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Final impact assessment of the novel highly efficient and fuel flexible medium-scale HiEff-BioPower CHP technology using a solid oxide fuel cell (SOFC)

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Abstract

The EU Horizon 2020 project HiEff-BioPower (grant agreement No 727330, duration: 10/2016 – 09/2021) aimed at the development of a new, innovative, fuel flexible and highly efficient biomass CHP technology for a capacity range of 1 to 10 MW total energy output, suitable e.g. for on-site generation at larger residential apartment buildings or local heat grids. The new technology shall define a new milestone in terms of CHP efficiency and contribute to a sustainable energy supply based on renewable energies using otherwise unused residual biomass. It consists of a fuel-flexible updraft gasification technology with ultra-low particulate matter emissions, an integrated gas cleaning system and a solid oxide fuel cell (SOFC). The technology shall be applicable for a wide fuel spectrum for residual biomass (wood pellets, wood chips or selected agricultural fuels like agro-pellets) and achieve high gross electric (40%) and overall (90%) efficiencies as well as almost zero gaseous and particulate matter (PM) emissions (close or below the level of detection) as non-energy benefits. At the end of the project, final technology data has become available, as well as techno-economic analyses and market studies. Based on this data, this paper presents final results from the environmental impact assessment of the new HiEff-BioPower technology.

Introduction

As part of it's recent Fit-for-55 package, the European Commission's targets to achieve a share of at least 40% renewables in the Union's final energy consumption [1]. As the current solid biomass combustion in the EU is already significant and a further expansion is planned, it is important to consider a maximum of efficiency, reduction of emissions and the usage of sustainable biomass especially from residues that would be otherwise not be used at all. As result of complex feedstock composition and heat integration, most combined heat and power (CHP) systems based on biomass fuels are still realised only for medium and large-scale plants with typically 0.2 MW_{el} up to more than 100 MW_{el}. Although mature technologies like steam turbine cycles or Organic Rankine Cycle (ORC) processes exist, major drawbacks of the current systems are their restricted fuel flexibility especially regarding the utilisation of forestry or agricultural residual biomass as well as their limited electric efficiencies of typically 14 to 27% [2]. Considering this background, the H2020 project HiEff-BioPower aimed at the development of a new, innovative, fuel flexible and highly efficient medium-scale biomass CHP technology for a capacity range of 1 to 10 MW total energy output. It consists of (i) a fuel-flexible fixed-bed updraft gasifier, (ii) a novel gas cleaning system and (iii) a solid oxide fuel cell (SOFC). The technology shall be applicable for a wide fuel spectrum of biomass residues like wood pellets, wood chips, short rotation coppice (SRC), selected agricultural fuels like agro-pellets or fruit stones/shells and shall achieve at the same time high gross electric and overall efficiencies as well as almost zero gaseous and particulate matter (PM) emissions (close or below the level of detection).

Therefore, in advance of any large-scale future deployment of new technologies, the potential environmental impacts have to be adequately assessed. Accordingly, the overall project methodology was divided into a technology development part (process simulations, computer aided design of the single units and the overall system, test plant construction, performance and evaluation of test runs, risk and safety analyses) and a related comprehensive technology assessment part covering techno-economic, environmental and overall impact assessments as well as market studies regarding the potentials for application. This paper presents final results of the HiEff-BioPower overall impact assessment. More information on the technical details and backgrounds of the project is presented under https://www.hieff-biopower.eu/.

Objectives

The objectives of the overall impact assessment (IA) are to estimate the expected effects of a broad market introduction of the new, fuel flexible HiEff-BioPower CHP technology in the EU. Accordingly, this paper will have a major focus on European greenhouse gas (GHG) and air pollutant emissions, as well as fuel and energy consumption. With the background of ambitious EU climate protection targets, biomass solid fuel heating is often intended to be scaled up for taking a major role in future low-carbon energy heating and power generation strategies. E.g. the Green-X EUCO27 scenario developed on behalf of the European Commission expects biomass heat production to grow from 80 Mtoe in 2014 to 104 Mtoe in 2030 and biomass energy demand for electricity generation is expected to increase from 14 Mtoe in 2014 to 24 Mtoe in 2030 [3]. In this context, the analysis how the new HiEff-BioPower technology compares to competing technologies is one major objective of this impact assessment. In parallel to the reduction of GHG emissions, the EU also aims to further improve air quality throughout Europe. In 2016, the amended Directive on the reduction of national emissions of certain atmospheric pollutants (2016/2284/EU) has been passed. With this legislation the European Union laid the foundation to take further steps towards the long-term target of achieving a level of air quality that does not have significant negative impacts on and risks to human health and the environment. In this context, solid fuel combustion in old and outdated heating systems has been identified as one of the main sources for particulate matter (PM) related ambient air pollution in the EU. While particulate matter is often distinguished by different sizes of particles, for the purposes of this impact assessment the aggregated indicator of total suspended particle (TSP) is used. Other important air quality-relevant pollutants are carbon monoxide (CO), organic gaseous compounds (OGC) and nitrogen oxides (NO_X). Therefore, estimating the effects of the new HiEff-BioPower CHP technology on TSP, CO, OGC and NO_X emissions compared to competing state-of-the-art technologies is another major objective of this impact assessment.

Methodology

The approach used for this impact assessment is derived from the Impact Assessment Guidelines of the European Commission [4], [5]. Four application cases have been identified for the analysis:

- Application A1 covers “small” CHP systems (200 kW_{el} / 260 kW_{th}) for base load district heating or heat supply for large companies in Central Europe (Germany, Austria) with around 8,000 annual full-load operating hours and up to three start-up and shutdown cycles per year.

- Application A2 covers “small” CHP systems (200 kW_{el} / 260 kW_{th}) for base and medium load coverage (e.g. district heating, hotels, industry) in Central Europe (Germany, Austria) with around 5,000 annual full-load operating hours, 2,000 part-load operating hours, and up to twelve start-up and shutdown cycles per year.

- Application B1 covers “large” CHP systems (1,000 kW_{el} / 1,300 kW_{th}) for base load district heating or heat supply for large companies in Central Europe (Germany, Austria) with around 8,000 annual full-load operating hours and up to three start-up and shutdown cycles per year.

- Application B2 covers “large” CHP systems (1,000 kW_{el} / 1,300 kW_{th}) for base and medium load coverage (e.g. district heating, hotels, industry) in Central Europe (Germany, Austria) with around 5,000 annual full-load operating hours, 2,000 part-load operating hours, and up to twelve start-up and shutdown cycles per year.

For each application case different technologies and fuels could be utilised. Therefore, the HiEff-BioPower technology is compared to other systems, which represent most likely alternatives to the new technology for customers or investors. The abbreviated names for each technology are given in parenthesis and these abbreviations are used throughout this paper in graphs and tables:

- Wood chip biomass boiler + electricity from the grid (BB_WC)

- Wood pellet gas engine (GE_WP)

- Wood chip HiEff-BioPower CHP (HEBP_WC)

- Miscanthus pellet HiEff-BioPower CHP (HEBP_MP)

The BB_WC and the GE_WP scenarios assume the use of existing state-of-the-art technologies, while the HEBP_WC and HEBP_MP scenarios suppose the use of the new HiEff-Biopower CHP system, albeit with different fuels (wood chips in the case of HEBP_WC, miscanthus pellets in the case of HEBP_MP).

All scenarios for the different application cases use the same assumptions for the stock of appliances. For each year t the stock is calculated from the formula

$$\text{stock}_{i,t} = \text{stock}_{i,t-1} + \text{sales}_{i,t-1} - \text{sales}_{i,t-T-1},$$

where i refers to the application case and T signifies the technical lifetime of the systems. The sales for each year t are derived from the HiEff-Biopower market study [6], and represent the technical sales potential for the full market segment that the HiEff-BioPower technology could address in future. The steps carried out to estimate this market potential were as follows: (1) estimation of the total current stock of CHP plants in the capacity range relevant for the HiEff-BioPower technology for the industry and district heating sectors, (2) assessment of the future market size according to the current stock, the renovation rates of the technologies, and the expected increase (or decrease) of the heat demand in each part of the market segment, and (3) estimation of the potential HiEff-BioPower sales in the future by considering the potential market shares of the technology compared to state-of-the-art biomass technologies providing heat and electricity (determined by a benchmarking analysis based on environmental and economic competitiveness). The final market study identified three different projections (high/medium/low) for the technical sales potential. This paper focuses on the medium sales projection exclusively. The assumption concerning the technical lifetime T is resulting from the HiEff-BioPower system development. Decommissioned appliances are assumed to be replaced and lead to additional sales.

To analyse the aspects illustrated in the preceding section, the impact assessment model generates (among others) the following outputs for every year t until 2050, each technology scenario and each application case:

- GHG emissions in CO_{2eq}/year resulting from fuel and grid electricity consumption, respectively
- TSP, CO, OGC and NO_X emissions resulting from fuel and grid electricity consumption, respectively
- Fuel and grid electricity consumption

The heat demand differs between the defined application cases, but is similar among the four technology scenarios for each application case. Furthermore, all scenarios presume that the typical nominal output of appliances in Europe needs to decrease by about 2% per year as expected effect of improved insulation of the buildings due to the EU Energy Performance of Buildings Directive (“EPBD”). The amount of fuel necessary to meet the heat demand, the electricity production and the net grid electricity consumption, which may be negative, were derived during the techno-economic analysis for each technology scenario. The techno-economic analysis in the project was based on inputs from the manufacturing partners regarding expected investment and operation costs as well as on experiences from the scientific partners regarding the expected performance data and emissions.

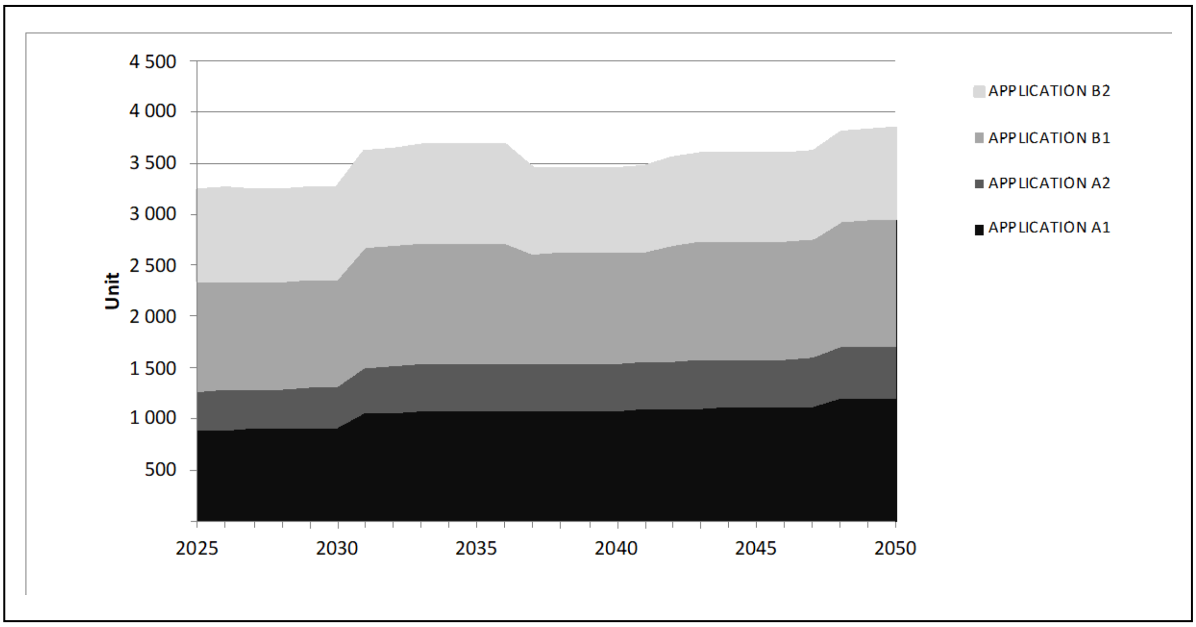
The defined parameters have been compared with available data from comparable state-of-the-art CHP systems. Based on this, the impact assessment model calculates greenhouse gas and air pollutant emissions arising from fuel and grid electricity consumption. The emission intensities needed for this calculation were also derived from the techno-economic analysis or taken from additional literature. The emissions of the state-of-the-art technology BB_WC are based on the emission limits according to the Austrian labelling UZ37 for wood chip boilers [7], while the emissions regarding the GE_WP are referred to the emission limits according to the German “Technical Instructions on Air Quality Control” [8] for gas engines. The greenhouse gas emission intensities for the fuels also take life cycle emissions into account. In the case of grid electricity, a general decrease of the emission intensity is to be expected. The GHG emission intensity of EU average grid electricity and its development in the future has been taken from the EU Ecodesign Impact Accounting [9].

Results achieved

Development of sales and stock

The sales numbers as illustrated in Figure 1 are total sales, including e.g. also sales that replace decommissioned end-of-life systems. Based on this, EU-wide stock data for the impact assessment is further calculated with a sales-driven stock model. In the following it is assumed that all sales are taken over by one or the other technology, in order to compare the potential total impact corridor of the different technologies considered for the relevant market segment. For the purposes of the impact assessment, stocks of new systems are calculated from a defined reference year (2025) onwards. This reference year is an assumption for a future market introduction, based on the final outcomes of the technology development at the end of the HiEff-Biopower project. Accordingly, potential historical stocks are not carried over, and the model then combines total sales data from the reference year onwards with average lifespans characteristic for each application to calculate stock data successively for each year of the simulation period, using the equation presented in the preceding section.

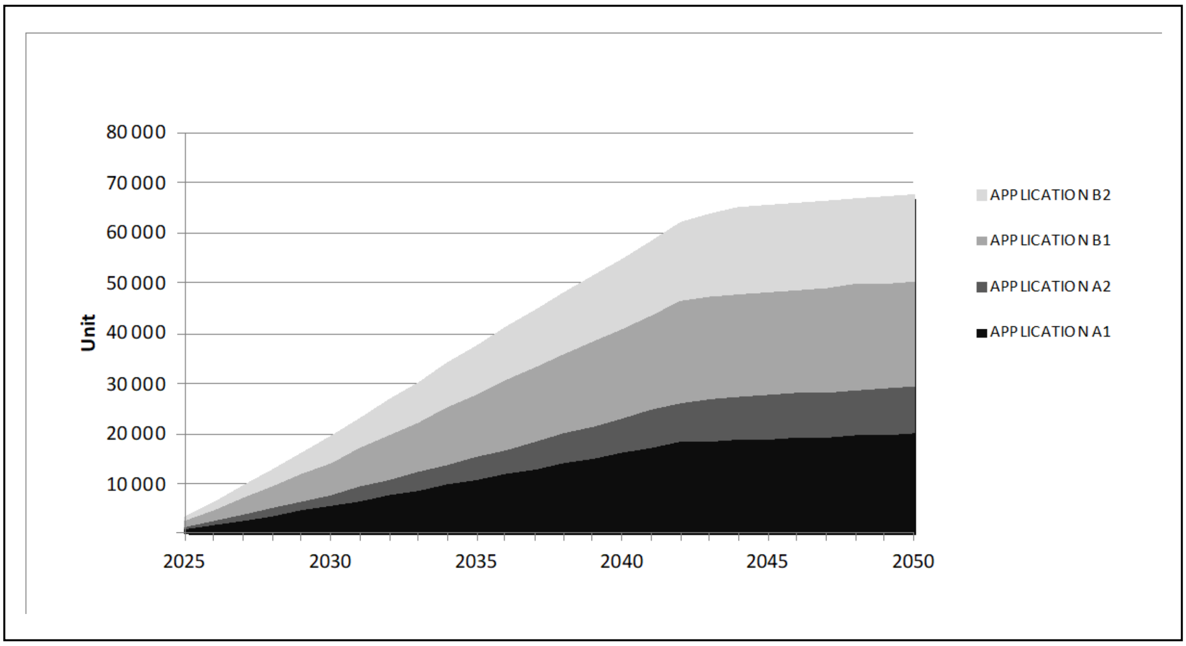
Figure 1. EU-wide development of sales for the four application cases until 2050



Source: Own illustration, based on HiEff-BioPower market study [6]

As can be seen in figure 1 and figure 2 for the considered cases, applications A1 and B1, closely followed by application B2, dominate the market in absolute numbers of potential sales and consequently in stock sizes. The medium sales scenario from the HiEff-BioPower market study [6] is represented here but the low and high sales scenarios present the same general pattern. Sales dynamics are similar in all applications with variability stemming from assumptions made on historical sale patterns in the market study. Cumulative sales lead to stocks increasing at a steady growth rate until about 18-20 years after 2025, when the growth rate strongly decreases because from that point onwards the sales do not solely add to the stock of new systems but also come to replace end-of-life systems installed after 2025. Stock levels in the EU (see figure 2) reach 19,846 units in application A1 and 9,407 in application A2 in 2050. Applications B1 and B2 technology stocks reach 21,094 and 17,277 units in 2050, respectively.

Figure 2. EU-wide development of the stock for the four application cases until 2050



Source: Own illustration, based on HiEff-BioPower market study [6]

Greenhouse gas (GHG) emissions

As described in the preceding section, GHG emissions are calculated by multiplying fuel and net grid electricity consumption with the respective emission intensities. Table 1 shows the fuel emission intensities used for modelling. According to the EU Ecodesign Impact Accounting [9], average EU-28 GHG emissions of electric power generation are assumed to decrease from 0.40 kg CO_2/kWh_{el} in 2015 to 0.26 kg CO_2/kWh_{el} in 2050. According to data by the European Environment Agency, in 2020 grid electricity emission intensities were about 0.08 kg/kWh higher than the EU-average in Germany and about 0.15 kg/kWh lower than the EU-average in Austria [11]. All scenarios use the EU-average for the grid electricity emission intensity and its projected future development. It can be expected that the variation within EU-member state grid electricity emission intensity will decrease in the future due to higher shares of renewables. Therefore, it is likely that modelling each scenario on the member state level would not lead to substantially different results.

Table 1. GHG emission intensities and net calorific value (NCV) of fuels

Fuel	**GHG** ($kgCO_{2eq}/GJ$ fuel)	**NCV** (MJ/kg fuel)
Miscanthus pellets	11	16.2
Wood chips	4	12.4
Wood pellets	11	17.6

Source: EU Ecodesign Impact Accounting [9]

Overall, four technology scenarios are considered for each application: HiEff-BioPower technologies fuelled with wood chips or miscanthus pellets (HEBP_WC, HEBP_MP), a gas engine fuelled with wood pellets (GE_WP) and a traditional wood chip biomass boiler (BB_WC). The figures below also show that the stock volumes of heating systems first rapidly go up before plateauing, reflecting the assumptions made in modelling future sales and the expected technical lifetime of the technologies.

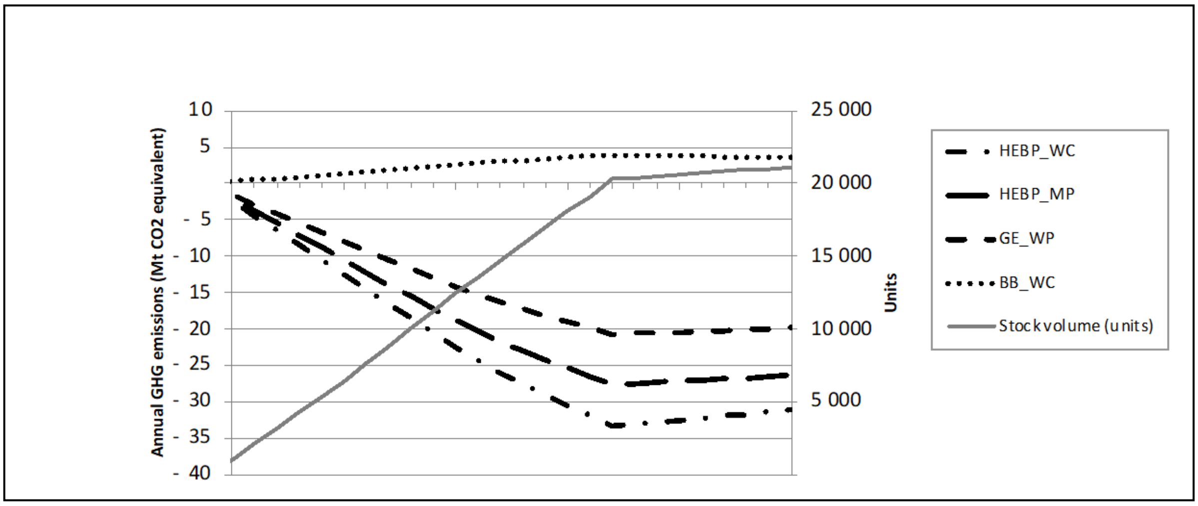
The scenarios with the new HiEff-BioPower technology using wood chips or miscanthus pellets help to save more GHG emissions than scenarios with the state-of-the-art conventional wood chip boiler and gas engine.

Avoided grid electricity GHG emissions are 5-6 times higher than direct emissions from fuel combustion for HiEff-BioPower with miscanthus pellets, and 13-15 times higher for HiEff-BioPower with wood chips. The difference comes from the fact that miscanthus pellets, as a more processed fuel, have a higher lifecycle GHG intensity than easy to produce wood chips.

Emissions from fuel combustion dominate total GHG emissions for the wood chip boiler in all applications (about 76% in 2050 in every application case). This technology scenario (because it does not displace grid electricity generation) also shows consistently higher emissions than the scenarios with the CHP technologies. For the gas engine CHP, avoided grid electricity GHG emissions are 2.3 to 2.5 times higher (in absolute values) than the direct GHG emissions from wood pellets combustion. The gas engine technology fuelled with wood pellets helps to avoid (through displaced grid electricity generation) about 60-64% of the amount of GHG emissions in 2050 that the HiEff-BioPower technology fuelled with wood chips would avoid. When the gas engine scenario is compared to the scenario with the HiEff-BioPower technology fuelled with miscanthus pellets, this value is between 75% and 79% in 2050. The wood chip biomass boiler generates mostly directly through fuel combustion about 12% (when wood chips are used as fuel) and between 14% and 16% (when miscanthus pellets are used as fuel) of the GHG emissions that the HiEff-BioPower systems help to avoid.

Regarding sales and stock volumes, applications A1 and B1, closely followed by application B2, dominate the market potentials. Applications B1 and B2, however, consist of larger systems (with higher thermal output) than A1 and A2. In addition, application B1 registers 8,000 full load hours against 5,000 for application B2 (plus 2,000 part-load hours). These underlying aspects of the model amplify the differences in potential market sizes when comparing the emission scenarios between applications. Application B1 presents the highest GHG emission levels and emission saving potentials (depending on the technology) in 2050 for all technologies considered. Then follows application B2, in which emission savings reach 44% (HEBP_MP), 46% (GE_WP) and 48% (HEBP_WC), respectively, of those seen in application B1 scenarios for the same technologies. The wood chip boiler scenario in application B2 is responsible for 52% of the emissions in 2050 as the same technology scenario in application B1. For the purposes of this paper, due to the highest emission levels and emission saving potentials, the scenario results with focus on application B1 will be presented and discussed more in detail (see following figures).

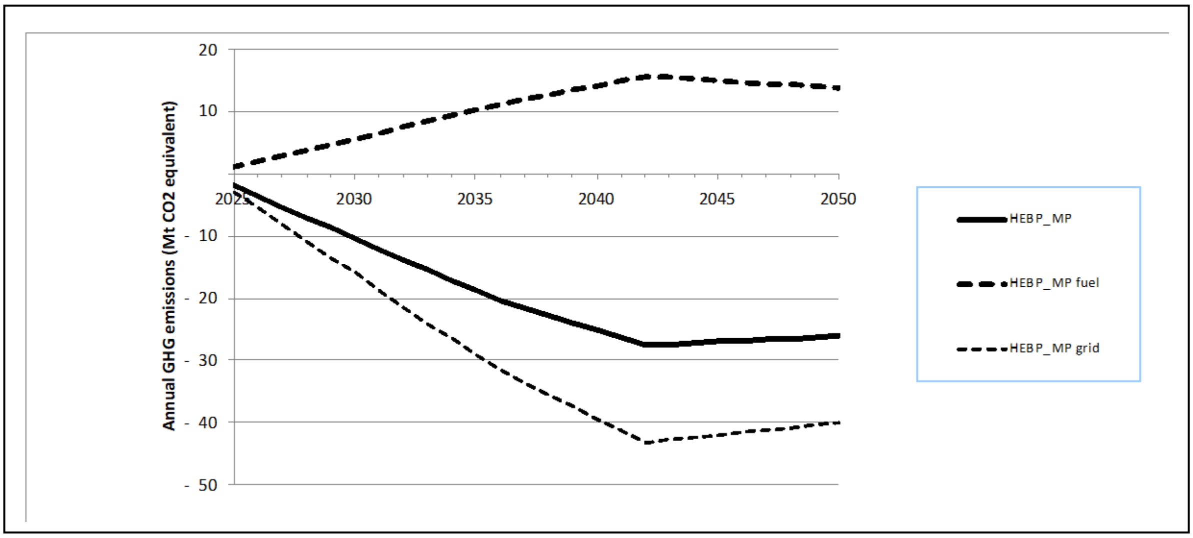
Figure 3. GHG emissions in the four technology scenarios for Application B1 (EU-28)



Source: Own illustration

The smaller systems in application A1 (but with the same 8,000 full load hours as in application B1) generate 19% of the emission levels and savings in application B1, consistently across technologies and types of emissions. Finally, application A2, characterized by the lowest market potential, small systems, and lower full load hours, reaches between 5% and 6% of the emission levels and savings in application B1. Exemplarily for application B1 (HEBP_MP), an additional graph shows in detail the contributions of fuel use and net grid electricity consumption in generating GHG emissions in the corresponding scenario (see figure 4). The terms “fuel” in the graphs refers to direct emissions resulting from biomass fuel use by the HiEff-BioPower systems. The term “grid” indicates net emissions from grid electricity generation (i.e., emissions from grid electricity actually consumed by the application case minus avoided emissions through the system’s own gross electricity output).

Figure 4. Detailed GHG emissions for the HEBP_MP scenario for Application B1 (EU-28)



Source: Own illustration

Air pollutant emissions (TSP, CO, OGC and NO_X)

Air pollutant emissions (i.e. TSP, CO, OGC and NO_X) are calculated by multiplying fuel and net grid electricity consumption with the respective emission intensities. Table 2 presents the air pollutant emission intensities for the four technology scenarios BB_WC, GE_WP, HEBP_WC and HEBP_MP. The emission intensities used for EU grid electricity can be found in Table 3. Following the Ecodesign Impact Accounting [9], air pollutant emission intensities are assumed to remain constant until 2050.

Table 2. Air pollutant emission intensities for the technology scenarios

Emissions	Unit	BB_WC	GE_WP	HEBP_WC	HEBP_MP
TSP	(mg/MJ)	25	7	0	0
CO	(mg/MJ)	120	333	20	20
OGC	(mg/MJ)	4	0	0	0
NO_X	(mg/MJ)	100	167	0	0

Source: HiEff-BioPower techno-economic analysis

Table 3. Air pollutant emission intensities for grid electricity (EU-28)

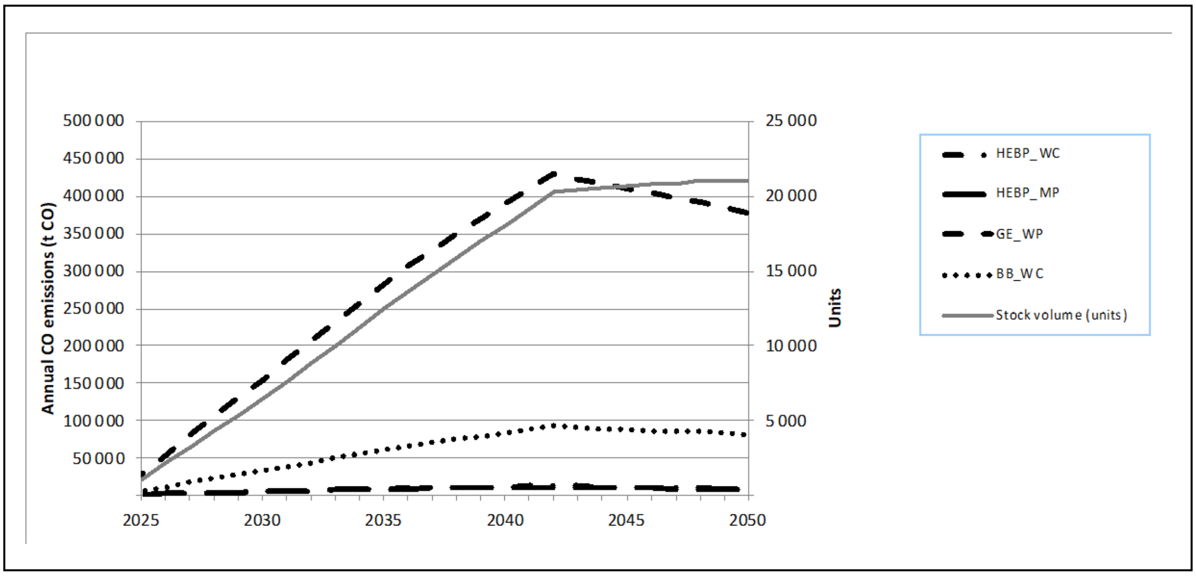
Emissions	Unit	Grid electricity generation (EU-28 mix)
GWP	kg/kWh	0.40
CO	g/kWh	0.11
OGC	g/kWh	0.01
TSP	g/kWh	0.02
NO_X	g/kWh	0.26

Source: GHG emissions from grid electricity based on [9]; non-GHG emissions from grid electricity are calculated, based on EMEP/EEA air pollutant emission inventory 2018

Total TSP, CO, OGC, and NO_X emissions are the result of contributions from solid fuel combustion and net electricity consumption. The latter means that emissions from grid electricity consumption are calculated as the difference between emissions from grid electricity actually consumed in each scenario and from grid electricity avoided through the gross electricity output of these CHP systems. As a result, net emissions from grid electricity consumption may be even negative, which indicates that grid electricity emissions have been avoided. Negative net emissions for HiEff-BioPower scenarios, in particular, result from vastly less emission intensive technologies (less fuel related emissions) further compensated by avoided emissions from grid electricity generation. The HiEff-BioPower systems show negative net emissions, except for CO. Net TSP emissions are positive in the gas engine scenarios. For this technology, OGC net emissions are negative while CO and NO_X emissions are positive and higher in the wood chip boiler scenarios, respectively. In any case, the new HiEff-BioPower technology scenarios show significant technical emission saving potentials compared to state-of-the-art conventional biomass boilers and gas engine CHPs. These results are sensitive to crucial technical parameters and other assumptions such as emission intensity of the different solid fuels used by different technologies. Further assumptions regarding the future development of grid electricity emission intensity and heat energy demand (driving thermal output, hence fuel requirements) are also very relevant for the overall behaviour of the model.

Independent of the application case or technology and all other aspects being equal, total stock emissions decrease in the long run when the stock's growth rate decreases or plateaus. The reason lies in the assumption that the typical size of systems in Europe decreases by 2% per year as expected effect of improved insulation and energy performance of buildings (based on EPBD, the EU Energy Performance of Buildings Directive). This rate then happens to be higher than the slowing rate of stock growth. Consequently, this means less fuel input, hence less fuel related emissions. According to the impact assessment results, Application B1 presents the highest emission levels and emission saving potentials (depending on the technology) for all technologies and types of emission considered. Application B2 comes second. Third are the smaller systems in application A1 (but with the same 8,000 full load hours as in application B1). Finally, application A2, characterised by the lowest market potential, small systems, and lower full load hours, reaches only a fraction of the emission levels and saving potentials observed in application B1. This follows from the sales and stock volumes where applications A1 and A2, closely followed by application B2, dominate the market potentials. Applications B1 and B2, however, consist of larger systems (with higher thermal output) than A1 and A2. In addition, application B1 registers 8,000 full load hours against 5,000 for application B2 (plus 2,000 part-load hours). These underlying aspects of the model amplify the differences in potential market sizes when comparing the emission scenarios between applications.

Figure 5. Total CO emissions and stock volume (Application B1, EU-28

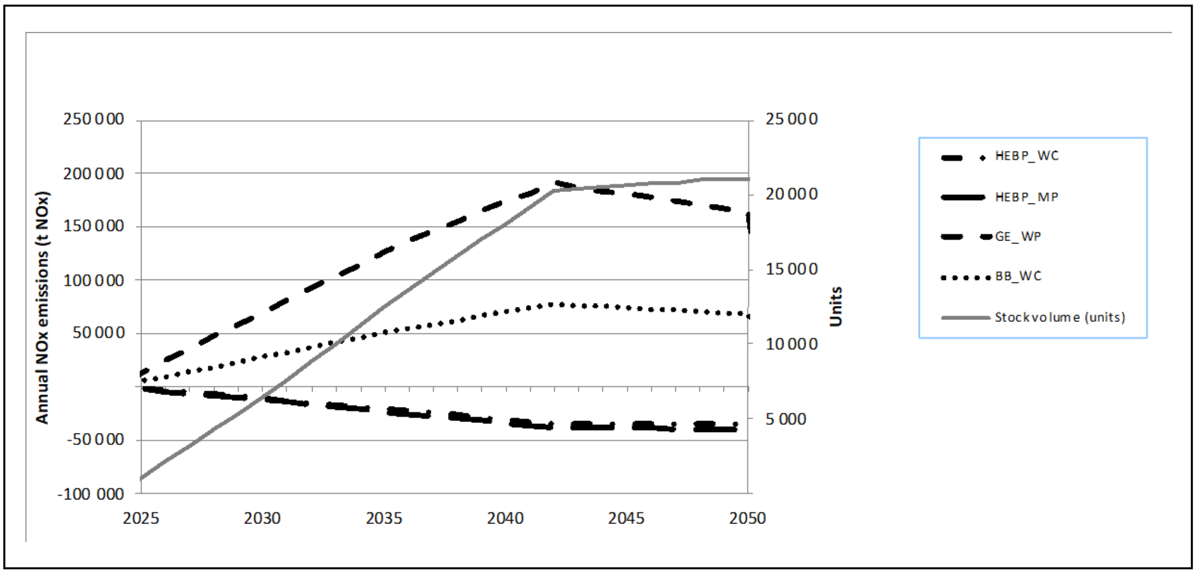


Source: Own illustration

Consequently, the scenario results with focus on application B1 will be discussed more in detail. The scenarios with the new HiEff-BioPower technology using wood chips or miscanthus pellets present significantly lower emission levels (for all four emission types) than scenarios with the state-of-the-art conventional wood chip boiler and gas engine. The emission totals presented in figure 5 and the following figures are the net sums of direct emissions from fuel combustion in the heating or CHP systems and indirect emissions from (EU-average) grid electricity generation.

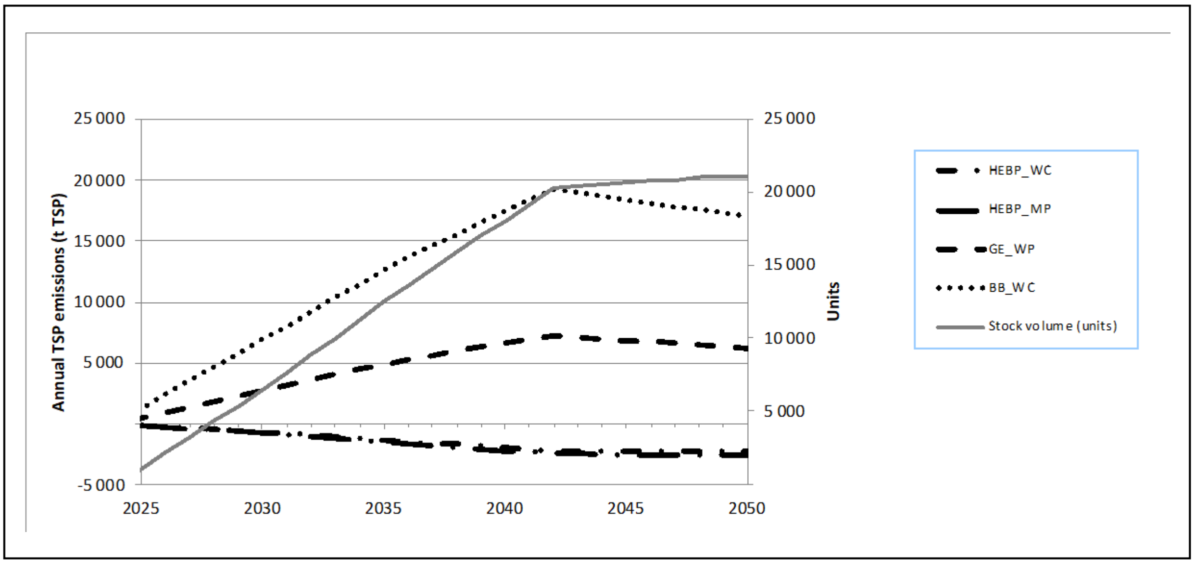
In all non-GHG emission categories, emissions from fuel combustion dominate the totals for the wood chip boiler (at least 99% in 2050). This technology scenario also shows consistently higher emissions than the one with the gas engine, except for CO and NO_X emissions (see figure 5 and figure 6). Emissions from fuel combustion (here wood pellets) dominate the net totals for the gas engine for CO and NO_X. Avoided grid electricity emissions reach 4% and 17% of the actual fuel combustion-related emissions (in absolute values) for CO and NO_X, respectively.

Figure 6. Total NOx emissions and stock volume (Application B1, EU-28)



Source: Own illustration

Figure 7. Total TSP emissions and stock volume (Application B1, EU-28)

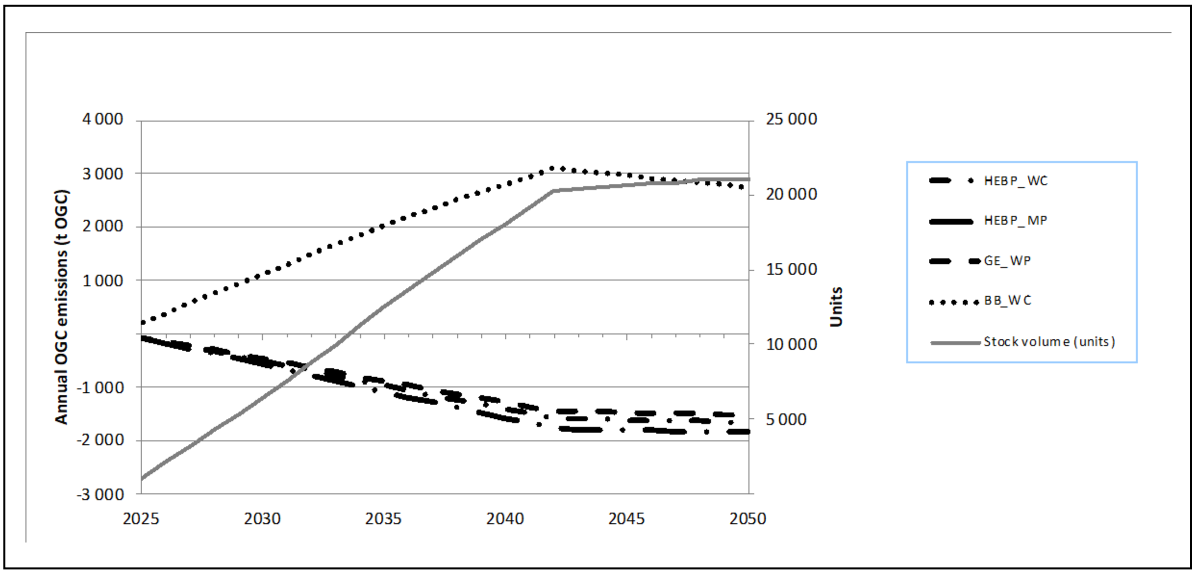


Source: Own illustration

In the case of TSP (figure 7), direct emissions from fuel combustion are almost four times the absolute value of avoided grid electricity TSP emissions in 2050. In the case of OGC emissions (figure 8), avoided indirect emissions are almost two orders of magnitude higher than the direct emissions due to fuel combustion. The gas engine technology fuelled with wood pellets helps to avoid (through displaced grid electricity generation) 82% of the amount of OGC emissions in 2050 that the HiEff-BioPower technology fuelled with miscanthus pellets avoids. This ratio is 91% when compared to the HiEff-BioPower technology fuelled with wood chips. For TSP emissions, the gas engine scenario has net “positive” emissions despite replacing grid electricity between two and three times higher than the absolute value of TSP emissions that are avoided in the HiEff-

BioPower scenarios. The gas engine scenario is also responsible for net positive emissions for CO and NO_X emissions. In the case of CO these emissions are between 40 and 50 times higher (in absolute value) than the emissions in the HiEff-BioPower scenarios in 2050.

Figure 8. Total OGC emissions and stock volume (Application B1, EU-28)



Source: Own illustration

The wood chip biomass boiler generates (mostly directly through fuel combustion) about 1.5 times the OGC and 1.7 to 1.9 times the NO_X emissions as the absolute value of emissions that are avoided in the HiEff-BioPower scenarios due to replaced grid electricity. The OGC emissions in the wood chip biomass boiler scenario are about ten times higher than the OGC emissions in the HiEff-BioPower scenarios in 2050, while the TSP emissions in the wood chip biomass boiler scenario are about seven times the absolute value of the TSP emissions avoided in the HiEff-BioPower scenarios because of replaced grid electricity.

Fuel and grid electricity consumption

Following the “efficiency first principle” [10], using and converting energy as efficient as possible is among the most important goals of the European Union’s energy policy. The different technologies analysed in this impact assessment also show variations with respect to their total annual efficiency. Table 4 illustrates the total annual efficiency levels for the different technologies and application cases. The total annual efficiency determines the fuel consumption reflected in the technology scenarios. Results for the total fuel consumption of applications A1, A2, B1, and B2 presented in the subsequent figures follow each application’s and technology’s stock dynamics. In all four applications, fuel consumption first increases with the growing stock of appliances. It then starts to decrease, around 2043 for application A1 and B1 and around 2045 for applications A2 and B2, due to the different technical lifetimes assumed for the corresponding technologies. The rate of stock growth starts decelerating at those periods because new systems not only add up to the stock but also replace end-of-life systems that were installed in and after 2025.

Table 4. Total annual efficiency levels for the different technologies and application cases

	BB_WC	**GE_WP**	**HEBP_WC**	**HEBP_MP**
Application A1	81%	76%	81%	81%
Application A2	81%	74%	79%	80%

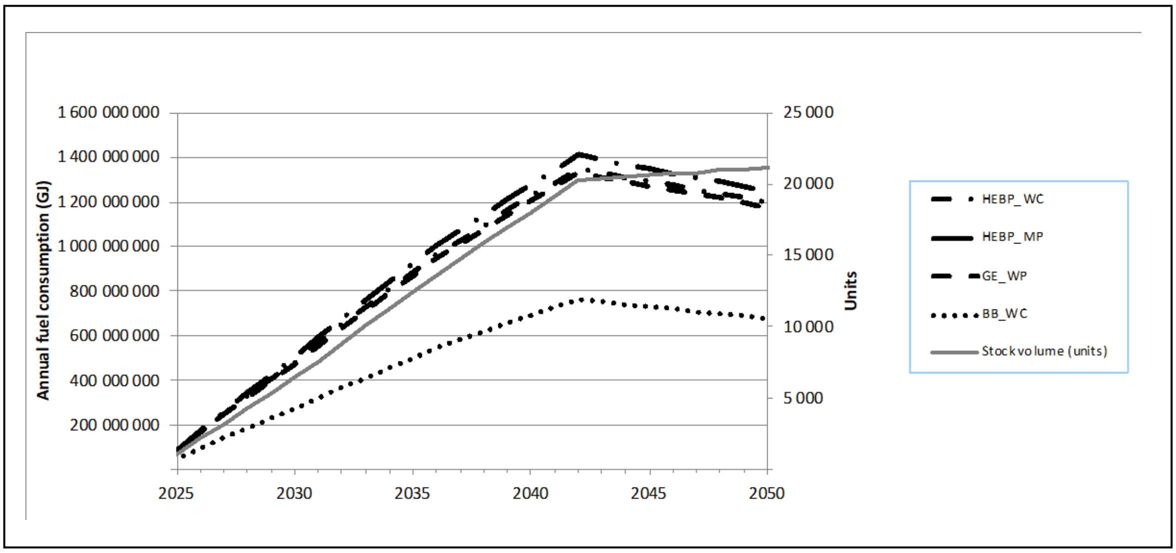
Application B1	81%	76%	81%	81%
Application B2	81%	74%	79%	80%

Source: HiEff-BioPower techno-economic analysis

The reason why fuel consumption then also decreases in the different applications lies in the assumption that the typical size of heating systems in Europe decreases by 2% per year as expected effect of improved insulation of the buildings (based on EPBD). This rate then happens to be higher than the slowing rate of stock growth, resulting in lower fuel input in absolute terms. Based on the model results, the calculated solid fuel consumption in 2050 is highest for application B1, followed by applications B2, A1, and A2. Application B1 also has the largest stock of installed systems in 2050, followed by A1 and B2 (in that order). Applications B1 and B2 consist of larger systems (with higher thermal output) than A1 and A2. In addition, applications A1 and B1 register 8,000 full load hours against 5,000 for application A2 and B2 (plus 2,000 part-load hours). The size of the systems explains why application B2 scenarios require more fuel than application A1 scenarios. Consequently, the following scenario results will be also discussed exemplarily and more in detail with focus on application B1 (see figure 9 and figure 10).

Comparing the technology scenarios with one another, within an application and across applications, mainly requires looking at respective total annual efficiencies and thermal outputs. In all applications, the wood chip boiler (BB_WC) presents the lower overall fuel use (see figure 9), which is to be expected because the technology consistently has the highest annual efficiency combined with the lowest thermal output and does not need fuel to generate electricity. Comparing fuel use for the HiEff-BioPower technology scenarios (HEBP) with fuel use for the gas engine (GE) scenarios shows that total fuel use of the stock is comparable across all application cases. The fuel use in the gas engine scenarios is a little lower due to the slightly higher total annual efficiency and the slightly lower thermal output at mixed load. The gas engine technology has the same level of thermal output as the wood chip boiler across all applications but a lower total annual efficiency.

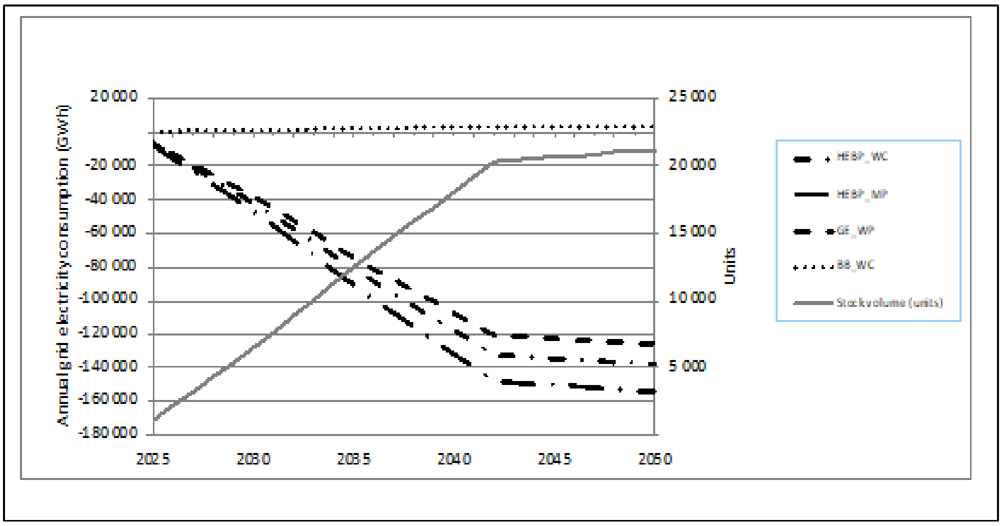
Figure 9. Fuel consumption in the four technology scenarios (Application B1, EU-28)



Source: Own illustration

For the wood chip boiler scenarios this equates the (limited) amount of electricity that the boiler requires for own function. For the gas engine and HiEff-BioPower CHP scenarios net grid electricity consumption is the difference between gross electricity production of the CHP system and the electricity needs of the corresponding technology scenario. In all applications, the HiEff-BioPower technologies present a higher gross electricity production than the gas engine. The HiEff-BioPower scenarios, with one exception, also have lower electricity consumption than the gas engine scenario. The HiEff-BioPower technology fuelled with miscanthus pellets consistently has a higher gross electricity production than the wood chip version, with a similar level of electricity consumption. In the end, the HiEff-BioPower scenarios using miscanthus pellets and wood chips feed more electricity to the grid than the gas engine, which explains why its curve runs lower in the negative part of the graphs than for any other scenario. In other words, the HiEff-BioPower scenarios displace more grid electricity through its own production than the gas engine scenarios. The absolute net electricity consumption values reflect the system and stock sizes. B1 and B2 applications use large systems, with more full load hours in B1. Application A2 uses small systems, coupled to the smallest stock size.

Figure 10. Grid electricity consumption (Application B1, EU-28)



Source: Own illustration

Conclusions

This paper presents results of the impact assessment of the use phase environmental performance of the new HiEff-BioPower CHP technology under development. The results are based on the final data available by the end of the project. Four application cases for space heating and domestic hot water supply were investigated: Application A1 covers “small” CHP systems (200 kW_{el} / 260 kW_{th}) for base load district heating or heat supply for large companies in Central Europe (Germany, Austria) with around 8,000 annual full-load operating hours and up to three start-ups per year. Application A2 covers “small” CHP systems (200 kW_{el} / 260 kW_{th}) for base and medium load coverage (e.g. district heating, hotels, industry) in Central Europe (Germany, Austria) with around 5,000 annual full-load operating hours, 2,000 part-load operating hours, and up to twelve start-ups per year. Application B1 covers “large” CHP systems (1,000 kW_{el} / 1,300 kW_{th}) for base load district heating or heat supply for large companies in Central Europe (Germany, Austria) with around 8,000 annual full-load operating hours and up to three start-ups per year. Application B2 covers “large” CHP systems (1,000 kW_{el} / 1,300 kW_{th}) for base and medium load coverage (e.g. district heating, hotels, industry) in Central Europe (Germany, Austria) with around 5,000 annual full-load operating hours, 2,000 part-load operating hours, and up to twelve start-ups. Furthermore, two variants of the HiEff-BioPower system (fuelled with wood chips and with miscanthus pellets, respectively) are compared to a state-of-the-art conventional biomass boiler fuelled with wood chips and a state-of-the-art CHP gas engine system fuelled with wood pellets. The analysis includes effects of putting these four technologies on the entire European market until 2050. Thereby, emissions (GHG, TSP, CO, OGC, NO_X), fuel and net grid electricity consumption have been taken into account.

All absolute quantities (of emissions etc.) presented in this report should be interpreted in the context of a technology still under development. At this stage, it was important to understand the dynamics of the different application cases to be analysed and their sensitivities to technical parameters and other modelling assumptions. This kind of reasoning will inform both future development of the impact assessment tools and support decision-making regarding the general direction of the technology development and deployment. The modelling results help to identify the main emission drivers for the different technologies considered. In all CHP technology scenarios (HiEff-BioPower and gas engine), greenhouse gas emissions are driven by grid electricity consumption and since CHP technologies generate their own electricity, use part of it but feed most of it to the grid, avoided emissions from grid electricity quickly overcompensate direct GHG emissions from fuel use in these scenarios, meaning that net GHG emissions are actually negative. In the wood chip boiler scenario, on the other hand, greenhouse gas emissions are driven by fuel and grid electricity consumption.

Regarding CO, OGC, TSP, and NO$_X$ emissions, whether solid fuel combustion or indirect emissions from grid electricity generation is the main driver depends on the technology and the type of emissions. The HiEff-BioPower systems show negative net emissions, except for CO where direct emissions from fuel combustion are higher than avoided emissions from electricity generation. In any case, the new HiEff-BioPower technology scenarios show significant technical emission saving potentials compared to state-of-the-art conventional biomass boilers and gas engine CHP. These results are sensitive to crucial technical parameters such as emission intensity of the different solid fuels used by different technologies. Further assumptions regarding the future development of grid electricity emission intensity and heat energy demand (driving thermal output, hence fuel requirements) are also very relevant for the overall behaviour of the model.

Regarding sales and stock volumes, applications A1 and B1, closely followed by application B2, dominate the market potentials. Applications B1 and B2, however, consist of larger systems (with higher thermal output) than A1 and A2. In addition, application B1 registers 8,000 full load hours against 5,000 for application B2 (plus 2,000 part-load hours). These underlying aspects of the model amplify the differences in potential market sizes when comparing the emission scenarios between applications. Application B1 presents the highest absolute emission saving potentials (depending on the technology) for all technologies and types of emission considered. Application B2 comes second. Third are the smaller systems in application A1 (but with the same 8,000 full load hours as in application B1). Finally, application A2, characterised by the lowest market potential, small systems, and lower full load hours, reaches only a fraction of the emission levels and saving potentials observed in application B1.

Considered together, all the insights gained give some meaningful indications on the most prominent aspects to be considered for the further long-range HiEff-BioPower system design and policies aimed at supporting such new technologies. The considerable reductions of air pollutant emissions that this technology makes possible mean that this type of new biomass fuelled CHPs can contribute significantly to reaching the European Union's energy and clean air policy goals by using residual biomass that otherwise would not be used at all. Furthermore, if the market potentials for the large systems (applications B1 and B2) can be fulfilled, any further improvement in the HiEff-BioPower design could have significant additional positive effects.

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References

[1] Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, COM/2021/557 final

[2] Obernberger I., Thek G., Reiter D. Economic evaluation of decentralised CHP applications based on biomass combustion and biomass gasification, Proc. of the 2nd Mid-European Biomass Conference, Jan 2008, Graz, Austria, Austrian Biomass Association (Ed.), Austria

[3] VITO, Utrecht University, TU Wien, INFRO, Rütter Soceco, PwC, 2017: Sustainable and optimal use of biomass for energy in the EU beyond 2020

[4] European Commission: Impact Assessment Guidelines, Brussels, 2009

[5] European Commission: Better Regulation Guidelines – Commission Staff Working Document, SWD (2017) 350, Brussels

[6] Moretti C., Corona B., Shen L., Junginger M. Final Market study for Europe: Comprehensive road map for large scale deployment of the SOFC-CHP in the EU between 2019-2025, 2021, https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5de6e806a&appId=PPGMS

[7] Federal Ministry for Sustainability and Tourism, 2017: Österreichisches Umweltzeichen Richtlinie UZ37: Holzheizungen; Version 6.0; Vienna, Austria

[8] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2002: Technical Instructions on Air Quality Control; Berlin, Germany

[9] Kemna R. et al. (2019): "Ecodesign Impact Accounting - Status Report 2018", prepared by VHK for the European Commission, January 2019, Delft, The Netherlands

[10] COMMISSION RECOMMENDATION of 28.9.2021 on Energy Efficiency First: from principles to practice. Guidelines and examples for its implementation in decision-making in the energy sector and beyond. Brussels, 28.9.2021 C(2021) 7014 final

[11] European Environment Agency (EEA 2022): Greenhouse gas emission intensity of electricity generation in Europe, https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1, (Accessed May 2022).