Final Impact Assessment of a Small-Scale Biomass Gasifier Fuel-Cell CHP System for Clean On-site Power Generation

Thomas Goetz, Lena Tholen, Jan Kaselofsky, and Thomas Adisorn

Abstract The EU Horizon 2020 funded project 'FlexiFuel-SOFC' (Grant Agreement n° 641,229, 2015–2019) developed a new and highly efficient small-scale biomass Combined Heat and Power (CHP) system for clean on-site cogeneration. It shall replace traditional systems based on fossil fuels, being at the same time fuel flexible for utilizing solid biomass residues (e.g. wood chips or olive stones), robust, cost efficient, and distinguish itself by high electric and overall efficiencies as well as almost zero emissions. In particular small-scale CHP technologies suitable for micro-generation are challenging, but biomass gasification and solid oxide fuel cells (SOFCs) offer significant potentials and important co-benefits, such as security of energy supply as well as emission reductions in terms of greenhouse gases or air-quality related pollutants.

This paper presents final impact assessment results from the development of the novel CHP system, consisting of a fuel flexible small-scale fixed-bed updraft gasifier, a compact gas cleaning unit and an SOFC for electricity generation. System efficiencies and emissions of solid fuel combustion and grid electricity effects were evaluated. Gasifier-fuel cell CHP technologies produce significantly less fuel-related emissions compared to traditional heating systems and also produce electricity with fewer emissions than traditional grid electricity generation systems.

Such new developments are also influenced by several national and international policies and measures, which can prevent or incentivize the potential market of the new technology. Therefore, complementary to the results of the final impact assessment, this paper also addresses selected policies on EU and Member States level with relevance for small-scale CHP technologies. In doing so, this paper asks from an innovation point of view how the current policy mix hinders or supports the market uptake of such small-scale CHP technologies. The paper factors in relevant elements of the policy package such as the CHP Directive, the Renewable Energy Directive and the Energy Performance of Buildings Directive.

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P. Bertoldi (ed.), *Energy Efficiency in Domestic Appliances and Lighting*, Springer Proceedings in Energy, https://doi.org/10.1007/978-3-030-79124-7_10

1 Introduction

Traditionally, 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 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]. 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 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 consumption at the building or to be sold to the electric power grid. In addition to efficiency potentials, B-IGFCs also offer 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 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° 641,229, see also http://flexifuelsofc.eu) developed a new, innovative, highly efficient and fuel-flexible biomass CHP technology. The new technology integrates 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 was developed for the residential sector with a capacity range of 25–150 kW (fuel power) and the utilisation of cost efficient residual biomass feedstocks to enlarge the applicable fuel spectrum. Overall the new system shall achieve an operation with significantly reduced emissions (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 provides a significant advance in the technology performance of small-scale biomass based CHP systems.

This paper provides an overview of environmental aspects relevant for biomass gasifier fuel cell systems in general and also presents a generic approach for assessing related impacts. All results are based on the final work performed in 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 policy framework and recommendations are provided for aligning technical and policy evolution to harness maximum environmental and overall benefits.

2 Environmental Considerations of 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 section 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, small enterprises, hospitals and hotels. Respective findings of the final environmental impact analysis from the EU Horizon 2020 project ‘FlexiFuel-SOFC’ are presented based on the data inputs from all project partners.

2.1 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) follows a well-defined structure. For the presented final impact assessment, the main aspects, as defined by the Impact Assessment Guidelines of the European Commission [2], are used as basis and further modified for the purpose of the analysis. A holistic method is described based on the following steps:

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

2.1.1 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, other technology specific aspects have to be tackled. For CHP using renewable energy sources, this applies especially to constraints 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 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.

2.1.2 Step 2: Define Objectives: Efficiency First

Overall, demand side energy efficiency should provide the ‘first fuel’ for any future economic development [4]. 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 carbon dioxide (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 final 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 in particular.

2.1.3 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. EU-28) and time horizon (e.g. 2050) of the analysis. 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 to a certain extent. Accordingly, based on the 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 also be applied to hotels, hospitals, or enterprises with permanent electricity and heat demand over the whole year. It uses olive stones (Application A1) or wood chips (Application A2) as biomass solid fuel and is characterized by 8000 effective full load hours annually for electricity generation.
- Application B is a system with about 21 kW_{th} nominal heat output and about 5 kW_{el} electric power at nominal load, to be used typically for space and process heating as well as domestic hot water supply for large apartment buildings or public buildings with a buffer storage system. Olive stones (Application B1) or wood chips (Application B2) are used as the fuel. 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 4000 effective full load hours annually for the electricity generation part.

For each of the application cases, the new FF-SOFC technology is compared to state-of-the-art technologies that have the same nominal heating capacity. Four different technologies or technology combinations are modelled and compared to the new FF-SOFC technology. Due to the envisaged decentralised operation and consumption strategy no general limitations in terms of electricity grid feed-in capacities are assumed.

- Biomass boiler with grid electricity (BBwGRID): In this scenario a biomass boiler is employed for heat production, while the electricity demand is supplied from the grid. The biomass boiler has a nominal heating capacity of about 70 kW_{th} (Application A) and 21 kW_{th} (Application B), respectively. In the scenarios, the biomass boiler is either fuelled with olive stones (Applications A1 and B1) or wood chips (Applications A2 and B2).
- Biomass fired small scale CHP (BCHP): In this scenario a small biomass CHP is used to produce electricity and heat. The CHP has a nominal heating capacity of about 70 kW_{th} (Application A) and 21 kW_{th} (Application B), respectively. The gross electric capacity is 31 kW_{el} (Application A) or about 9 kW_{el} (Application B). The biomass CHP is fuelled with wood chips across all application cases (Applications A1, A2, B1 and B2).
- Natural gas fired CHP (NGCHP): Likewise, a small CHP is used to produce electricity and heat. The CHP has a nominal heating capacity of about 70 kW_{th} (Application A) and 21 kW_{th} (Application B), respectively. The gross electric capacity is about 42 kW_{el} (Application A) or about 9 kW_{el} (Application B). The natural gas fired CHP is fuelled with natural gas across all application cases (Applications A1, A2, B1 and B2).
- PuroWIN with photovoltaics (PWINwPV): In this scenario, the Windhager PuroWIN ultra low emission boiler is used to supply heat. The PuroWIN boiler is combined with a photovoltaic system that supplies electricity to the boiler. Surplus electricity is fed into the grid. The boiler has a nominal heating capacity of about 70 kW_{th} (Application A) and 21 kW_{th} (Application B), respectively. The photovoltaic system is seized to have a gross electric capacity of 144 kW_{el} (Application A) and about 22 kW_{el} (Application B). The PuroWIN boiler is either fuelled with olive stones (Applications A1 and B1) or wood chips (Applications A2 and B2).

The environmental performance parameters from the FlexiFuel-SOFC technology have been compared within an 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. Results for Total Suspended Particles (TSP), 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 Figs. 1 and 2.

Taking the available results from the FF-SOFC project into account, the environmental performance analysis shows significant technical emission saving potentials of the FF-SOFC, PuroWIN and CHP scenarios compared to the standard biomass boiler. Though the absolute differences are small and, due to rounding, cannot be seen in Figs. 1 and 2, the TSP emission intensity of the new FF-SOFC technology is lower than those found for the biomass fired CHP and the PuroWIN boiler. The large difference between the emission intensity of the biomass boiler between

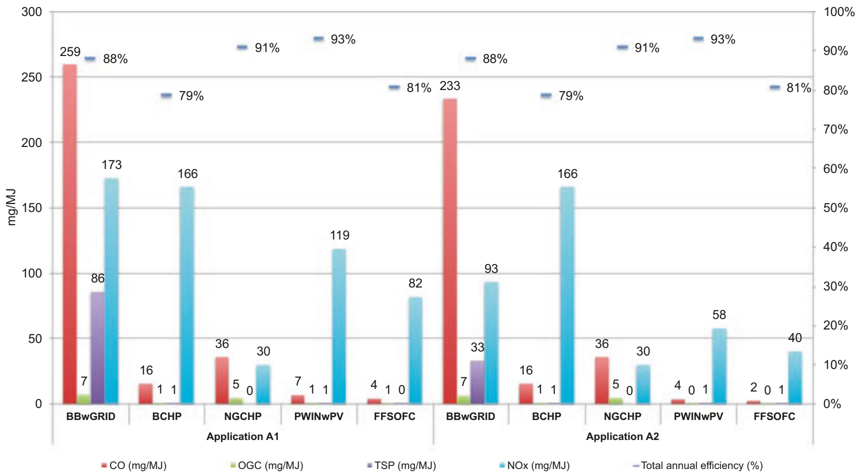


Fig. 1 Application A emission factors and energy efficiency compared
Source: Own illustration

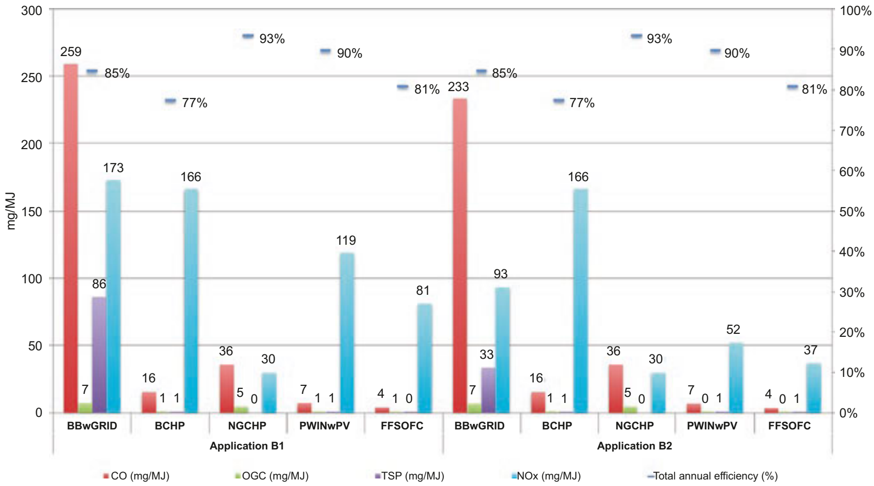


Fig. 2 Application B emission factors and energy efficiency compared
Source: Own illustration

Applications A1 and A2 and Applications B1 and B2, respectively, can be explained by the fuel type (olive stones in the case of Applications A1 and B1, wood chips in the case of Applications A2 and B2). For other air pollutants, such as organic gaseous compounds (OGC) and carbon monoxide (CO), the FF-SOFC technology is associated with considerably lower emission intensities than the biomass boiler as well as the biomass and natural gas fired CHP. The FF-SOFC also constitutes an improvement compared to the PuroWIN boiler, though the improvement is not as large as those of other technologies.

Accordingly, the FF-SOFC technology has the potential to reach considerable 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 FF-SOFC system. The 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 FF-SOFC technology. Nevertheless, even now, the FF-SOFC technology constitutes a small, but considerable, improvement compared to the biomass fired CHP. The biomass fired CHP is an adequate case for comparison as it also co-generates heat and power. For the other biomass technologies, the total annual efficiency of the FF-SOFC is lower than those of the biomass boiler and, even more so, the PuroWIN boiler. This can be explained by the more complex CHP system operation of the FF-SOFC compared to the heat only operation of the biomass boiler and PuroWIN boiler, respectively. Nevertheless, further increasing the total annual efficiency of the FF-SOFC will remain a major goal of future research and development.

Based on the previous definitions and findings, for the macro-scale EU wide impact assessment, five technology scenarios have been modelled. In every technology scenario the demand for heating systems estimated in the market study is supplied exclusively by the technology giving the scenario its name, i.e. in the FF-SOFC scenario every heating system sold for the application case under consideration is a FF-SOFC appliance. As such, the scenarios provide insights into ‘extreme’ pathways with 100% of sales switch to a given technology. This approach has the advantage of only requiring total sales and stock data for each application case, and no market share split is required at this stage. This provides upper and lower limits for the available corridor for the emission saving potential, which is especially relevant for new technologies that are still under development, and for which only very preliminary data is available.

As an 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 life spans 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 a technology still under development, this assessment does not seek to dwell into every last detail regarding absolute amounts, e.g. of emitted pollutants. The emphasis is put on comparing the general dynamics of different options and explaining the results for model calibration with the aim to give recommendations regarding the general future technical or policy evolution. The stock is assumed to have a size of zero in the first year of the period under consideration (2023). The model assumes that appliances that are decommissioned after their lifetime will be replaced by a new appliance of the same type.

2.1.4 Step 4: Impact Analysis

The analysis in step 4 quantitatively evaluates the operation-related impacts of the options identified in the previous step. Each technology option is modelled on its own and then compared to the other technologies. Following this approach, the most relevant impact categories and associated indicators for the analysis are presented.

Air emissions are the most pertinent use-phase environmental indicators for B-IGFCs, including CO_2 as the relevant greenhouse gas. Regarding harmful emissions, particulate matter (PM), given in this paper as 'Total Suspended Particles' (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. The fuel type is an important influencing factor in terms of combustion processes and technology requirements, as the two fuel types (i.e. olive stones and wood chips) considered in the model do amount to different air pollutant emission intensities.

As peculiarity for CHP systems, the emissions need to be treated as a combined result of direct on-site fuel combustion and grid electricity effects. Avoided grid electricity consumption is taken into account by subtracting the product of the grid's emission intensity and the gross electricity generation of the CHP or PV from the emissions caused by burning the fuel. The following results are calculated with 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] (GHG emission intensities do include Life Cycle Analysis (LCA) aspects for fuel processing and transportation). Due to this method, all technology scenarios except for the biomass boiler with grid electricity scenario may lead to negative emissions if the emissions avoided by not consuming grid electricity overcompensate the emissions caused by fuel combustion. In the case of non-GHG emissions, every technology scenario that implies an on-site electricity generation results in negative net emissions (see Figs. 3–6, exemplarily for Application A2). The biomass boiler with grid electricity and the natural gas CHP scenarios produce positive net GHG emissions, while the other scenarios lead to negative net GHG emissions (see Fig. 7). This is due to the GHG emission intensity of grid electricity being significantly higher than the GHG emission intensity of the solid biomass fuels even in the year 2050 and under consideration of the life cycle. A side effect of this is that scenarios which model technologies with a higher gross electrical capacity, and consequently generating more electricity, lead to lower net GHG emissions. The biomass fired CHP has a gross electric capacity that is more than 10 kW_{el} (Application A) and about 4 kW_{el} (Application B) higher than the

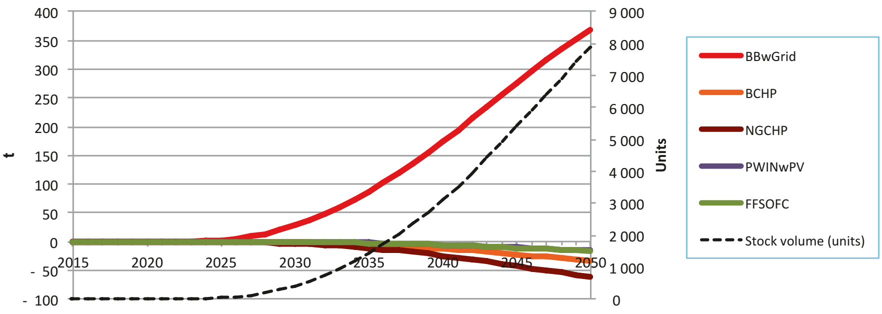


Fig. 3 Total net TSP emissions (t) and stock volume (units), EU-28, Application A2
Source: Own illustration

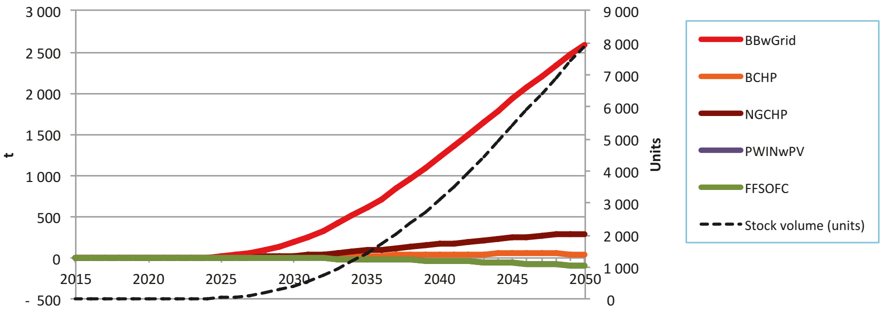


Fig. 4 Total net CO emissions (t) and stock volume (units), EU-28, Application A2
Source: Own illustration

FF-SOFC. Accordingly, the net GHG emissions seen in the BCHP scenarios are lower than those seen in the FF-SOFC scenarios.

An important driver of future fuel consumption and, consequently, emissions is the future development of energy demand per building. Presuming all other aspects being equal, the total stock emissions may decrease in the long run even with an increasing stock. The model assumed 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.

2.1.5 Step 5: Comparison of Options

Based on the market study, Application B has a market potential about twice as high as Application A. Yet, due to the larger nominal system capacity and a higher number of annual full load operating hours, absolute values (irrespective of the sign) for fuel and grid electricity consumption, as well as air pollutant and GHG emissions

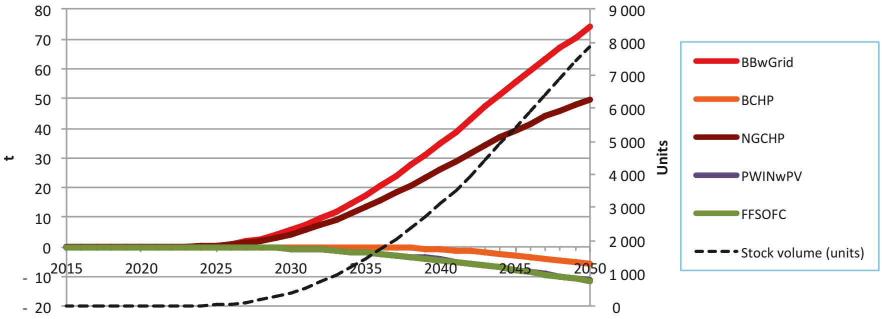


Fig. 5 Total net OGC emissions (t) and stock volume (units), EU-28, Application A2
Source: Own illustration

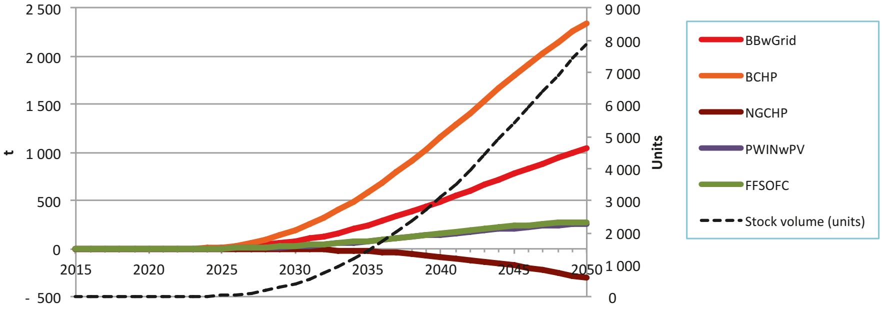


Fig. 6 Total net NO_X emissions (t) and stock volume (units), EU-28, Application A2
Source: Own illustration

tend to be considerably higher in the Application A scenarios. Comparing the technology options with each other, one finds that, when avoided emissions are considered in the calculation of net emissions, the FF-SOFC technology allows for net negative GHG emissions. This distinguishes the FF-SOFC scenario from the biomass boiler with grid electricity and natural gas fired CHP scenarios, which show positive net GHG emissions. At the same time, the PuroWIN boiler with photovoltaics and the biomass fired CHP scenario lead to even lower (i.e. more negative) emissions. This is mainly due to a higher amount of electricity being generated by these technologies for a given heat demand. All results are dependent on the development of the emission intensity of grid electricity assumed for the future.

As with GHG emissions, air pollutant emissions are calculated by adding the emissions caused by on-site solid fuel combustion to the emissions caused off-site by generating grid electricity. If electricity is generated on-site by a CHP or PV, the emissions avoided by replaced grid electricity generation are added to the emissions caused by fuel combustion. Consequently, air pollutant emissions become negative when avoided off-site emissions overcompensate on-site emissions. The scenarios with the new FF-SOFC technology lead to air pollutant emissions that are lower or similar to those seen in the scenarios with the state-of-the-art biomass fired

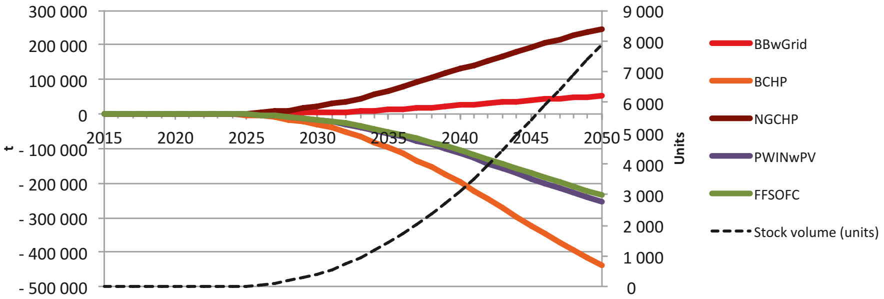


Fig. 7 Total net GHG emissions (t) and stock volume (units), EU-28, Application A
Source: Own illustration

technologies. Compared to a state-of-the-art natural gas fired CHP, the FF-SOFC scenario produces higher NO_X emissions (due to the fuel's higher nitrogen content), slightly higher TSP emissions, and lower CO and OGC emissions.

Besides the environmental aspect, (fuel) efficiency is a very important parameter, both regarding energy costs and energy security. Compared to the most similar technology options, the biomass fired CHP, the FF-SOFC technology has a slightly higher total annual efficiency. As there is no general financial reward for the superior emission reduction performance of the ultra low emission FF-SOFC technologies at the moment, higher efficiencies and thus lower energy costs may become an important selling point. 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 innovative technologies. Related to this, also the selection for product-specific incentive programmes to foster a voluntary early retrofit or replacement of old installations with much better new products depends usually on (very) high efficiency levels. The high relevance of such policies and measures for CHP is therefore further addressed in the following section.

3 A Policy Package for Small-Scale CHP Technologies

The new and highly efficient FlexiFuel-SOFC technology is distinguished by high electric and overall efficiencies as well as almost zero emissions. However, many barriers (financial barriers, information barriers, regulatory barriers etc.) still exist and market forces alone are often unlikely to initiate broad market diffusion. Even if well thought-out and long-term business plans are available, it is often challenging for companies to sell a new technology to a large number of customers. Therefore, policy is needed to overcome these barriers and to exploit the existing high potential. That is why policy makers have to develop adequate strategies to influence the market development. Experience shows that several instruments need to interact and reinforce each other in a comprehensive policy package. Every policy is tailored to overcome one or a few barriers, but there is no one-fits-all policy [8]. Due to scope limitations in this paper, it is not possible to describe and analyse all relevant policies and measures in detail. Therefore, the next section focuses on a few key instruments at EU level.

3.1 A Policy Package on EU Level

Currently, there are several efforts in the European Union to implement policies and measures to address cogeneration. The aim is to enhance the technology, increase energy efficiency, and improve air quality. Two Directives with a high influence on the development of cogeneration systems are the Renewable Energy Directive (RED) and the Ecodesign Directive. Other Directives primarily address air quality or influence cogeneration indirectly, e.g. by setting higher energy prices. The Energy Efficiency Directive (EED) strongly influences cogeneration as the CHP-Directive 2004/8/EC was repealed in 2014 and replaced by the EED. Figure 8 illustrates the policy package on EU level for cogeneration with a focus on three directives. It is important to notice that this is not to say that other policies such as the Energy Performance of Buildings Directive (EPBD) and the Energy Labelling Directive do not have a relevant direct or indirect influence on the technology. In the scope of this paper, however, the focus is on the illustrated instruments.

The Ecodesign Directive 2009/125/EC [10] (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}. In addition to energy performance criteria, the regulation entails emission limits for PM, OGC, CO and NO_X. Both energy and emission standards depend on the boiler’s rated heat output, on the boiler type (automatically or manually stoked) or on the fuel type (biomass or fossil fuel). Manufacturers have to meet the standards, which will become valid as of January 2020. Some types of boilers are excluded from current regulation including non-woody biomass boilers, which includes fuels such as straw, grains, olive stones, or nut shells. Other exceptions include boilers generating heat exclusively for providing hot drinking or sanitary water; boilers for heating and distributing gaseous heat transfer media such as vapour or air (Commission Regulation 2015/1189, Art. 1, 2). A review of Commission Regulation 2015/1189 is scheduled prior to 1 January 2022. For the long-term perspective, the review will include an assessment to set potentially stricter requirements beyond 2020 for energy efficiency and emissions regarding PM, OGC and CO. In addition, the review will factor in whether it is appropriate to also regulate “non-woody biomass boilers with Ecodesign requirements for their specific types of pollutant emissions.” Ecodesign can be considered as a driver for innovative technologies such as

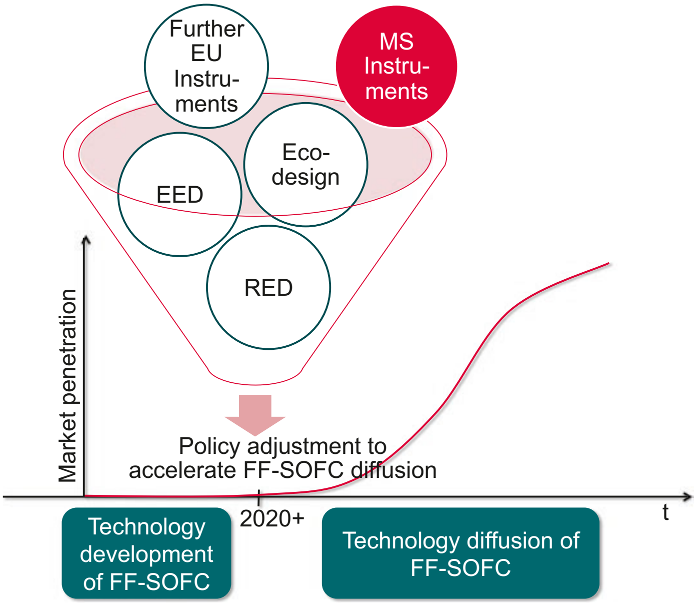
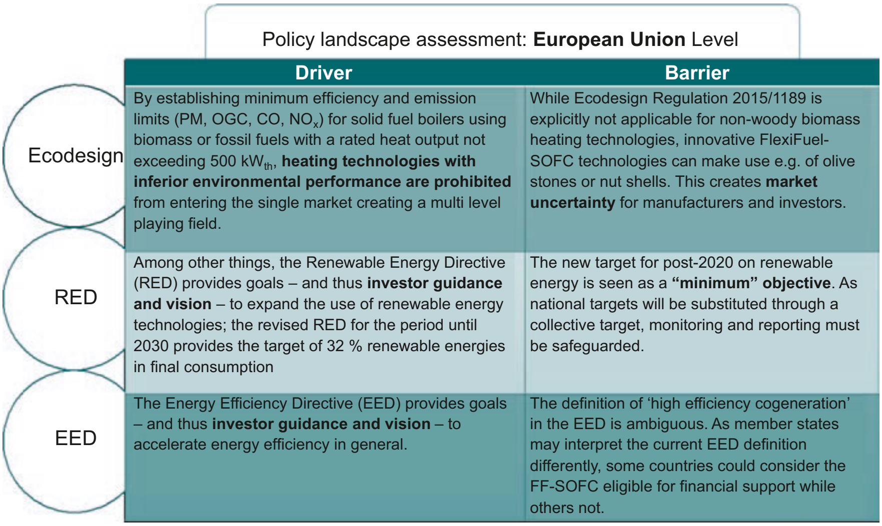


Fig. 8 Towards a policy package for fuel flexible CHP technology
Source: [9]

FlexiFuel-SOFC. Only highly efficient solid-fuel boilers meeting the standards are allowed to be put onto the EU single market. However, as FlexiFuel-SOFC boilers can also make use of non-woody biomass, which remains unregulated under the current Ecodesign implementing measure, there remains some market uncertainty.

Besides Ecodesign, the Renewable Energy Directive 2018/2001/EU (RED) builds a general policy framework [11]. The RED contributes to facilitating the use of renewable energy for heating by establishing objectives to expand the share of renewable energy (including biomass) in the energy mix of Member States. Generally, the RED may draw increasing attention of policy makers to the FlexiFuel-SOFC technology as a means to promote the use of renewable energy in the heating sector. In January 2019, the RED was revised (RED II). It provides, among other things, a new target of 32% renewable energy in final consumption for the EU by 2030 and a sub-target of an indicative 1.3% yearly increase of renewable energy in heating and cooling installations, calculated on a period over 5 years starting in 2021. RED II does also set sustainability criteria for solid biomass.

Another relevant Directive is the Energy Efficiency Directive (EED), which seeks to ensure the EU headline target on energy efficiency, paving the way for more efficient heating technologies in residential buildings [12]. The EED requires Member States to develop strategies for the implementation of high-efficient CHP and district heating. The Directive was revised in December 2018. The recast includes a new energy efficiency target for the EU for 2030 of 32.5%, with an upwards revision clause by 2023.



Policy landscape assessment: **European Union** Level

	Driver	Barrier
Ecodesign	By establishing minimum efficiency and emission limits (PM, OGC, CO, NO_x) for solid fuel boilers using biomass or fossil fuels with a rated heat output not exceeding 500 kW_{th}, **heating technologies with inferior environmental performance are prohibited** from entering the single market creating a multi level playing field.	While Ecodesign Regulation 2015/1189 is explicitly not applicable for non-woody biomass heating technologies, innovative FlexiFuel-SOFC technologies can make use e.g. of olive stones or nut shells. This creates **market uncertainty** for manufacturers and investors.
RED	Among other things, the Renewable Energy Directive (RED) provides goals – and thus **investor guidance and vision** – to expand the use of renewable energy technologies; the revised RED for the period until 2030 provides the target of 32 % renewable energies in final consumption	The new target for post-2020 on renewable energy is seen as a **"minimum" objective**. As national targets will be substituted through a collective target, monitoring and reporting must be safeguarded.
EED	The Energy Efficiency Directive (EED) provides goals – and thus **investor guidance and vision** – to accelerate energy efficiency in general.	The definition of 'high efficiency cogeneration' in the EED is ambiguous. As member states may interpret the current EED definition differently, some countries could consider the FF-SOFC eligible for financial support while others not.

Fig. 9 Drivers and barriers of selected policies
Source: [9]

3.2 *Drivers and Barriers of Selected EU Policies*

All the mentioned regulations constitute both positive drivers as well as negative barriers for uptake of the FlexiFuel-SOFC technology. Figure 9 gives a brief overview of these drivers and barriers.

4 Conclusions and Outlook

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

Two specific application cases were investigated, which represent the most promising fields of application for the new technology in the European market: Application A for hotels, small enterprises, hospitals and small district heating networks; Application B for public buildings and multi-family homes. Furthermore, for each of the application cases, the new FF-SOFC systems are compared to four state-of-the-art technology options: A biomass boiler (with electricity demand supplied from the grid), a biomass fired CHP, a natural gas fired CHP and the Windhager PuroWIN boiler that is supplemented by a photovoltaic system for electricity generation. Thereby, on-site air emissions as well as grid electricity consumption effects have been jointly taken into account. The impact assessment for the

FlexiFuel-SOFC demonstrates general dynamics of different application cases and their sensitivities to technical parameters and other modelling assumptions. This modelling shows the impacts a wide-scale introduction of the FlexiFuel-SOFC technology might mean for air pollutant emissions, GHG emissions and thereby supports 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 the CHP technologies and the PuroWIN boiler with PV technology package 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 negative. For air pollutant emissions, a similar overcompensation of on-site emissions by avoided off-site emissions is seen for certain technologies and air pollutants as well. Compared to the other scenarios with biomass-firing technologies, the FF-SOFC technology scenarios lead to lower or at least similar air pollutant emissions. It has to be mentioned that such results are sensitive to several crucial technical parameters of the FF-SOFC technology, such as e.g. emission intensities of the different solid fuels used by the application cases. Furthermore, 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 model.

Additionally, the gained results have to be set in relation to policy developments addressing the CHP sector. Especially for smaller CHP systems targeting the residential sector, policies that address the typically required size of heating appliances may considerably affect the development and usage profiles of such systems. Regulation, such as the Ecodesign Directive, the Energy Efficiency Directive and the Renewable Energy Directive 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 energy system.

Acknowledgements The research leading to the presented results has received funding from the European Union Horizon2020 Programme (H2020/2014-2020) under Grant Agreement n° 641229. The authors also express their gratitude to the other project partners and all the members of the consortium for their good cooperation.

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