gasification pressure	kPa	101.3	
Gasification temperature	˚C	800	
Equivalence Ratio (ER)	–	0.25	
Specific air mass flow rate consumption	$kg/kg_{T\&WW}$	108	
Unit Fuel oil consumption	L/ $ton_{T\&WW}$	0.2	It is for start-up of the gasifier. $ton_{T\&WW}$ refers to amount of T&WW that enters to gasifier after pre-process step
Unit Electricity consumption	$kWh/ton_{T\&WW}$	83	$ton_{T\&WW}$ refers to amount of T&WW that enters to gasifier after pre-process step
Conversion 2			
Isentropic efficiency of compressor	%	90	
Mechanical efficiency of compressor	%	99	
Net produced power	kWh/yr	2820.8 MT&WW (kg/hr) + 2293.3	as functional of mass flow rate of biomass
Specific mass flow rate of flue gas exited from gas turbine	$kg/kg_{T\&WW}$		
CO		0.226	
CO2		1.62	
H2		0.00247	
H2O		0.645	
CH4		0	
N2		5.316	
O2		0.082	
S		0	
SO2		0.0013	
H2S		0	
NH3		0	
NO		0.049	
N2O		0	
CL2		0	
HCL		0	
NO2		0.000037	
H2SO4		0	
NO3		0	

is the difference between the present value of cash inflows and the present value of cash outflows over a period of time and it is calculated based on Eq. (1) (Safarian et al. 2014):

$$NPV = \sum_{n=1}^{t} \frac{CF_n}{(1+r)^n} - C_c \qquad (1)$$

where CF_n is the annual cash flow, being the difference between Revenues (R) and Expenditures (E); Operation and Maintenance Costs ($C_{O\&M}$),r is the discount rate (8%, 10% and 13% for Scenarios 1, 2 and 3, respectively); C_c is the total capital costs of investment and is the lifetime of the investment (15 years). DPP gives the number of years to break even from undertaking the initial expenditure, by

discounting future cash flows and recognizing the time value of money and it is calculated according to Eq. (2):

$$DPP = \frac{LN(\frac{1}{1-\frac{C_c \times r}{CF}})}{LN(1+r)}. \qquad (2)$$

The periodic cash flow, with all the revenues and expenditures, is calculated by considering the incomes from the generated electricity, and the credits for the Waste Treatment Bill (WTB) (Luz et al. 2015). The expenditures also include the $_{Cc}$ and $C_{O\&M}$. C_c is divided into three categories: hardware price ($_{Cg}$), installation cost (25% of C_g) and engineering costs, the engineering costs includes engineering and design (13% of C_g), purchasing & construction (14% of C_g), fuel handling/preparation (9% of C_g) and electrical/balance of plant (6% of C_g) (Porcu et al. 2019; Sara et al. 2016). C_g is the overall price of gasifier system on the basis of various capacities. In this work, we considered 0.75, 1.5, 2, 5, 10, 20, 50, 100, 200, 300, 400 and 500 kW for the small-scale existing gasifiers capacities and extracted their prices from various companies (Fig. 2) (Chongqing Fengyu Electric Co. 2019; GreenVinci Biomass Energy Co. 2019; Labs 2019; Qingdao Kexin New Energy Technology.Co. 2019; Shandong Rotex Machinery. 2019; Tiger Machinery Group Co. 2019).

The whole yearly $C_{O\&M}$ can be determined by the sum of the costs for the maintenance cost (2% of $_{Cc}$), insurance and tax (2% of $_{Cc}$), waste disposal (15% of $_{Cc}$), electricity cost, liquid fuel cost and personnel cost. Electricity costs are calculated based on electricity consumers and liquid fuel costs are estimated for fuel consumers with 7000 h/year of plant availability (Porcu et al. 2019; Sara et al. 2016). The unitary cost of electrical and fuel energies supplied in Iceland are equal to 0.03 \$/kWh and 1.08 \$/lit (0.91 €/\$ as conversion rate) (Safarian and Unnthorsson 2018). Personnel cost includes annual labour, cost. A total of two employees wer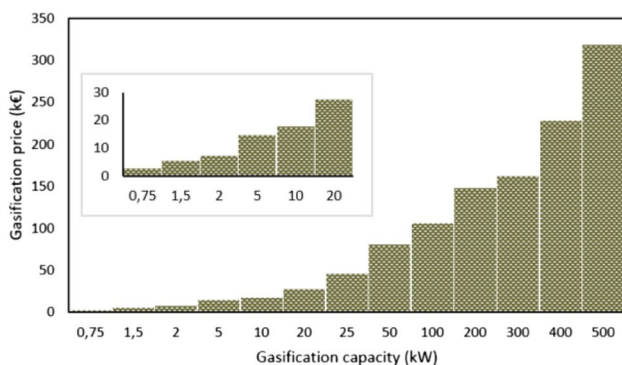e assumed for plant operation management (1 person/ shift and 2 shifts/day), with a yearly cost of 60,000 €/year per person in Iceland.

In relation to revenues, the selling price of electricity to normal households and small businesses in Iceland is about 124.69 \$/MWh (Orkusetur 2019). Hence, the sale price of the generated electricity based on waste gasification was considered at 109.89 \$/MWh (100 €/MWh) in our work. Moreover, The Icelandic municipalities pay a fee (WTB) by weight, to the private companies, for the collection and disposal the MSW in sanitary landfills. The WTB for collection and disposal of the MSW varies from 90–170 €/ton through over Iceland. The highest amout is related to Vestmannaeyjar, an archipelago off Iceland's south coast with 111 km distance from Reykjavik (the Capital of Iceland). All produced waste in Vestmannaeyjar need to be collected and transferred to other Icelandic municipalities for disposal. Hence, WTB for this area is in the top due to geographical conditions and expensive transportation. In this work, a mean value of 130 €/ton is used.

Environmental Assessment

Assessment of the environmental impacts of projects involves evaluating and providing information on the probable effects of specific undertakings on the environment. The environmental indicators studied in this work are global warming (GWP), acidification (AP) and eutrophication (EP) potentials. GWP concentrates on greenhouse gas emissions (GHG) including CO_2, CH_4 and NO_2 that trap heat through emitting radiation in the atmosphere (Safarian et al. 2018, 2019b). Acidification is also an environmental problem caused by acidified streams and soil due to anthropogenic air pollutants of SO_2, NH_3, H_2SO_4, H_2S, HCL, SO_3 and NO_x. The main substances with eutrophication impacts are also NO_x, NH_3, N_2, and NO_3 in the case of air. The environmental assessment methods applied in this paper are based on IPCC 2007 and other research works in this field (Nguyen et al. 2013; Paengjuntuek et al. 2015). The GWP, AP and EP factors for key input to the system are summarized in Table 4 (Nguyen et al. 2013; Safarian and Unnthorsson 2018).

Results and Discussion

Technical Performance

The calculations performed in this paper show that it is beneficial technically and energetically to produce electrical power from the waste biomass downdraft gasification integrated with power generation. Whether this technology can be successfully applied for the purpose of electricity distribution in small municipalities geographically isolated depends on economic and environmental considerations.

Fig. 2 Gasifier prices for different capacities

Table 4 GWP, AP and EP factors for different inputs (Nguyen et al. 2013; Safarian and Unnthorsson 2018)

Input	Unit	GWP factor (kgCO$_{2eq}$/unit)	AP factor (gSO$_{2eq}$/unit)	EP factor (gNO$_{3eq}$/unit)
Electricity generated by geothermal	kWh	0.058	1.95	2.8
Transport by truck	ton.km	0.3	2.1	4.2
Liquid fuel used in gasifier	lit	2.76	10.5	21
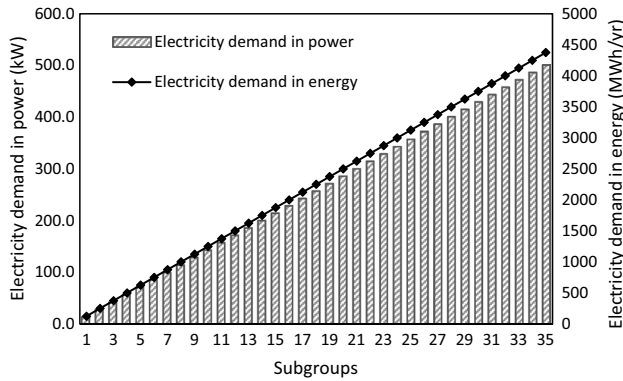
Fig. 3 Electrical energy and power demand for each subgroup

Fig. 4 Input T&WW and installed power for subgroups

The yearly electricity consumption per capita in the household sector in Iceland is around 2.5 MWh per capita. Based on these data, Iceland occupies the fourth place in electricity consumption in the world (Norway, Sweden and Finland have the first, second and third statues, respectively) (explained 2019). By using these data, the yearly electricity consumption and power demand for each subgroup are calculated and shown in Fig. 3. Obviously, as the population grows, energy demand also increases. Power demand varies form 14.3 kW for the first subgroup with 50 persons (10 households) to 499,4 kW for the last one with 1750 persons (350 households).

By considering the demanded power for each subgroup and existing gasifiers capacities (Sect. 2.3), the required gasifiers capacities which need to be installed for each case have been extracted and depicted in Fig. 4. As a constraint, more than two gasifiers have not been taking in account for each subgroup. For example, one gasifier with 20 kW capacity has been selected to satisfy 14.3 kW as the requested power for the first subgroup. However, for the second subgroup, two gasifiers with 5 and 25 kW need to be installed to supply 28.5 kW demanded. Analysing the subgroups 9 and 10 shows that, it is possible that both have the same installed power (150 kW), equally two gasifiers with 100 and 50 kW were considered for both with the requested power of 128,4 and 142,7 kW, respectively. The same happens for the cases of 6 and 7 (100 kW), 11 to 14 (200 kW), 16 and 17 (250 kW), 18 to 21 (300 kW), 22 to 24 (350 kW), 25 to 28 (400 kW), 29 to 31 (450 kW) and 32 to 35 (500 kW).
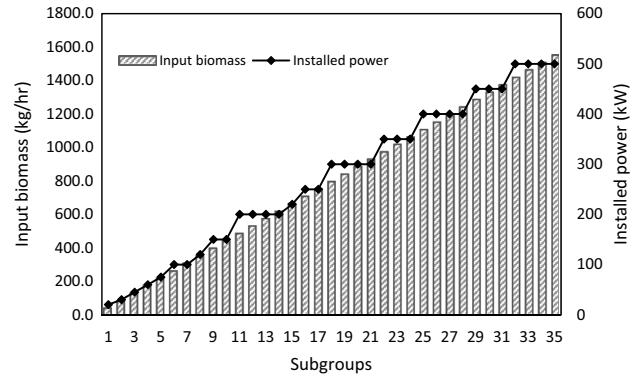
Figure 4 also shows the relation between the installed power and the amount of T&WW that is fed to the system for treatment and power production. Clearly, the installed power does not increase in the same proportion as that of the input waste, due to different capacities used for each system. For some cases, the installed gasification capacities are oversized, so the required investments of the capital costs and O&M costs need to be considered depending on the size of the components.

Economic Assessment

Costs and Revenues

The total cost of the generation plant for each population subgroup for the basic scenario (scenario 1) is shown together with the corresponding installed power in Fig. 5. The total cost varies from about 1100 k€ (Subgroup 1) to more than 2000 k€ (Subgroup 35). The total cost increases as the installed power grows, this trend is kept till up 5, but subgroups 6 and 7 present relatively lower cost in comparison to the former subgroup. It can be explained that the requested power of these subgroups (100 kW) are met only by using one gasifier. This is also similar for the subgroups of 11–14 (200 kW), 18–21 (300 kW), 25–28 (400 kW) and 32–35 (500 kW).

Percentage shares depicted in Fig. 6 are contributions of hardware, installation, engineering and annual O&M costs in total cost for basic scenario. The yearly O&M costs occupy
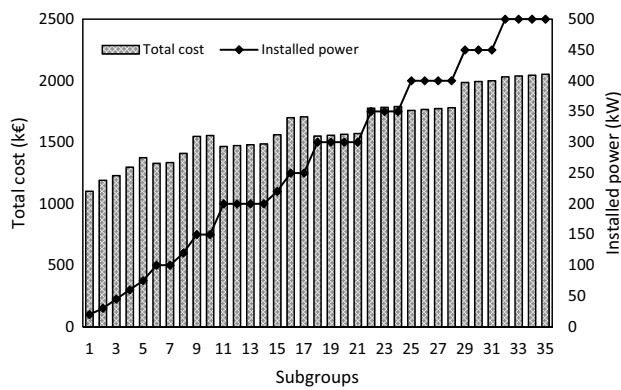
Fig. 5 Total costs on the basis of the installed power for scenario 1

Fig. 7 Specific cost of T&WW gasification per input waste and per capita

more than 70% of total cost for the first subgroup, it has also the dominant statue among different kinds of costs for subgroups 1–8. However, the highest share is related to gasification system price for subgroups 9–35.

Figure 7 presents the specific cost for the implantation of new facilities for power production by using T&WW gasification, per ton of waste treated. It has been pointed out that the specific cost per ton of T&WW is inversely proportional to the installed capacity, at higher installed capacity lower the specific costs. Figure 7 also shows the specific costs per capita, indicating that for lower population, higher cost per inhabitant is required.

If decision makers want to implement the gasification technology in Icelandic cities, a viable solution for the subgroups 1–5 to reduce the specific costs could be to make connection between neighbour municipalities by making commons investments for bigger gasification facilities, where the T&WW of two or three municipalities could be gasified together.
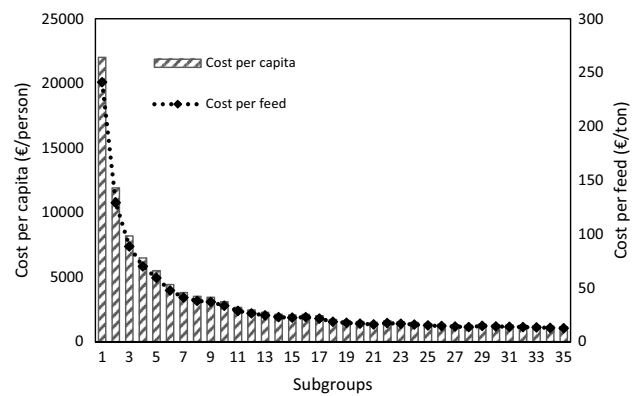
Regarding revenues, they are obtained by commercialization the generated electricity through the T&WW gasification and the WTB fee for the treatment and disposal of T&WW. Table 5 shows the revenues of the sale of electricity, the WTB fee and total revenue for each subgroup. The revenues have a direct relation with the amount of T&WW production and treated per year, since the higher the input waste, the higher the products. The amount of treated T&WW varies from 304.5 ton/year (subgroup 1) to 10,851.5 ton/year (subgroup 35).

Selling of electricity varies from 12.5 k€ (subgroup 1) to 437.5 k€ (subgroup 35) and the gains because of WTB fees for the T&WW treatment, range from 39.6 k€ (subgroup 1) to 1410.7 k€ (subgroup 35). It is worth mentioning that for all subgroups, the incomes obtained with the WTB fee are equivalent to more than 70% of total revenues.

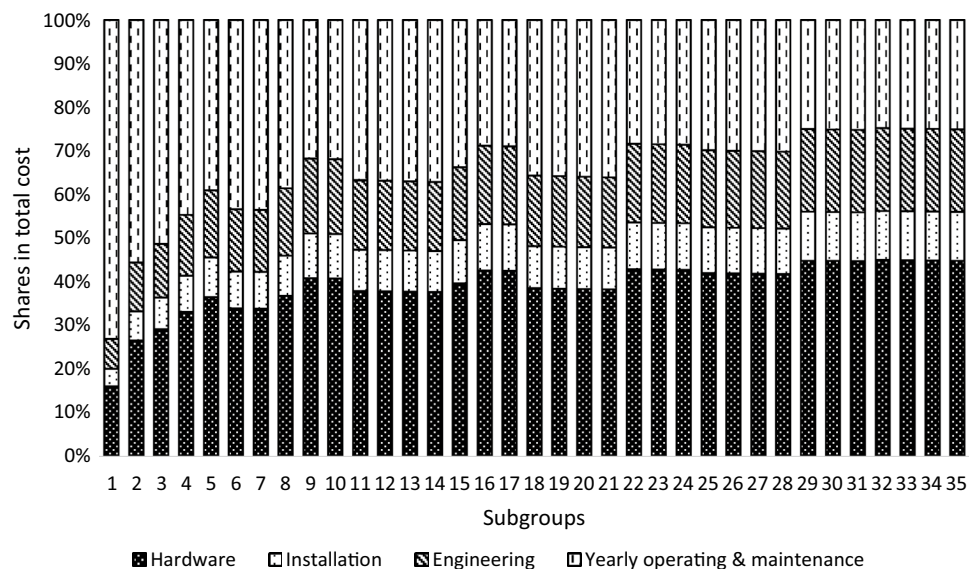Fig. 6 Percentage shares of total cost for scenario 1

Table 5 The annual revenue based on sale of electricity and waste treated

Subgroups	Income with sale of electricity (k€/year)	Income with WTB (k€/year)	Total income (k€/year)	Subgroups	Income with sale of electricity (k€/year)	Income with WTB (k€/year)	Total income (k€/year)
1	12.50	39.59	52.09	19	237.50	765.47	1002.97
2	25.00	79.91	104.91	20	250.00	805.79	1055.79
3	37.50	120.24	157.74	21	262.50	846.12	1108.62
4	50.00	160.57	210.57	22	275.00	886.44	1161.44
5	62.50	200.89	263.39	23	287.50	926.77	1214.27
6	75.00	241.22	316.22	24	300.00	967.10	1267.10
7	87.50	281.55	369.05	25	312.50	1007.42	1319.92
8	100.00	321.87	421.87	26	325.00	1047.75	1372.75
9	112.50	362.20	474.70	27	337.50	1088.08	1425.58
10	125.00	402.53	527.53	28	350.00	1128.40	1478.40
11	137.50	442.85	580.35	29	362.50	1168.73	1531.23
12	150.00	483.18	633.18	30	375.00	1209.06	1584.06
13	162.50	523.51	686.01	31	387.50	1249.38	1636.88
14	175.00	563.83	738.83	32	400.00	1289.71	1689.71
15	187.50	604.16	791.66	33	412.50	1330.04	1742.54
16	200.00	644.49	844.49	34	425.00	1370.36	1795.36
17	212.50	684.81	897.31	35	437.50	1410.69	1848.19
18	225.00	725.14	950.14				
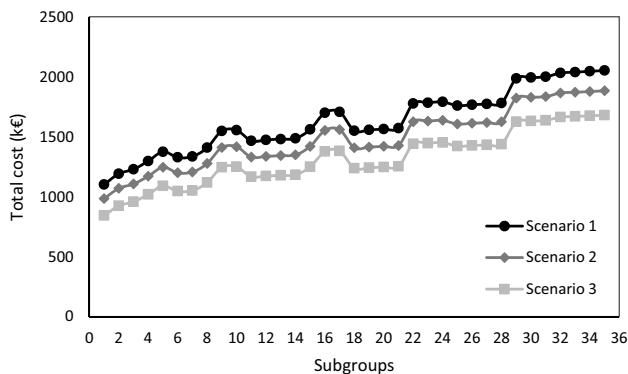
Fig. 8 Total costs for different scenarios

Economic Assessment of Three Scenarios

To have a comparison between different scenarios, the total costs required for power generation based on T&WW gasification, during the period of analysis, for each subgroup are shown together in Fig. 8. Higher interest rates tend to reduce total cost during 15 years of operation. The total costs are as follows, with the interest rate of 8% for Scenario 1 range of 1100 k€ (subgroup 1) to 2050 k€ (subgroup 35), the costs with interest rate of 10% for Scenario 2 range of 983 k€ (subgroup 1) to 1882 k€ (subgroup 35), and total costs with interest rate of 13% for Scenario 3 range of 842 k€ (subgroup 1) to 1680 k€ (subgroup 35). In fact, for the higher interest rate, the smaller present investment is required to achieve the revenue required for the project to succeed. However, the costs alone do not reflect economic-effectiveness of the project. The costs, revenues and their effects together on NPV need to be investigated to demonstrate which project is the most beneficial from the economic perspectives.

The economic assessments, based on the indexes of NPV and DPP for scenarios 1, 2 and 3, are shown in Figs. 9, 10 and 11, respectively. Different from the discount rate, NPVs for three scenarios are positive in 94% of the subgroups (3–35) and negative in the remaining 6% (1 and 2). In other words, implementation of T&WW gasification integrated with power generation unit in Iceland could be economic beneficial projects for places with more than 150 inhabitants or for installed capacities higher than 45 kW. It is worth noting that, in scenario 1 with the interest rate of 8%, NPV is averagely 11% and 25% greater than scenarios 2 and 3, respectively.

In addition, changing the interest rate does not have significant impact on DPP for all studied scenarios; it is lower than 2 years in 88% of the subgroups (5–35) and attractively it is lower than 6 months from subgroup 13 reducing to 4 months for subgroup 35. These all show that employing small-scale T&WW gasification could be an economic alternative in Icelandic municipalities.

The subgroups that do not show economic feasibility for these scenarios could have the strategy of merging in municipalities to reduce the costs and increasing the yields, then
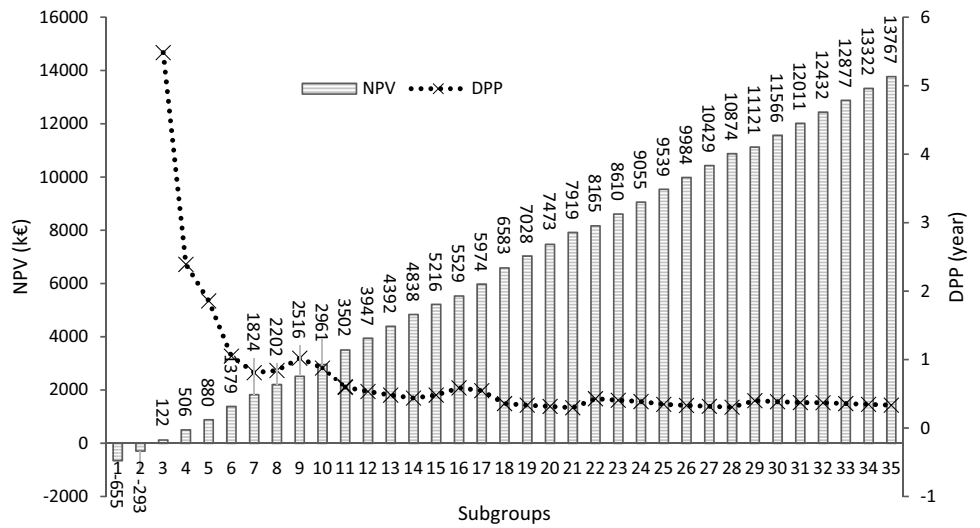
Fig. 9 Economic analysis for scenario 1

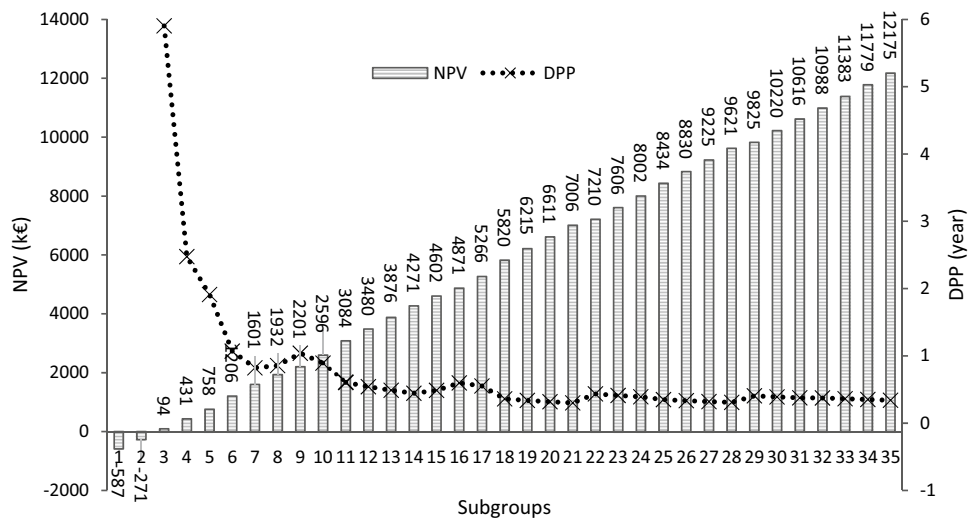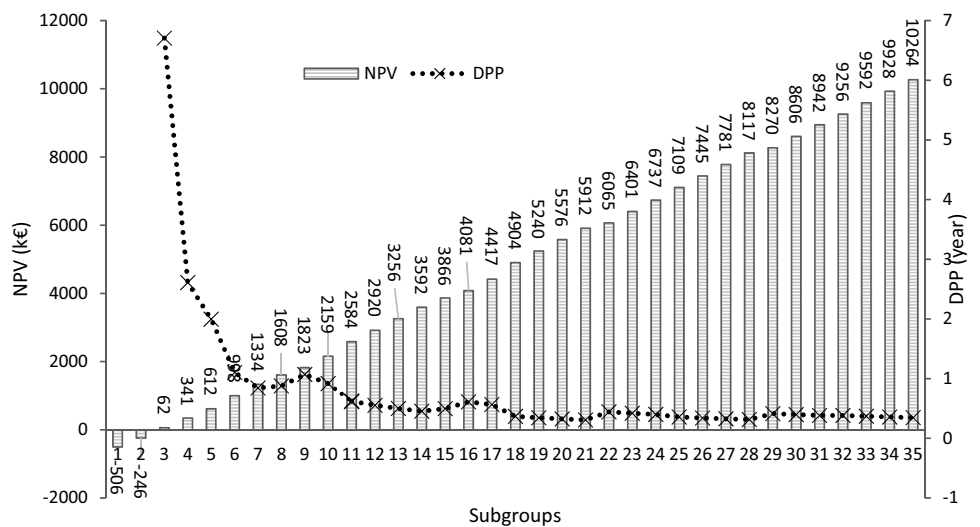**Fig. 10** Economic analysis for scenario 2

Fig. 11 Economic analysis for scenario 3

looking after the possibility of a higher amount of waste and making viable to install a treatment facility. Another way is to establish a minimum value for the fee of waste collection and disposing. Hence, it was carried out a sensitivity analysis, to find the minimum WTB, to have viable installation of a hypothetical T&WW gasification plant, independent of its size (Table 6). The minimum WTB varies from about 380 € per ton of waste (subgroup 1) for all scenarios to zero from subgroup 14 in scenario 1, subgroup 15 in scenario 2 and subgroup 17 in scenario 3. In other words, in places with more than 700 inhabitants or with the higher installed capacity of 200 kW, projects could be run economically without receiving any fee for collection and disposal of waste.

Environmental Assessment

The environmental impact assessment of timber and wood waste gasification integrated with power production unit is analysed with three categories of global warming, acidification and eutrophication potentials. tonCOThe GWP of T&WW gasification for 35 studied subgroups and average GWP contributions through the gasifying are shown in Fig. 12. It is clear that as the household numbers/population grow, the electricity consumptions increase, therefore greenhouse gas emissions (GHG) are increased. The GHG emitted through T&WW gasification is around 13 $tonCO_{2eq}$ (Subgroup 1) to 469 $_{2eq}$ (Subgroup 35), yearly.

The largest contribution in GWP is made by transport through the consumption of the diesel fuel following with gasifier in conversion step and cutting, handling and drying in the preparation process. Of the process in the chain, conversion 2 containing combustion chamber, gas and steam turbines occupies the smallest share in GWP contributions because when biomass is burnt, carbon dioxide releases back to the atmosphere but this biogenic CO_2 is not counted as a contributor to global warming.

The acidification and eutrophication impacts for T&WW gasification for all studied cases are shown in Fig. 13. Regarding AP index, production of electricity from timber and wood waste gasification creates 173.6 $tonSO_{2eq}$ (Subgroup 1) to 6187.2 $tonSO_{2eq}$ (Subgroup 35) per year. Moreover, electricity generation through the T&WW gasification releases 331.9 $tonNO_{3eq}$ (Subgroup 1) to 11,827.7 $tonNO_{3eq}$ (Subgroup 35), annually. The most important contribution for AP and EP impacts is made by the emissions of particulate matters through the transport sector, following by pre-process and conversions steps (Fig. 13).

Conclusions

In this paper, power supply chain by using timber and wood waste gasification has been analysed and assessed from the technical, economic and environmental perspectives. The technical assessment focused mainly on input waste, installed power, and electrical power generation. The economic assessment conducted relied on the economic indicators of total cost, specific costs, revenues, NPV and DPP, bringing together three different economic scenarios, with interest rates of 8% for Scenario 1, 10% for Scenario 2 and 13% for Scenario 3. Additionally, a sensitivity analysis was carried out, to investigate the effects

Table 6 Minimum WTB for treatment of T&WW to get a NPV more than zero

Subgroup	Minimum WTB (k€/ton)		
	Scenario 1	Scenario 2	Scenario 3
1	0.381	0.384	0.387
2	0.186	0.188	0.192
3	0.115	0.117	0.120
4	0.082	0.084	0.087
5	0.063	0.065	0.069
6	0.043	0.045	0.047
7	0.032	0.033	0.035
8	0.026	0.027	0.029
9	0.025	0.026	0.029
10	0.018	0.020	0.022
11	0.010	0.011	0.013
12	0.006	0.007	0.008
13	0.003	0.003	0.005
14	From 14 to 35 is zero	0.001	0.002
15		From 15 to 35 is zero	0.001
16			0.003
17			From 17 to 35 is zero

Fig. 12 GWP of T&WW gasification for electricity production and GWP contributions
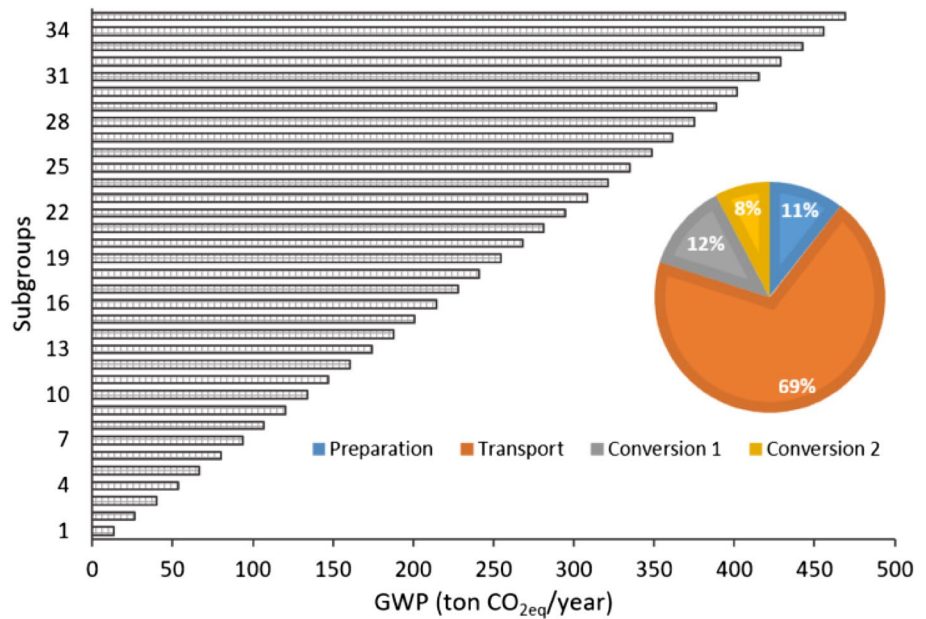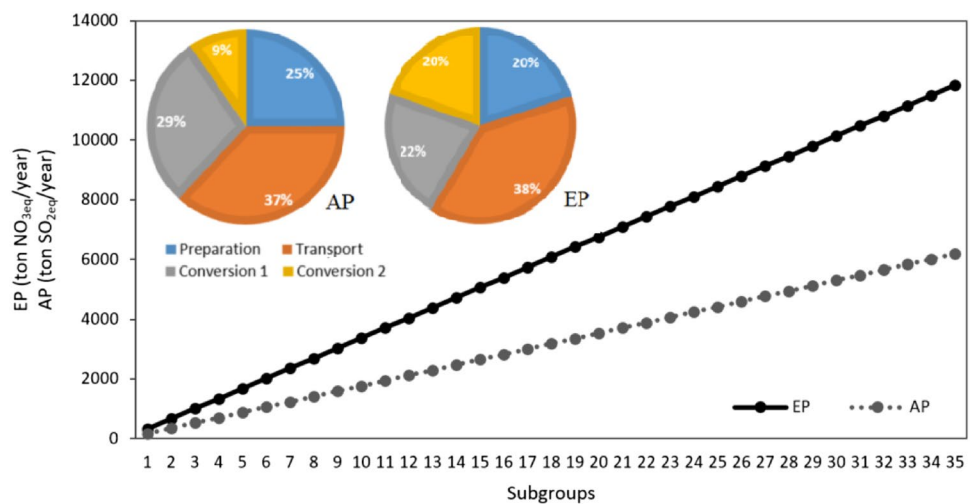

Fig. 13 AP and EP of T&WW gasification for electricity production, AP and EP contributions

of the fee paid by the Icelandic municipalities for collection and disposal of wastes (WTB). The environmental analysis was also directed based on the environmental impacts of global warming, acidification and eutrophication potentials.

We clustered Icelandic municipalities with population lower than 2000 to 35 subgroups based on various number of households/inhabitants. In each subgroup, the study was conducted over hypothetical cases, according to the number of households as each household includes five persons. The costs of equipment, installation, engineering, operation and maintenance and the interest rate of the investment were considered. Regarding revenues, they come from of the electricity sale and the fee paid by the Icelandic municipalities for collection and disposal of waste.

The results show that changing the interest rate does not have significant impact on NPV and DPP for all studied scenarios. The NPV is positive for the municipalities with more than 30 households/150 inhabitants or for a hypothetic gasification plant with the capability to generate greater than 45 kW (for subgroups 3–35). The NPV in scenario 1 (8% for interest rate) is averagely 11 and 25% higher than scenarios 2 and 3, respectively. Moreover, for all studied scenarios, DPP is lower than 2 years in 88% of the subgroups as well as lower than 6 months for 60% of them.

The economic assessment could be also feasible for subgroups (1 and 2), because the WTB fee paid by the Icelandic municipalities for collection and disposal of waste and the quantity of waste can be adjusted. They also can merge together for making viable to install a treatment facility.

Regarding environmental assessment, electricity generation based on T&WW gasification would lead to a GWP of 13 tonCO$_{2eq}$ (Subgroup 1) to 469 tonCO$_{2eq}$ (Subgroup 35), AP of 173.6 tonSO$_{2eq}$ (Subgroup 1) to 6187.2 tonSO$_{2eq}$ (Subgroup 35), and EP potential of 331.9 tonNO$_{3eq}$ (Subgroup 1) to 11,827.7 tonNO$_{3eq}$ (Subgroup 35), yearly. Of the process in the chain, the largest contribution for all impacts is made by transport through the diesel fuel consumption following with gasifier in conversion step and cutting, handling and drying in preparation process.

Compliance with Ethical Standards

Conflict of interest All authors declare that they have no conflict of interest.

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