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Green on-site power generation: Environmental considerations on small-scale biomass gasifier fuel-cell CHP systems for the residential sector

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Abstract

Contemporary combined heat and power (CHP) systems are often based on fossil fuels, such as natural gas or heating oil. Thereby, small-scale cogeneration systems are intended to replace or complement traditional heating equipment in residential buildings. In addition to space heating or domestic hot water supply, electricity is generated for the own consumption of the building or to be sold to the electric power grid.

The adaptation of CHP-systems to renewable energy sources, such as solid biomass applications is challenging, because of feedstock composition and heat integration. Nevertheless, in particular small-scale CHP technologies based on biomass gasification and solid oxide fuel cells (SOFCs) offer significant potentials, also regarding important co-benefits, such as security of energy supply as well as emission reductions in terms of greenhouse gases or air pollutants. Besides emission or air quality regulations, the development of CHP technologies for clean on-site small-scale power generation is also strongly incentivised by energy efficiency policies for residential appliances, such as e.g. Ecodesign and Energy Labelling in the European Union (EU). Furthermore, solid residual biomass as renewable local energy source is best suited for decentralised operations such as micro-grids, also to reduce long-haul fuel transports. By this means such distributed energy resource technology can become an essential part of a forward-looking strategy for net zero energy or even smart plus energy buildings.

In this context, this paper presents preliminary impact assessment results and most recent environmental considerations from the EU Horizon 2020 project ‘FlexiFuel-SOFC’ (Grant Agreement n° 641229), which aims at the development of a novel CHP system, consisting of a fuel flexible small-scale fixed-bed updraft gasifier technology, a compact gas cleaning concept and an SOFC for electricity generation. Besides sole system efficiencies, in particular resource and emission aspects of solid fuel combustion and net electricity effects need to be considered. The latter means that vastly less emission intensive gasifier-fuel cell CHP technologies cause significant less fuel related emissions than traditional heating systems, an effect which is further strengthened by avoided emissions from more emission intensive traditional grid electricity generation. As promising result, operation ‘net’ emissions of such on-site generation installations may be virtually zero or even negative. Additionally, this paper scopes central regulatory instruments for small-scale CHP systems in the EU to discuss ways to improve the framework for system deployment.

Introduction

Traditionally, combined heat and power (CHP) systems are often based on fossil fuels, such as natural gas or heating oil, but the transition to efficient energy systems using renewable energy sources is urgently needed in particular in the heating sector to achieve world-wide sustainability targets. Based on EU classifications, combustion plants are rated >50 MW_{th} for large systems and <1 MW_{th} for small appliances (residential heaters and boilers), with medium combustion plants (MCP) in between. Today, CHP is still mainly realised in the medium and large-scale sector, especially for renewable biomass fuels. However, the applied traditional technologies have restrictions regarding fuel flexibility and electric efficiencies.

In contrast, dedicated biomass integrated gasification fuel cell systems (B-IGFCs), are deemed to achieve much higher efficiency levels [1]. Thereby, adaptation to small scale generation applications based on renewable energy sources (such as solid biomass) is specifically challenging, because of feedstock compositions and heat integration. Small-scale cogeneration systems are thereby typically intended to replace or complement traditional heating equipment in residential buildings. In addition to space heating or domestic hot water supply, a part of the fuel energy is used to generate electricity for the own consumption of the building or to be sold to the electric power grid. In addition to efficiency potentials, B-IGFCs also offer further important co-benefits, such as security of energy supply as well as emission reductions in terms of greenhouse gases (GHG) or air pollutants. In particular, solid residual biomass as renewable local energy source is also best suited for decentralised operations such as micro-grids to avoid inefficient long-haul fuel transports to centralized power plants.

Against this background the EU Horizon 2020 project ‘FlexiFuel-SOFC’ (Grant Agreement n° 641229, see also http://flexifuelsofc.eu) aims at the development of a new, innovative, highly efficient and fuel-flexible biomass CHP technology integrating a small-scale fixed-bed updraft gasifier, a novel and compact gas cleaning concept (covering particle precipitation, removal of HCl, H_2S and other sulphur compounds as well as tar cracking) and a high temperature solid oxide fuel cell (SOFC) for electricity generation. The technology shall be developed for the residential sector with a capacity range of 25 to 150 kW (fuel power) and shall allow the utilisation of cost efficient residual biomass feedstocks to enlarge the applicable fuel spectrum. Overall the new system shall achieve an equal-zero emission operation (regarding CO, OGC, NO_x, HCl, SO_x, PAH and PM and due to the utilisation of biomass also regarding CO_2), in combination with high electric and overall efficiencies. A two-phase approach for the construction of testing plants, the performance of test runs and accompanying assessments shall result in a significant increase of the technology performance of small-scale biomass based CHP systems.

The presented paper provides an overview of environmental aspects relevant for biomass gasifier fuel cell systems in general and presents also a generic approach for assessing related impacts. All given results are based on the work performed in the first phase of the ‘FlexiFuel-SOFC’ (‘FF-SOFC’) project. Following the opportunities and challenges to be addressed, the development of respective technologies for clean on-site heat and power generation is also strongly linked to sufficient incentives. Besides technology aspects, a well-aligned and comprehensive energy efficiency and environmental policy framework is crucial. Accordingly, the obtained results are set into relation with the EU major policy framework and recommendations are portrayed for aligning technical and policy evolution to harness environmental and overall benefits.

Environmental considerations on small scale biomass CHP

In advance of any large-scale future deployment of new technologies, such as efficient CHP systems fostered e.g. by polices and measures, the potential environmental impacts have to be adequately assessed. Accordingly, a systematic approach is needed to evaluate the specific environmental and policy implications. The following chapter describes a generic assessment method, typically used e.g. before the implementation of polices and measures for the EU or other markets, as well as the most relevant parameters and effects to be considered. The described approach is applied by Wuppertal Institute for small-scale biomass gasifier fuel-cell CHP systems for the residential sector and respective findings of the preliminary environmental impact analysis from the EU Horizon 2020 project ‘FlexiFuel-SOFC’ are presented, based on the data inputs by all project partners.

Assessing environmental impacts

Based typically on consecutive results from comprehensive market studies (provided for the FlexiFuel -SOFC project by partner Utrecht University) and data from techno-economic analyses (provided for the FlexiFuel-SOFC project by partner BIOS in cooperation with all other partners), the subsequent environmental impact assessments (IA) also need to follow a well-defined inherent structure. Prototypical structures for such analyses can be derived from various sources. For the presented exemplary IA, main aspects as defined by the Impact Assessment Guidelines of the European Commission [2] are used as basis. However, for assessing the deployment of innovative technologies still under development, some modifications are necessary since the context is not the same, as e.g. for the purposes of dedicated EU Ecodesign and Energy Labelling Directive Impact Assessments. Therefore a holistic method is described based on different steps as follows:

> Step 1: Problem Definition → Step 2: Define Objectives → Step 3: Develop Options →
> Step 4: Impact Analysis → Step 5: Comparison of Options

Step 1: Problem definition – Energy and resource efficiency

Besides general objectives of world-wide sustainability targets, such as mitigating global warming by reducing greenhouse gas and air pollutant emissions as well as the dependence on fossil fuels, also other technology specific aspects have to be tackled. For CHP using renewable energy sources, this applies especially also for constrains regarding the availability of biomass feedstocks.

Global trends concerning population, crop yields, diet, climate change, etc. usually suggest an expansion of cropland – if at all – only for the purpose to feed the world population. Further land requirements for dedicated energy crops would come on top, whereby the sustainable availability of arable land is definitely the essential limiting factor. If land is converted from natural habitats to agricultural areas, there is significant risk for severe biodiversity loss as well as other negative environmental impacts. For example, if major carbon sinks, such as forests, grass- and peatlands, are destroyed to provide space for cultivation, further negative consequences on greenhouse gas balances are the inevitable effect. As long as the overall demand for cropland grows for the needs of food production, any land use for crop production for material or energy purposes will lead to additional direct and indirect land use change [3]. If not strictly controlled, this might also lead to unintended and inefficient long-haul fuel transports, e.g. from tropical countries, where conditions for cheap feedstock production are most favourable.

Availability of water is another limiting factor for growing biomass feedstocks, both in terms of quality and quantity, as agriculture already uses about 70% of fresh water globally [3]. Any expansion of intensive energy crop cultivation would be adding to this. In particular in water scarce regions, this may lead to another form of competition with food production. Thereby, extreme weather events due to climate change might further increase uncertainties in terms of available water resources.

The above-mentioned exemplary environmental impacts related to the ‘water, energy and food nexus’ apply to many ‘first generation biofuels’. However, there are also new pathways for more sustainable production and alternative use of biomass for energy purposes that can help to reduce potential pressures on the environment.

Step 2: Define objectives – Efficiency first

Overall, demand side energy efficiency should provide the ‘first fuel’ for any future economic development [4]. Secondly, on the supply side any use of fuel, also for renewable biomass, should be as efficient as possible. In this context, in particular energy recovery from waste and residual biomass can save significant GHG emissions without requiring additional land use change. Specifically, the inevitable part of municipal organic waste and residues from agriculture as well as forestry provide significant energy potentials, which are still largely untapped worldwide. In the same vein, the cascading use of biomass to produce (construction) material first, then recovering the energy content of the resulting waste, can further maximize the CO_2 mitigation potential of biomass.

Thereby, comprehensive further research is still required, especially concerning the proper balance of residues remaining on-site for soil fertility and removal for energy provision, as well as with regard to nutrient recycling e.g. by ash utilization. Nevertheless, promising approaches exist or are under development to maximize benefits and to minimise negative environmental effects. In this context, the presented specific results from the ‘FlexiFuel-SOFC’ project concentrate on the principles for efficient use of solid biomass fuels from agricultural or forestry residues in small-scale CHP systems based on B-IGFCs during the operation phase, when energy efficiency and pollution control during energy recovery has to be addressed.

Step 3: Develop options – System application cases

Before starting an impact assessment, framework conditions have to be established, in particular the geographical scope (e.g. the EU-28) and time horizon (e.g. 2050) of the analysis. Furthermore, based on market studies and techno-economic analyses the most promising fields of application for the new technology need to be defined. For the analysed systems, decentralised operation close to fuel feedstocks is envisaged to avoid increasing levels of transportation of biomass with market penetration, which could otherwise offset emissions reduction benefits. Accordingly, based on the preliminary results of the ‘FlexiFuel-SOFC’ project, the following specific application cases have been identified for the European market (with focus on Central Europe):

- Application A is a system with about 70 kW_{th} nominal heat output and 20 kW_{el} electric power at nominal load to be used typically for base load heat and electricity production for small district heating networks (micro grids). It can be also applied e.g. for hotels, hospitals, or enterprises with permanent electricity and heat demand over the whole year. It uses bulk agro pellets as non-woody biomass solid fuel, and is characterized by 8,000 effective full load hours annually for electricity generation.

- Application B is a system with about 21 kW_{th} nominal heat output and 6 kW_{el} electric power at nominal load, to be used typically for space and process heating as well as domestic hot water supply for farms, large apartment buildings, public buildings, small enterprises or micro grids. As biomass solid fuel traditional wood chips are used. The system is optimized for heat-controlled operation (electricity and heat production in winter and transitional period; heat supply without electricity production in summer). It is characterized by 4,000 effective full load hours annually for the electricity generation part.

- Application C is a system with about 40 kW_{th} nominal heat output and 6 kW_{el} electric power at nominal load, to be used typically for heat and domestic hot water (DHW) supply for residential buildings such as multi family houses or apartment buildings. It is optimized for heat-controlled operation (electricity and heat production in winter; DHW supply without electricity production in transitional period and summer). Wood chips are used as biomass solid fuel and 2,500 effective full load hours annually are assumed for the electricity generation part.

Furthermore, for each of the application cases, three basic technology performance levels have been evaluated, which cover the most likely alternative technologies for the addressed market segment in Europe (focus on Central Europe/Austria, e.g. for operating hours and PV sunlight availability). Due to the envisaged decentralised operation and consumption strategy no general limitations in terms of electricity grid feed-in capacities are assumed.

- Base Case (BC) or ‘Business as usual (BAU)’ assumes that a standard biomass boiler generates the necessary thermal output for heat supply, while electricity needs of the application case are covered with grid electricity.

- Best Available Technology (BAT) assumes a state of the art biomass boiler (the highly efficient Windhager PuroWIN ultra low emission boiler, on the EU market since 2016) to generate the necessary thermal output, combined with a photovoltaic (PV) system to cover the electricity needs of the application case. The system is also connected to the grid to feed in potential excess PV electricity production or to cover electricity demand surpassing PV electricity output.

- Best Not yet Available Technology (BNAT) represents the newly developed ‘FlexiFuel-SOFC’ system. The needs for both, heat and electricity, in each application case are covered by the CHP system, which is also connected to the grid to feed in potential excess fuel cell electricity production or to cover electricity demand surpassing the CHP electricity output.

The environmental performance parameters from the first phase of the FlexiFuel-SOFC project have been compared within a preliminary environmental performance analysis with respective data from other state-of-the-art systems in order to evaluate and quantify the relative performance and improvement potentials of the new technology on a single product level. Preliminary results for TSP (Total Suspended Particles, also referred to as 'total dust') and energy efficiency (%, based on fuel input in terms of net calorific value 'NCV' / lower heating value (LHV) / lower calorific value (LCV), as well as combined useful heat and electricity output) are presented in Figure 1.

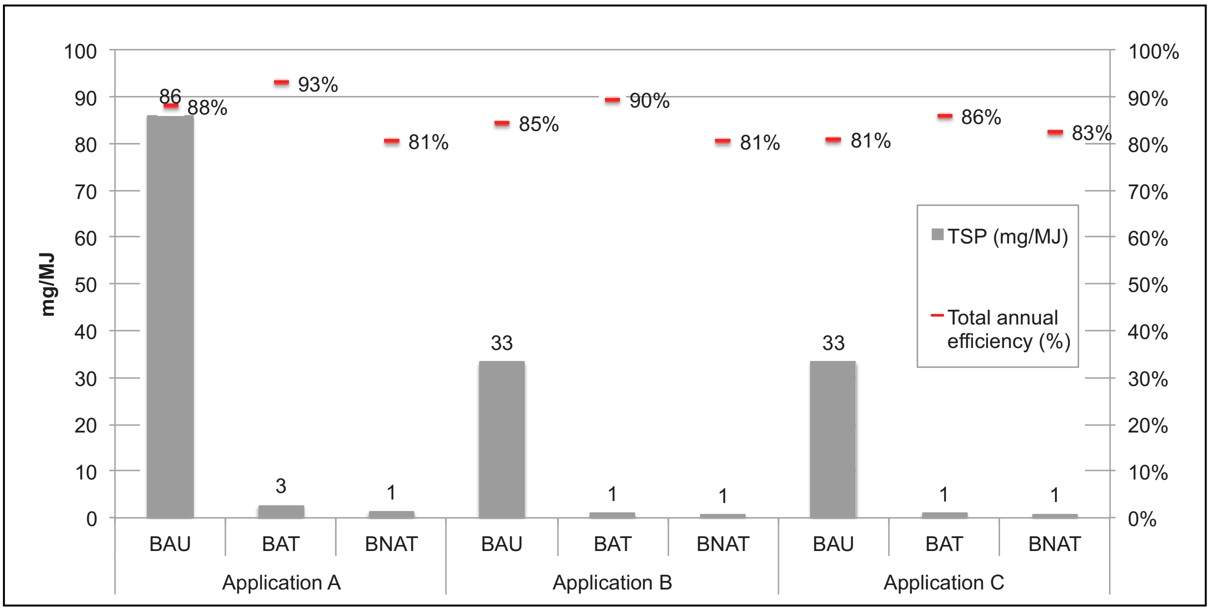

Figure 1: Preliminary TSP emission factors and energy efficiency compared

Source: Own illustration

Taking the available results from the FF-SOFC project into account, the preliminary environmental performance analysis revealed significant technical emission saving potentials of BAT and BNAT compared to BAU standard systems. Thereby TSP (total suspended particles) and (not illustrated) OGC (organic gaseous compounds) and CO (carbon monoxide) show similar reduction trends.

Following this, BAT and BNAT technologies have the potential to reach large on-site emission reductions in a short time period if broad market diffusion rates can be achieved in the future. Based on the current results and input data it can also be concluded that even stringent future Emission Limit Values (ELVs) in the EU for new installations (e.g. as part of a future revision of the EU Ecodesign Lot15 regulation on solid fuel boilers), should be no constraint for the much better new BAT and BNAT systems. The preliminary environmental performance analysis also revealed that in contrast to the very low emission levels, there remains a further technical optimisation potential especially for the total annual efficiency levels of BNAT FF-SOFC technologies compared e.g. to the highly efficient PuroWIN BAT system. This can be explained mainly by the current status of the FF-SOFC technology being still under development (e.g. no final insulation applied), the more complex CHP system operation (compared to heat only operation for BAU and BAT) as well as the technically more challenging usage of agro pellet fuel for Application A. Consequently, these aspects will be further addressed in the final phase of the FF-SOFC project.

Based on the previous definitions and findings, for the macro-scale EU wide impact assessment, the following three basic technology scenarios have been considered for each application case and the analysed specific market segment for heating and CHP systems:

- BC scenario as 'Business as usual' (BAU) development: sales and stock consist of Base Case standard appliances throughout the simulation period.

- BAT scenario: Sales are switched to assumed 100% Best Available Technology from the given reference date 2020 onwards.
- BNAT scenario: Sales switch to assumed 100% Best Not yet Available Technology from the given date 2020 onwards.

It has to be noted that such scenarios provide insights into ‘extreme’ pathways with 100% of sales switch to a given technology performance level within the analysed market segment at a given date while also providing a baseline, which assumes no changes besides the continuation of current trends. The result is a corridor showing the range of available technical potentials that can be addressed by a variable deployment of the new technology, e.g. as result of different polices and measures. This approach with ‘extreme’ pathways has the advantage to require solely total sales and stock data for each application case, and no market share split is required at this level. This provides upper and lower limits for the available corridor, which is especially relevant for new technologies that are still under development, and for which only very preliminary data is available.

As essential part of this step, the application of a dynamic stock model is needed to calculate scenarios for the development of future stock sizes for the different technologies. Generally, based on market study data, stock data can be computed with a sales-driven model combining the last known or reconstructed stock volume data for applications, historical and expected total sales, and average lifespans for the different applications and system components. Stock data are calculated successively for each year of the simulation period, using classical stock dynamics model equations. Accordingly, as relying on preliminary values for several key parameters (such as emission intensities) of technologies still under development, this preliminary assessment does not seek to dwell into every last detail regarding absolute amounts, e.g. of emitted pollutants. At such an early stage emphasis is laid more on comparing the general dynamics of different options and explaining results for model calibration with the aim to give recommendations regarding the general future technical or policy evolution. As technology development progresses, later iterations of the assessment (after final development of the FF-SOFC technology) will address the relevant parameters more in detail.

Step 4: Impact Analysis

The analysis in step 4 evaluates quantitatively the operation-related impacts of the options identified in the previous step. Each option needs to be analysed on its own: first the baseline, that is one BAU scenario per application case; and next, also the BAT and BNAT scenarios respectively. Following this approach, the most relevant impact categories and associated indicators for the analysis are presented.

The most pertinent use-phase environmental indicators for B-IGFCs concern air emissions, including carbon dioxide (CO_2) as the relevant greenhouse gas. Regarding harmful emissions, particulate matter (PM, given in this paper as ‘Total Suspended Particles’ or TSP), organic gaseous compounds (OGC) and carbon monoxide (CO) are parameters typically addressed for biomass combustion systems as well as by related standards and regulations. The derived absolute emission levels depend on assumed stock volumes and product lifetimes, which dictate the pace of (re-)investment cycles. Total annual efficiencies determine fuel requirements for a given energy output. Also the used fuel type is an important influencing factor in terms of combustion processes and technology requirements, e.g. for Application A using a much more challenging non-woody biomass solid fuel (agro-pellets), compared to Applications B and C using traditional woody biomass fuels (wood-chips).

As peculiarity for CHP systems, emissions need to be treated as combined result of direct on-site fuel combustion and grid electricity effects. Taking into account also avoided emissions from off-site grid electricity generation, resulting CHP net emissions may be virtually even negative. Based on basic emission values per fuel type for solid fuel combustion and average emission intensities per type of electricity generation of conventional power generation in Europe [5][6] (for GHG emission rates, including also LCA aspects for fuel processing and transportation), this applies for BAT and BNAT scenarios with less emission intensive on-site technologies in combination with avoided emission-intensive off-site grid electricity generation (see Figure 2 and Figure 3). For the defined application cases, BNAT net emissions decrease further mainly because FF-SOFC devices require less grid electricity consumption (contrary to BAT devices and their intermittent PV systems), hence their gross electrical output (the same as for BAT devices) is more avoided grid electricity which results also in more virtually 'negative emissions'.

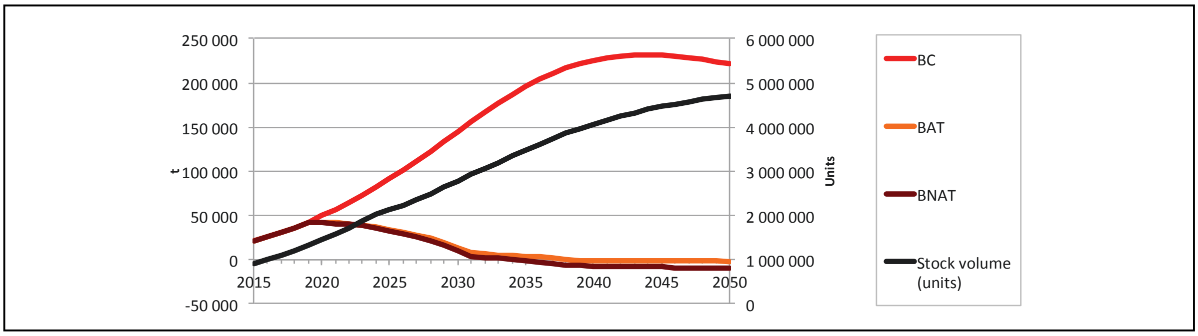

Figure 2: Total net TSP emissions (t) and stock volume (units), EU-28, Applications A, B & C

Source: Own illustration

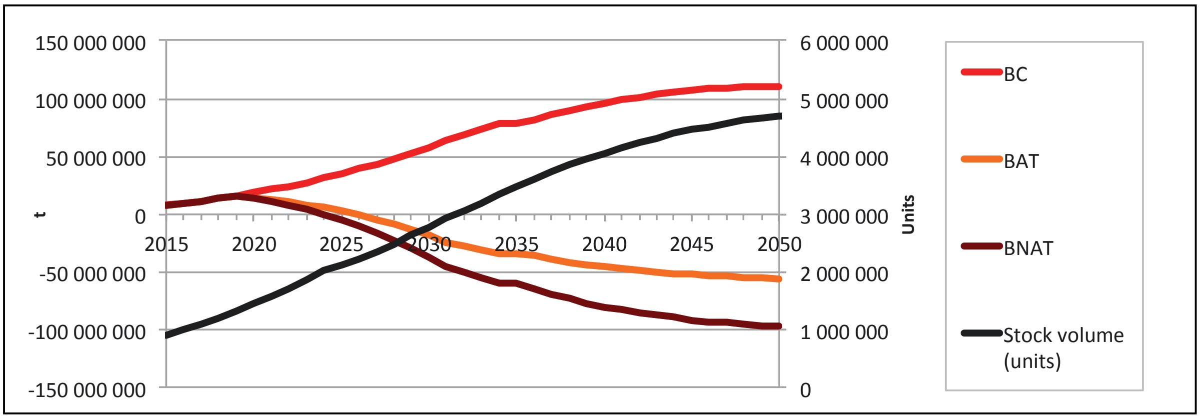

Figure 3: Total net GHG emissions (t) and stock volume (units), EU-28, Applications A, B & C

Source: Own illustration

Further important drivers are the assumptions made regarding the dynamics of key parameters such as the future energy demand per building. E.g. presuming all other aspects being equal, total stock emissions may decrease in the long run even in BAU although the stock still increases. The reason lies in the assumption that the typically required nominal output of heating appliances will decrease as expected effect of improved insulation and energy performance of buildings (e.g. in Europe, based on the European Performance of Buildings Directive 'EPBD' [7]). Consequently, this would mean that less fuel input per unit is required, resulting directly in less fuel related emissions.

Step 5: Comparison of options

Based on the defined operation parameters, total emission saving potentials from Application A are expected to dwarf those of the other two applications, especially due to the larger nominal system capacity, the high number of annual full load operating hours and the more challenging non-woody biomass fuel. Application B is a smaller device with much lower thermal output (less required fuel input), less operating hours per year, and uses ‘cleaner’ woody biomass fuel. Application C runs even less full load operating hours than Application B, generates more heat, but less electricity, i.e. relies more on grid electricity for BC systems.

In general, net grid electricity effects are most relevant regarding the total GHG emissions for BAU, BAT, and BNAT devices. Net GHG emissions in the BAU scenarios are particularly higher due to higher EU traditional power grid emission intensities while both BAT and BNAT GHG net emissions may even virtually decrease below zero due to lower emission intensities combined with the avoided grid electricity. This is also the case even with decreasing future power grid electricity emission intensities (according to current trends) taken into account.

Regarding non-GHG emissions, on-site solid fuel combustion is by far the main driver in baseline scenarios while emissions from fuel combustion and net grid electricity emissions also tend to (over)-compensate each other in BAT and BNAT scenarios. Table 1 compares qualitatively the gained results for the preliminary assessment of the different application cases. Subsequently, during the final phase of the FF-SOFC project, the preliminary environmental performance analysis and impact assessments will be updated and further refined as soon as final measurement data from the technology development will be available.

Table 1: BNAT (FF-SOFC) saving potentials compared to BAU scenarios

Impact indicator	Application A	Application B	Application C
Net electricity effects	+++	++	+
GHG emissions	+++	++	+
Non-GHG emissions	+++	++	+

Note: (+) more absolute saving potentials

As result of the preliminary analysis, especially BNAT for Application A and B systems appear highly relevant for available saving potentials, but also regarding derived non-environmental parameters, e.g. for large potential energy costs savings (solid fuel costs minus avoided grid electricity costs). Intensive use to maximise full load operation hours and electricity generation may even further increase economic attractiveness, which needs however to be adequately balanced e.g. with repair and maintenance costs and the lifetime of system components. Besides the environmental aspect, (fuel) efficiency is also economically a very important parameter, as there is on the other side currently no general financial rewarding for the superior emission reduction performance of the ultra low emission FF-SOFC technologies.

Furthermore, efficiency is typically also the most relevant ranking criteria when regulators implement Minimum Energy Performance Standards (MEPS). The same applies to product energy labels, which allow a better visibility and the active promotion of very innovative technologies. Related to this, also the selection for product-specific incentive programmes to foster e.g. a voluntary early retrofit or replacement of old installations with much better new products depend usually on (very) high efficiency levels. The high relevance of such policies and measures for CHP is therefore also further addressed in the following section.

Environmental policy aspects for CHP

In the last 20 years, much has been done to support cogeneration, i.e. an environmentally friendly way to generate electricity and useful heat. In Europe, several policies on EU and Member States (MS) level were introduced to foster the technology. At the same time, the aim was to increase the overall energy efficiency of the technology and to reduce harmful emissions to the environment, giving directly or indirectly general incentives also for the development of innovative B-IGFCs.

In 1997, a strategy to promote CHP and to dismantle barriers to its development was published [8]. From that time, the way was open for an accelerated development towards cogeneration. The next Figure 4 illustrates the relevant main EU policies on a timeline. The Directives, which are written in bold are key policies that have a strong influence on CHP, the other measures have an indirect effect. All together, they form a comprehensive policy package including clear targets, taxes, minimum standards, capacity building and financial incentives. In addition, it is important to consider that EU level measures are complemented by EU Member State's national policies. Some MS, like Germany, Belgium and the Netherlands have already introduced ambitious plans that go far beyond the requirements of the EU. The relevant EU policies with implications also for small-scale systems are described below.

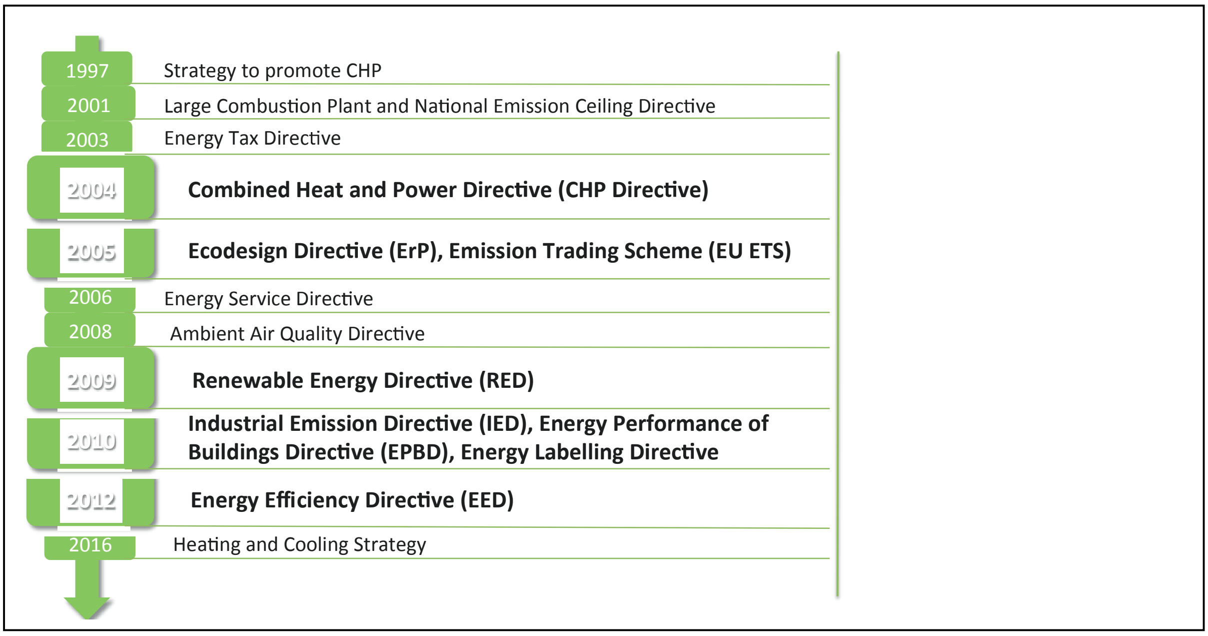

Figure 4: Evolution of the EU legislative regime on cogeneration

Source: Own illustration

In 2004, the CHP Directive 2004/8/EC [9] was published with the aim to 'increase energy efficiency and improve security of supply by creating a framework for promotion and development of high efficiency cogeneration of heat and power based on useful heat demand and primary energy savings'. This was the first Directive with a focus only on cogeneration technologies. In 2012, this Directive was repealed by the Energy Efficiency Directive (EED) 2012/27/EU [10] and forms today the basis for the CHP development on EU level.

In contrast to the EED, the Ecodesign Directive 2009/125/EC [11] (also referred to as 'Energy related Products' or ErP Directive) forms a framework to set minimum performance requirements for specific product groups. Several Ecodesign implementing measures address cogeneration, e.g. regulation 2015/1189 applies to solid fuel systems with a nominal heat output of 500 kW_{th} or less as well as to solid fuel cogeneration boilers with an electrical capacity of less than 50 kW_{el}. The regulation sets MEPS and emission limit values (ELVs) for particulate matter, organic gaseous compounds, carbon monoxide and nitrogen oxides. Manufacturers have to meet these requirements, valid as of January 2020, to put products on the EU single market.The minimum requirements of the Ecodesign Directive go hand in hand with the Energy Labelling Directive 2010/30/EU [12], which provides depicted information to consumers on the efficiency of energy-related products. Respective information is provided for many product groups through a label, which is attached to each covered product to be sold on the European market. Due to this increased transparency, consumers and investors, which are the main target group, shall opt for more efficient products. In the wake of increased demand for energy-efficient technologies, manufacturers are, in turn, incentivised to develop more innovative products. For this purpose the European Commission determined for the current regulation that energy classes A++ and A+ rated heating appliances, which indicate the most energy-efficient technologies in this product group, are reserved for cogeneration as well as renewable energy sources. Hence, the EC deliberately decided to direct investment decisions of consumers and investors towards low-carbon cogeneration technologies.

Besides cogeneration-specific Directives, the Renewable Energy Directive (RED), and the Energy Performance of Buildings Directive (EPBD) build a general policy framework. These framework

Directives do not affect CHP specifically but have a strong influence in fostering the market. Thereby, the Renewable Energy Directive 2009/28/EC [13] has also an indirect role in influencing cogeneration applications with its specific role for biomass. Besides other aspects, the Directive establishes objectives to expand the share of renewable energy in the energy mix of the MS.

Even though the RED does not include a specific target on the expansion of cogeneration, in particular, MS can meet EU renewable energy objectives, among others (e.g. cofiring), also by biomass cogeneration. In addition, the Directive requests annual National Renewable Energy Action Plans (NREAPs), which shall provide planning security for investors.

Another relevant regulation is the Energy Performance of Buildings Directive 2010/31/EU [7] by stipulating in a holistic way that buildings become more energy-efficient. Existing buildings are supposed to meet energetic standards (Article 7) and all new buildings will have to be 'Nearly Zero-Energy Buildings' (NZEB) by the beginning of 2021. Furthermore, for new buildings, the Directive instructs that 'the technical, environmental and economic feasibility of high-efficiency alternative systems' should be taken into account. This also includes cogeneration as well as district heating or cooling systems, especially those that rely on energy from renewable sources. Hence, the EPBD requests MS to factor in CHP and district heating for providing building energy, which may have a positive effect on the demand for respective systems. However, given that the EPBD facilitates the reduction of energy demand in buildings, it should be acknowledged that buildings would also require less absolute energy for space heating. If net zero-energy buildings are achieved, the demand for CHP may alter and e.g. several building owners or settlements may have to team up so that heat energy demand is suitable for an economically feasible operation of a single joint CHP system.

Overall, the existing EU policy package for cogeneration has a strong influence on the potential market share of B-IGFC systems. The high number of policies demonstrates the relevance of CHP technology and the envisaged role in the coming years, and among others, EED, EPBD and the Ecodesign Directive/Labelling Directives are currently also under review to further enhance their future effectiveness. The next Figure 5 summarizes CHP relevant policies and differentiates between the nominal power range of the affected systems and the type of fuel.

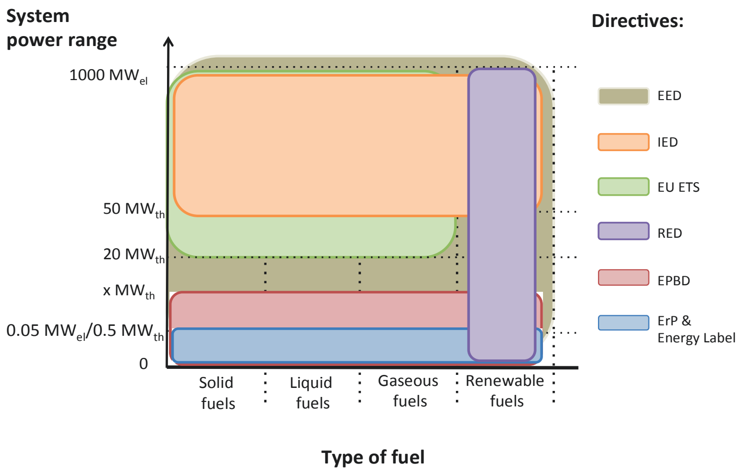

Figure 5: EU policies relevant for CHP, depending on fuel and nominal power range

Source: Own illustration (based on [14])

Conclusions and outlook

This paper provides insights into the most essential environmental aspects of small-scale gasifier fuel cell CHP systems, based on preliminary environmental impact assessment results for the technology developed in the EU Horizon 2020 project ‘FlexiFuel-SOFC’.

Three specific application cases were investigated, which represent the most promising fields of application for the new technology on the European market: Application A for hotels, enterprises, small district heating networks; Application B for farms, small enterprises, micro grids as well as Application C for smaller residential buildings. Furthermore, for each of the application cases, the new FF-SOFC systems as ‘Best Not yet Available Technology’ (BNAT) were compared to traditional biomass boilers (Base Case or BC) and to state of the art biomass boilers associated with a PV system (Best Available Technology or BAT), which represent the most likely alternative technologies to be replaced on the European market. Thereby, on-site air emissions as well as grid electricity consumption effects have been jointly taken into account. Most relevant was for the preliminary impact assessment of the FlexiFuel-SOFC project to demonstrate general dynamics of different application cases and their sensitivities to technical parameters and other modelling assumptions. This kind of reasoning will inform how to use environmental impact assessment approaches to support directly decision-making processes regarding the general direction of the technology development and for policy making.

The presented results clearly identify the main emission drivers for the different technologies considered. In all scenarios, greenhouse gas (GHG) emissions are driven by grid electricity consumption effects. Since BAT and BNAT technologies generate their own electricity, avoided off-site grid electricity emissions quickly overcompensate direct on-site emissions from fuel usage in these scenarios, meaning that net GHG emissions are virtually negative. Regarding non-GHG emissions, on-site solid fuel combustion is by far the main driver in baseline scenarios while emissions from fuel combustion and net grid electricity emissions even tend to (over)-compensate each other in BAT and BNAT scenarios. BNAT scenarios show significant technical emission saving potentials compared to BC and even BAT systems, mainly because vastly less emission intensive BNAT devices consistently help to avoid more grid electricity consumption than intermittent BAT PV systems. It has to be mentioned that such results are sensitive to several crucial (preliminary) technical parameters of the FF-SOFC technologies that are still under development, such as e.g. emission intensities of the different solid fuels used by the application cases. Further assumptions regarding the future development of EU grid electricity emission intensities and heat energy demand (driving thermal output, hence fuel requirements) are also very relevant for the overall behaviour of the modelling.

Considered together, the gained insights give some meaningful indications on the most prominent environmental aspects to be considered for the further long-range system design within the FlexiFuel-SOFC project. The maximisation of electricity full load operation makes BNAT systems - with the current set of assumptions - most attractive, due to relevant on-site and grid electricity emission reductions (displaced EU grid electricity generation by own electricity production). Therefore, Applications A and B have overall saving potentials much larger than Application C, which make them most relevant for closer scrutiny. Of the two, Application A has by far the larger impact, especially due to significantly higher nominal heating and electric capacities, longer operating hours and the used agro-pellet non-woody biomass fuel.

Additionally, the gained results have to be set into relation with policy developments addressing the CHP sector. Especially for smaller CHP systems targeting at the residential sector, policies that address the typically required size of heating appliances may affect considerably the development and usage profiles of such systems. Most prominently, e.g. in Europe, based on the European Performance of Buildings Directive ‘EPBD’, the expected effect is that heat requirements of buildings will decrease significantly as consequence of improved insulation and energy performance of buildings. Accordingly, this may lead especially in the residential sector to altered system requirements, causing a shift from single dwelling heating systems towards micro-grids supplying several dwelling units to allow economically attractive annual operation hours. Additionally, very specific regulations for appliances, such as Ecodesign and Energy Labelling may further incentivise the market of residential scale B-IGFC systems. Overall, in this context FF-SOFC systems may provide one of the essential key technologies for efficient decentralised power and heat generation based on renewable energy sources to pave the way towards a decarbonized energysystem.

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