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Fit4Micro

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Technical report on Life Cycle Assessment 1

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Table of Contents

This project has received funding from the European Union's Horizon Europe Research and Innovation Program under Grant Agreement n. 101083536.

1. Terms and Definitions

mGT	Micro gas turbine
FPBO	Fast pyrolysis bio-oil
SPO	Stabilised pyrolysis oil
HPO	Hydrotreated pyrolysis oil

2. Goal and scope definition

The following section will provide an overview of the purpose of the study, followed by a detailed explanation of the scope, including defining the system, system boundaries, and specifying the functional unit.

2.1. Goal of study

This study is part of the EU project Fit4micro, dedicated to innovatively developing and demonstrating an integrated heat and power supply solution for buildings—an integrated system providing combined heating, power generation, and cooling, all powered by biofuel.

The Life Cycle Assessment (LCA) is conducted with the aim of facilitating decision support in technology development and support sustainable implementation of the technology. The primary objective of this study is to assess the environmental impact of the micro gas turbine (mGT) system when fuelled with hydrogenated pyrolysis oil (HPO) in various use case scenarios and with different feedstock sources for the biofuel production process. Scenario development encompasses 18 different potential applications of the mGT in the future, spanning various building types, locations, and building standards.

Insights from this LCA will not only provide stakeholders with a comprehensive understanding of critical focal points within the system but also provide valuable insights into potential risks, challenges, and opportunities, thereby informing the ongoing optimisation of environmental performance, and ensuring that the technology is implemented and used where it represents the competitive choice from an environmental sustainability perspective. The development of scenarios aims to shed light on the implications of applying the technology across different conceivable future scenarios.

2.2. System definition

The main system comprises a micro turbine integrated with two technology options to meet demands for electricity, heating, and cooling.

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The first option involves combining the micro turbine heat production with a compression heat pump, particularly relevant in cold climates. This setup may utilize part of the electricity generated by the turbine during cold periods, enhancing the overall heat efficiency of the system.

In warm climates requiring cooling, the main system can be augmented with an adsorption chiller. This chiller harnesses heat from the turbine, consuming electricity solely for pumping purposes.

The final possibility is to incorporate solar PV to supply electricity to the heat pump, consequently reducing the demand for biofuels. Thus, the system under study is a hybrid one, comprising the following four systems (an illustrative overview of this setup can be observed in Figure 1).

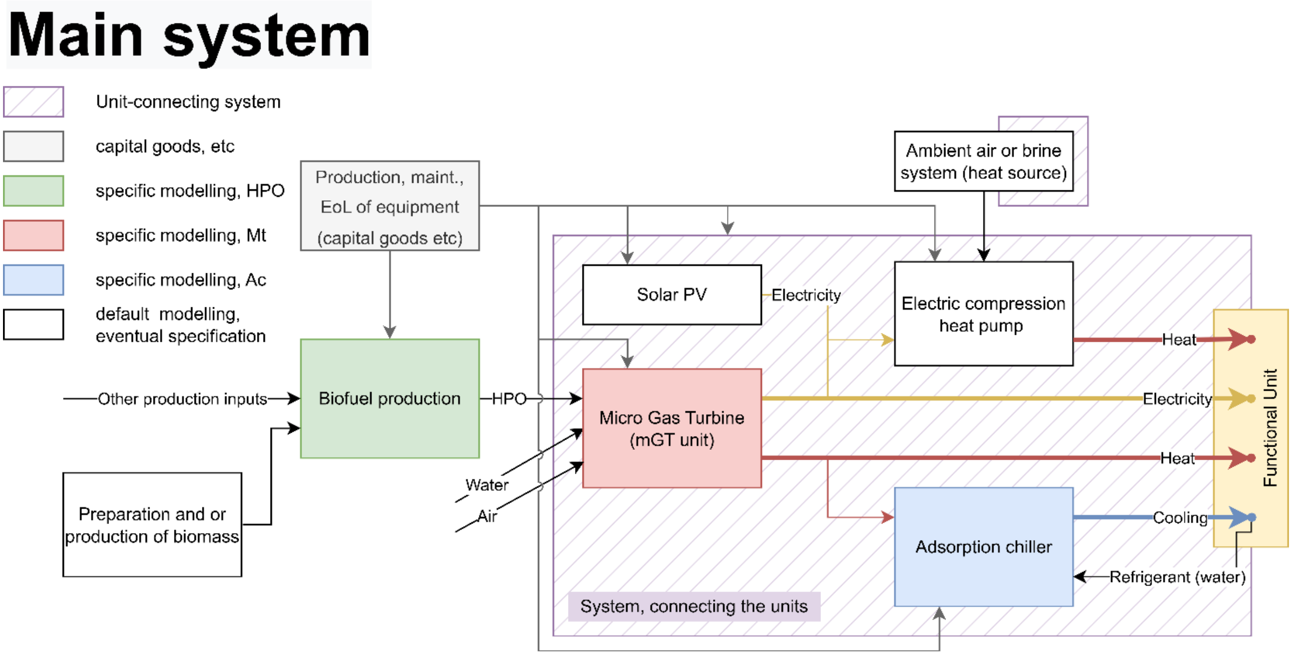

Figure 1 Overview of main system.

2.3. Functional unit and reference flow

The functional unit serves as a quantifiable measure of the system, enabling the assessment of its environmental impacts. Given that this system fulfils various functions and is subjected to seasonal and geographical influences affecting its utilisation, the functional unit must accommodate these factors.

To address seasonal and geographical variations, the operational modelling spans one year and includes scenario development. Consequently, the functional unit for this system is modelled as the electricity, heating, and cooling energy generated by the system over a one-year period:

- **The function** being assessed is the combined heating, cooling and power need for a building complex.
- **The functional unit (FU)** is the combined heating, cooling and power need for a building-complex during a one-year period.
- **The reference flows** delivering the FU reflects different use patterns based on the building-complex type, the geography, and the energy system context of the building-complex, as reflected in the scenarios.

Functional unit	Electricity [MJ*y^{-1}] + Heating [MJ*y^{-1}] + Cooling [MJ*y^{-1}]

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2.4. Systems boundaries and cut-off criteria

The system boundaries define what is included and excluded from the life cycle assessment of the mGT. This life cycle assessment will include all life cycle stages from cradle to grave, covering processes such as raw material extraction, material manufacturing, product manufacturing, utilisation, and end-of-life.

To enhance the efficiency of the life cycle process, simplify matters, and to avoid damaging IP rights, multiple material compounds within the mGT have been grouped and calculated together, when they can reasonably be considered to share a similar environmental profile. Materials used in minimal quantities, which in the context of their overall environmental impact can be deemed insignificant, have been omitted from the study. When data has been incomplete or unavailable, relevant literature has supported the data and assumptions.

The life cycle assessment for the system is modelled with a consequential approach and the database Ecoinvent 3 – consequential. This means, that co-products from a single process, are handled with system expansion.

The geographical boundaries depend on markets, that are impacted by the study. In most cases, the data is related to the EU, but many materials, e.g. metals, are traded on global markets. Thus, the geographical scope concerning materials is mainly global, whereas in the different use-case scenarios, the geographical scope, and the consequences of applying the technology will have a national/regional/local geographical scope.

Regarding the temporal boundaries, the LCA was carried out as a component of the EU Fit4Micro project, involving an iterative process spanning four years.

Impact categories and indicators to determine the environmental impacts have been calculated with the following methods:

- Global warming potential single issue: IPCC 2021 GWP100 version 1.02 (GWP20 and GTP100 factors for sensitivity analysis)
- Across impact categories: Stepwise method, enabling estimation of externality costs
- Across impact categories: ReCiPe 2016 v1.1 midpoint, Hierarchist perspective.

3. Inventory analysis

The following section will provide a description of the input-output data included to investigate the system of analysis. This includes a clear explanation of the modelling assumptions that are applied. Since this system is a hybrid system, the inventory will include a section for each sub-system. Firstly, there will be a brief introduction to the life cycle inventory of the mGT, outlining the system flow. Subsequently, the different life cycle phases of the mGT will be described, providing an in-depth examination of the modelling assumptions. To accommodate performance variations dependent on the specifics of use situations, the modelling is based on the use case scenarios presented in Deliverable 5.1, and represented as 18 use case scenarios representing four geographical regions

Hereafter, the life cycle inventory for the biofuel is decribed. During the use phase, there is a biofuel input to the system. However, various feedstocks can be utilised in the system, and to accommodate the uncertainty linked to the biofuel input, three alternative feedstocks have been used to develop three different biofuel-scenarios. The modelling assumptions linked to the biofuel, will thus be described in this section.

In the final part of the chapter, there are three sections respectively, related to the inventory of the heat pump, Solar PV, and the adsorption chiller, which are the three different technology options, that the mGT can be combined with.

3.1. Life cycle phase: Raw material extraction

The production of biofuel can utilise alternative feedstocks, but it is assumed that the pyrolysis plant will only run on one of the alternative feedstocks. To accommodate for this uncertainty three scenarios have been developed. Each alternative feedstock will have different conversion efficiencies when producing FPBO. In WP2 experimental research is performed with three feedstocks. The results are not yet available and conservative estimations were made. The conservatively estimated efficiencies for the three alternatives can be seen in the table below.

Table 1 Selected properties for three alternative feedstocks.

	Origin	**Average Conversion efficiency to FPBO**			**Losses in process**	**Byproducts for heat and power**
		Mass	Energy	Carbon		
A1: Forest residue	Scandinavian scenario	65%	60%	60%	10%	30%
A2: Contaminated wood	Western Europe	55%	55%	55%	10%	35%
A3: Wheat straw	Eastern/central Europe	58%	50%	50%	10%	40%

3.1.1. Life cycle phase: Use stage

Each alternative feedstock needs to be modelled because the use of each feedstock has different consequences. To model the alternatives, it is necessary to know what would have happened if the feedstocks were not used for biofuel production. When using the feedstock for biofuel production these will then be the avoided impacts and should thus be modelled as a negative contribution. The avoided impacts from each feedstock will be elaborated on in the following three subsections.

3.1.2. Modelling of substitution in feedstock scenarios

The three alternative feedstocks forest residue, contaminated wood, and wheat straw are by-products from other products e.g. primary wood and wheat. Since this study follows a consequential approach, this multifunctionality will be handled by applying substitution. This will be described below.

The first alternative feedstock for biofuel production is forest residues (Figure 4), which are byproducts of primary wood harvesting. These residues are typically incinerated and used as a biomass source for heat, replacing wood chips. When redirected to fast pyrolysis for FPBO production, the conventional use of forest residues is substituted. As illustrated in Figure 4, this shift means that wood chips must instead be produced from primary wood products.

3.1.2.1. A1 Forest residue: Substitution of heat production and wood pellets from the use of forest residue

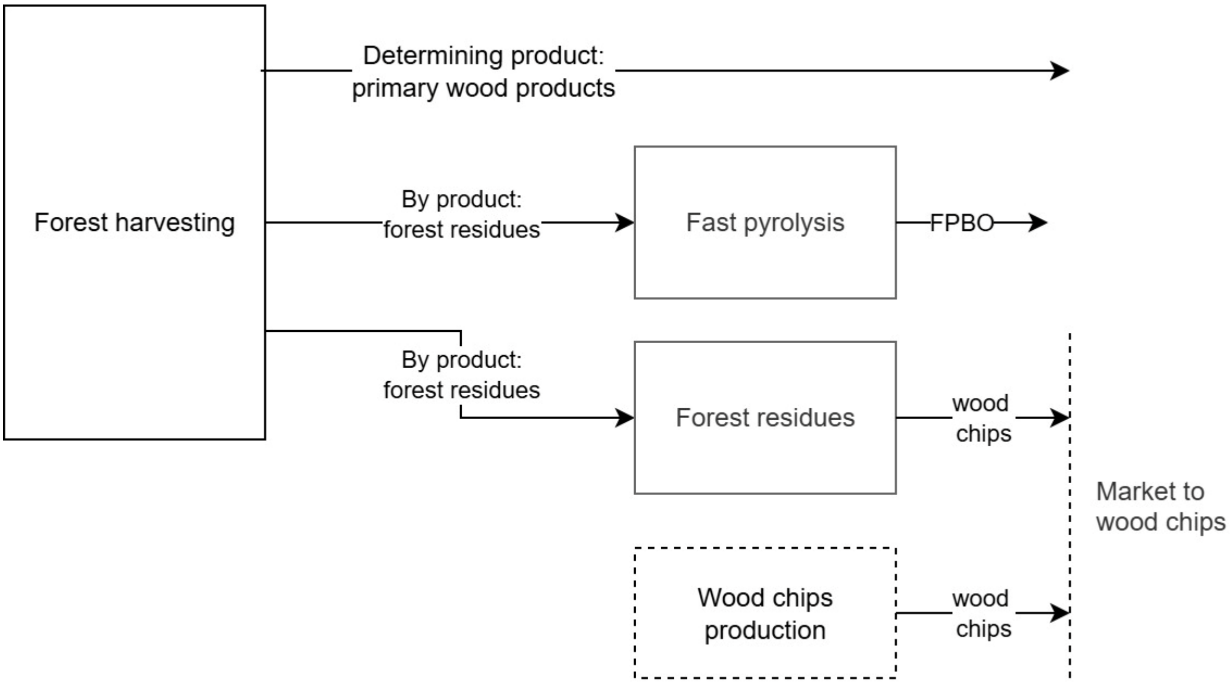

Figure 2 The figure illustrates how forest residues, typically used to produce wood chips, are redirected to FPBO production, shifting the source of wood chips to primary wood products.

3.1.2.2. A2: Substitution of a special incineration process and wood pellets from the use of contaminated wood

Contaminated wood refers to wood that has been treated with chemical preservatives or otherwise exposed to harmful substances. If not properly managed, it can pose environmental and health risks. Specifically, it should not be burned in uncontrolled environments due to the release of hazardous fumes, nor should it be landfilled, as it may contaminate soil and water sources.

In Europe, the standard end-of-life treatment for contaminated wood is incineration at specialized plants, where it contributes to local heat production. This process is illustrated in Figure 5. Unlike forest residues, contaminated wood is a constrained material and not considered a byproduct. The system flow further shows that when contaminated wood is used in FPBO production, the conventional pathway of incineration for heat and power is avoided.

This substitution of heat production occurs when contaminated wood is redirected to biofuel production (Figure 3). However, the consequences of this substitution depend on the specific use case. In the scenario illustrated, heat pumps are used as an example of a potential replacement technology. Heat pumps are expected to become a dominant solution in future district heating systems.

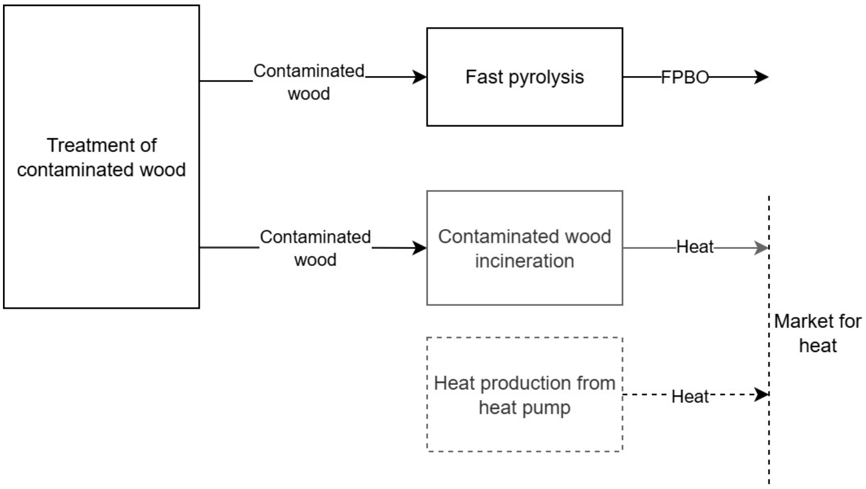

Figure 3 Substitution of use as wood pellets and induced heat production (in system with heat pump -based district heating as marginal technology) as a consequence of utilising contaminated wood for biofuel production.

3.1.2.3. A3: Substitution of processes from wheat straw

Wheat straw is an agricultural byproduct generated during the harvesting of wheat grain. It has a wide range of applications, and its use often depends on the availability of wheat grain—whether supply is scarce or abundant. Despite being produced in large quantities globally, and a currently partly underutilisation, wheat straw's versatility makes it a valuable resource.

When wheat straw is used for biofuel production, it replaces its conventional applications. However, since these applications vary depending on the context, the consequences of such substitution must be assessed through scenario-based modelling. One such scenario considers the use of wheat straw for heat production. In this scenario, the use of wheat straw for biofuel production substitutes its use in heat generation, as illustrated in Figure 4 Additionally, this shift also replaces the use of primary plantation wood pellets, which would otherwise have been used in biofuel production.

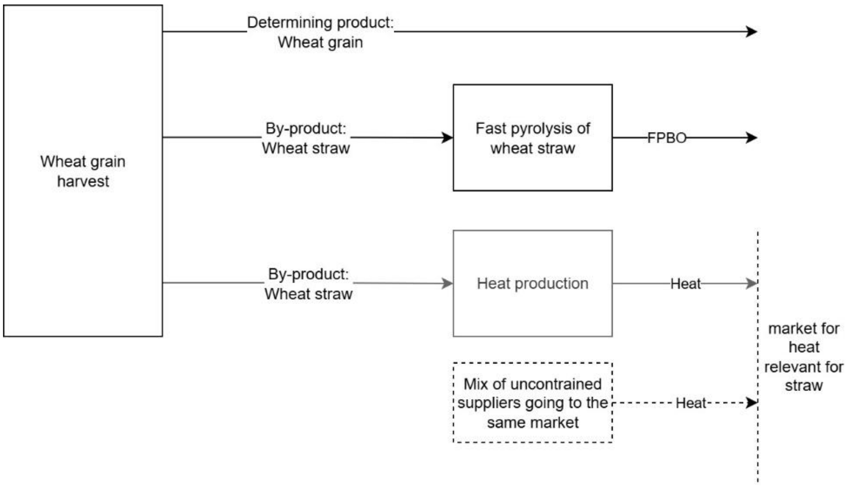

Figure 4 System flow of the production of wheat shows, that wheat grain is the determining product, and that wheat straw is a by-product. Wheat straw can be used as heat production, but when used for FPBO, this activity is avoided, as illustrated in the system flow.

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3.2. Pyrolysis Biofuel inventory

The mGT is modelled to run on biofuel in the life cycle use stage. To produce the biofuel (HPO), the feedstock is processed through three main steps; fast pyrolysis, stabilisation, and hydrotreatment. Additionally, the biofuel can be produced with a variety of input feedstocks, as described in Deliverable 2.7. To account for this the production and use of biofuel is modelled with the use of different scenarios. The modelling of biofuel falls in three scenarios covering three alternative feedstocks: forest residue, contaminated wood, and wheat straw.

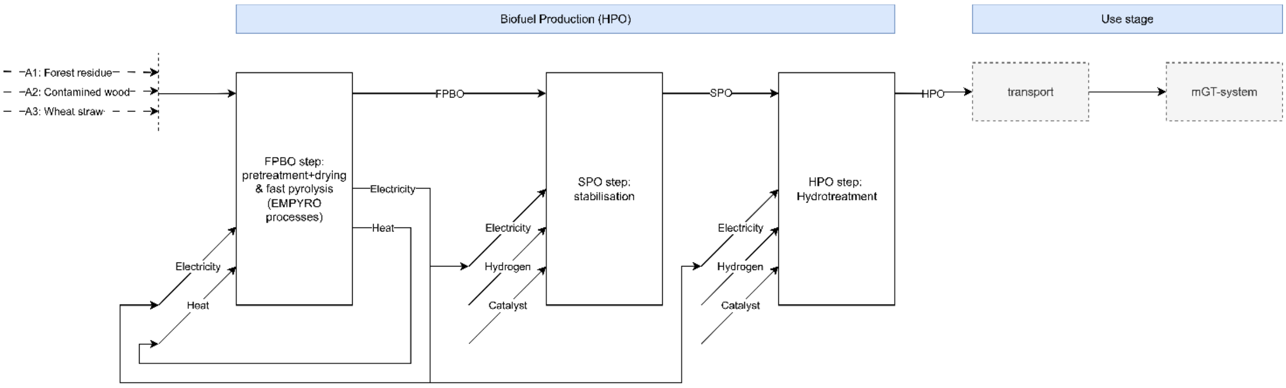

Figure 5 System flow for biofuel production

The three different feedstock alternatives used for producing the fast pyrolysis bio-oil (FPBO) are illustrated above in Figure 2, Figure 3, and Figure 4. The FPBO is hereafter stabilised to stabilised pyrolysis oil (SPO) and converted to hydrotreated pyrolysis oil (HPO) by mild hydrogenation. Further description of the process is in section 3.2.2.2.

3.2.1. Life cycle phase: Feedstock preparation

After the extraction of feedstocks, the material manufacturing takes place. This life cycle phase includes three activities before the biofuel production can take place: transportation, drying, and sizing of feedstocks. It is assumed that the plant location is near the source of biomass and collection point.

Table 2 Generalised feedstock assumptions.

Feedstock	Origin transport	Drying	Sizing
A1 forest residues	Scandinavia	Maximum moisture content of 50%	Potentially
A2 Contaminated wood	Western Europe	Maximum moisture content of 50%	Potentially
A3 Wheat straw	Eastern/central Europe	Maximum moisture content of 50%	Potentially

3.2.2. Life cycle phase: Biofuel production

After transporting, drying, and sizing the feedstocks, the production of the biofuel will occur. The production will take place at a pyrolysis plant. The production process has three steps: fast pyrolysis, stabilisation of FPBO, and hydrotreatment of FPBO. Depending on the specific use case and fuel choice, a further purification process can be necessary. The overview of the processes is in figure 5, and the results in terms of production related GHG emissions are in table 7

3.2.2.1. Modelling of pyrolysis plant

The pyrolysis plant is modelled with the data [Chemical factory, organics {RER}| chemical factory construction, organics | Conseq, U]. Since compositions of Synthetic gas plants vary depending on the function of the plant, the use of this data is thus a rough estimate. The lifetime of the plant is modelled to be 50 years and with a processing of 32-35 t/day of feedstock (dry matter)

The gas factory is used in the activity [Biomethane, high pressure {RoW}| biomethane production, high pressure from synthetic gas, wood, fixed bed technology | Conseq, U]. This can be used to model the operation of the pyrolysis plant.

3.2.2.2. Modelling of fast pyrolysis processing

Through fast pyrolysis the solid biomass is converted to liquid bioenergy carrier, FPBO. To fulfil the transformation, there is a need of feedstock, electricity, cooling water, quartz sand, and nitrogen purge. The cooling water is modelled as tap water [Europe without Switzerland}| market for tap water | Conseq, U]. Quartz sand is modelled as [Sand, quartz] or [Sand {GLO}| market for sand | Conseq, U]
Nitrogen purge is used for a purging process which enable the removal of oxygen and moist in a system through the flow of a dry nitrogen gas.

Modelling of pretreatment of FPBO

Before the upgrading of FPBO there is a pre-treatment process. The pre-treatment process has an input of electricity and some adsorbents to remove harmful contaminants.

For the residues in Fit4Micro there may be need for pretreatment of the FPBO before the stabilisation. Electrical energy for pumping etc, and Heat for drying of feedstock is supplied from heat and energy produced from byproducts from FP-process. The electricity also supplies electricity consumption in the following production steps.

Modelling of stabilisation of FPBO

The first upgrading process is the stabilisation of FPBO. The stabilisation of FPBO has four inputs: hydrogen, catalyst, electricity, and cooling water. It is assumed that after the pretreatment the FPBO, upgrading is independent of the feedstock applied. Variations may occur in reality and hydrogen consumption and product quality may differ a bit. Data on this is expected to be available for the final assessment.

The hydrogen is modelled with the data [Hydrogen, gaseous {RER}| hydrogen production, steam reforming | Conseq, U] or [Hydrogen, liquid {RER}| market for | Conseq, U]

In this process, 0,0001 kg /kg FPBO of the Picula catalyst (200 bar, T = 80 – 300 °C) is needed. The modelling of hydrogen supply will be modelled using different scenarios for energy sourcing, including fully renewable, in the final assessment.

The stabilisation process needs 0,015 kg H2/ kg FPBO, and the energy is modelled with the data [Electricity, low voltage {DK}| market for electricity, low voltage | Conseq, S] which has a kWh unit. Thus, the data in MJ is divided by 3,6.

Hydrogenation

Removing oxygen, adding hydrogen

The output of stabilising FPBO is Stabilized Pyrolysis Oil (SPO), which needs to be hydrotreated. In this process hydrogen gas removes undesired impurities. The catalyst used in the hydrogenation process is NiMo, which is a low-pressure nickel-molybdenum catalyst (100 – 120 bar, T = 300-425 °C).

In the Fit4micro project several ranges of hydrogen severity is being tested, where the main difference is the amount of hydrogen consumed. This means that "low severity" and "high severity" hydrogen results in different HPO where the consumption of hydrogen is dependent on the severity of hydrotreatment (HPO-, HPO and HPO+).

In the hydrogenation process, hydrogen is added in surplus amounts, and it is assumed that the relation between severity of hydrogen and surplus hydrogen isn't linear. It is thus assumed that a high range of hydrotreating consumes more hydrogen and thus results in a larger hydrogen loss. Modelling assumptions related to hydrogen consumption can be seen below.

Table 3 Modelling assumptions in relation to the consumption of hydrogen in the hydrogenation process. In the current modellingthe HPO variation is used.

	HPO-	HPO	HPO+
Stabilising hydrogen (wt.%)	1,5 wt.%	1,5 wt.%	1,5 wt.%
Hydrogenation Hydrogen (Wt.%)	3,2 wt.%	3,5 wt.%	4,2 wt.%
Total hydrogen content	4,7 wt.%	5 wt.%	5,7 wt.%
Assumed surplus hydrogen input	18 wt.%	20 wt.%	24 wt.%

Hydrotreatment with catalysts eliminates oxygen, and the higher severity the lower oxygen content, and the higher hydrogen content. In table 2, the lower severity hydrotreatment product is HPO-, HPO is the medium, and HPO+ is the higher severity hydrotreatment product. In the present modelling the HPO variation is included.

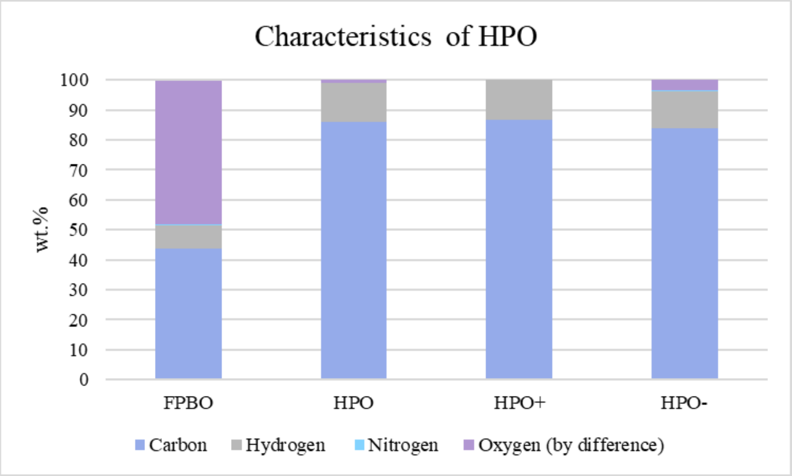

Figure 6 illustrating the differences in oxygen, carbon, hydrogen, and nitrogen level depending on the hydrogen severity.

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Upgrading: Purification/Distillation

This process depends on the fuel choice and results on the combustion tests and final results on NOx and CO from the WP3 & 4. In this distillation step fractions are separated, and the output can be either HPO-Naphta and HPO-Diesel.

3.3. Life cycle phase: Use stage

As illustrated in the system flow in Figure 1, the use of the mGT will result in a consumption of biofuel and require maintenance. It is furthermore assumed, that the mGT will be used in different situations. To account for this unpredictability and uncertainty in the use stage, different scenarios will be developed. This section will start with a brief description of the required maintenance of the system in use, followed by a description of the different use cases. Hereafter there will be a comprehensive description of how the biofuel is modelled, since it is assumed that the biofuel can be synthesised from various feedstocks sources.

3.3.1. Use case scenarios

The system of study is assessed on different building types, at different locations and with different building standards. Thus, giving a total of 18 different use cases. To accommodate the geographical factors, it has been decided to have a cold, average and a warm location in style of European Standards. Characteristics of the different use cases can be seen in the table below, and further information is to be found in deliverable 5.1

Table 4 illustrates that the system is assessed for both a multi-family home and an office building. These two building types are assessed in Athens, Strasbourg, and Helsinki. Furthermore, each location assesses the two building types according to two different building standards: a highly efficient building standard and a building standard compliant with the 1990s.

The table furthermore illustrates, that the system is assessed on two other building types: Health and lodging buildings. These buildings are only assessed at the geographical location Potsdam, but with three different building standards: one compliant with the standard before 1979, a standard related to 1980-2009 and a standard compliant with after 2009.

Table 4 Included factors for the development of scenarios related to different use cases.

Building type	**Multi-family home (MFH) & Office building**	**Health and lodging buildings**
Locations	Three locations: ▪ Athens ▪ Strasbourg ▪ Helsinki	▪ One location: ▪ Potsdam (Germany)
Building standards	Two building standards ▪ Typical 90s building standard of respective location ▪ Highly efficient building standard	▪ Three average buildings: ▪ Before 1979 ▪ Between 1980 and 2009 ▪ After 2009

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This results in a total of 18 distinct use case scenarios. Table 5 displays each scenario alongside its corresponding heating demand hours, cooling demand hours, and total heat demand hours.

Table 5 Characteristics of the different use cases.

Use cases		Heating hours	Heat demand hours	Cooling hours
Scenarios for Helsinki	MFH Helsinki 90’s std.	5517	6673	3
	MFH Helsinki highly efficient std.	4299	5746	0
	Office Helsinki 90’s std.	4810	4810	844
	Office Helsinki highly efficient std.	3812	3812	1093
Scenarios for Athens	MFH Athens 90’s std.	4233	6143	1842
	MFH Athens highly efficient std.	3180	5535	1757
	Office Athens 90's std.	4338	4338	3194
	Office Athens highly efficient std.	3089	3089	3322
	MFH Strasbourg 90’s std.	5198	6589	129
Scenarios for Strasbourg	MFH Strasbourg highly efficient std.	2957	5111	58
	Office Strasbourg 90’s std.	5107	5107	1091
	Office Strasbourg highly efficient std.	2489	2489	2078
	Health before 1979	6841	8760	607
Scenarios for Potsdam	Health 1980-2009	5555	8760	1024
	Health After 2009	4599	8760	2194
	Lodging before 1979	6887	8755	561
	Lodging 1980-2009	6344	8755	561
	Lodging After 2009	5754	8756	1343

3.3.2. Modelling of substitution in use case scenarios

Since the mGT can produce both heating, cooling, and electricity, this production consequently assumes the substitution of heat and electricity production from the respective marginal market supplier. The marginal supplier of heating and electricity respectively depends on the specific use cases, as the energy system will differ depending on the location where the use case is modelled. It can also depend on specific weather conditions. Suppliers (technologies) capable of adjusting the supply to changes in demand will typically be the marginal supplier.

To model the substitution of both electricity and heating, it is thus necessary to know the heating and electricity system and suppliers at each geographic location. In Table 6 current and near future zero alternative supply is outlined.

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Table 6 Heating and electricity grid for the three different geographic location, which defines the modelled use scenarios, and gives an indication of potential system expansion for heat and power.

		Electricity and heating grid	Relevant sources
Scenarios for Athens	Heating in Athens:	Majority of houses in Greece uses diesel heating oil. Natural gas, biomass and electricity are heat sources that each supply less than 12% of the houses in Greece with heat.	Heating systems in Greece
	Data {GR}	Heat, district or industrial, other than natural gas {GR}| heat and power co-generation, oil | Conseq, U	
	Electricity in Athens:	Expected future low voltage electricity in Greece is expected to have following reaction profile 37% PV, 50% wind, 10% Natural gas, 3% biomass	Electricity grid Greece
	Data {GR}	Electricity, low voltage {GR}| electricity voltage transformation from medium to low voltage | Conseq, U	
Scenarios for Strasbourg	Heating in Strasbourg:	The district heating of Strasbourg uses biomass and municipal waste incineration to cover base load and natural gas to cover peak load.	Factsheet Strasbourg
	Data {FR}	Heat, for reuse in municipal waste incineration only {FR}| market for heat, for reuse in municipal waste incineration only | Conseq, U	
	Electricity in Strasbourg:	Expected future low voltage electricity in France is expected to have following reaction profile: 42% PV, 49% wind, 8% biomass, 1% Geotherm, 0.3% hydro.	Electricity grid France
	Data {FR}	Electricity, low voltage {FR}| electricity voltage transformation from medium to low voltage | Conseq, U	
Scenarios for Helsinki	Heating in Helsinki:	In 2021 30% of the houses in Finland were supplied with heating from district heating. 26% of the heating came from wood, 24% from electricity13% came from ambient energy, which is the energy extracted from the environment by heat pumps.	Statistics Finland Heating residential buildings
	Data {FI}	Heat, district or industrial, other than natural gas {FI}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	
	Electricity in Helsinki:	Expected future low voltage electricity in Finland is expected to have following reaction profile: 0.05% PV, 31% biomass, 25% Nuclear, 21% wind, 17% Natural gas, 5% Coal.	Electricity grid Finland
	Data {FI}	Electricity, low voltage {FI}| market for electricity, low voltage | Conseq, U	

Scenarios for Potsdam	Heating in Potsdam	In 2020 around 51% of households were supplied with heat generated from natural gas.	Heating grid, Germany
	Data {GER}	Heat, district or industrial, natural gas {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Conseq, S	
	Electricity in Potsdam	Expected future low voltage electricity in Germany is expected to have following reaction profile: 33,5% PV, 50% wind, 13% Nat gas., 2% oil, 1% hydro, 1% geothermal	Electricity grid Germany
	Data {DE}	Electricity, low voltage {DE}| market for | Conseq, U	

4. Impact Assessment

4.1. Feedstock scenarios results

This section presents the Global Warming Potential (GWP100) results for three biofuel feedstock scenarios (Table 7), modelled using a consequential LCA approach. Each scenario reflects the environmental impact of using a specific feedstock for biofuel production, considering the avoided conventional use of that feedstock.

4.1.1. Scenario A1 – Forest Residues (Scandinavia)

Forest residues are byproducts of primary wood harvesting, typically used for heat production via incineration. In this scenario, their use in FPBO production avoids the need for burning forest residues and shifts wood chip production to primary wood. The significant negative CO_2 uptake reflects the induced biomass growth, contributing to carbon sequestration. The result is a net negative GWP100, primarily driven by biogenic carbon uptake.

4.1.2. Scenario A2 – Contaminated Wood (Western Europe)

Contaminated wood is a constrained material, usually incinerated in controlled facilities to avoid environmental hazards. Its use in FPBO production avoids these emissions. The high negative biogenic GWP100 is due to avoided emissions from incineration, not biomass uptake. Although it lacks the CO_2 uptake benefit seen in A1, the total GWP100 is nearly identical, showing that both substitution mechanisms (uptake vs. avoided emissions) can yield similar climate benefits.

4.1.3. Scenario A3 – Wheat Straw (Eastern Europe)

Wheat straw is an agricultural byproduct with diverse applications, including heat production. When diverted to biofuel production, the missing heat is substituted—often by fossil-intensive sources like coal, especially in regions like Poland. This leads to high fossil GWP100 emissions, and although there is some CO_2 uptake, it is insufficient to offset the fossil burden. The result is a net positive GWP100, indicating that wheat straw may be less favourable from a climate perspective in this regional context.

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Table 7 GWP100 results for three biofuel feedstock scenarios.

Impact category	Unit	Scenario A1 – forest residues	Scenario A2 – contaminated wood	Scenario A3 – Wheat straw
GWP100 - fossil	kg CO2-eq	0,15445	0,67685	3,17858
GWP100 - biogenic	kg CO2-eq	0,00124	-3,17377	0,19079
GWP100 - dLUC	kg CO2-eq	0,00103	0,00053	0,00023
GWP100 - CO2 uptake	kg CO2-eq	-3,02691	-0,23394	-2,28540
GWP100 - iLUC	kg CO2-eq	0,13945	0,00000	0,19200
Total GWP100	**kg CO2-eq**	**-2,73074**	**-2,73032**	**1,27620**

4.2. CO2 Emissions related to mGT operation in geographic use cases

Energy Demand and Biofuel Requirement

To quantify the environmental impact of the micro gas turbine (mGT) system across different building scenarios, the energy demand for heating and electricity was assessed for 18 use cases. The mGT system operates with a fixed output ratio of two-thirds heat and one-third electricity, and the total energy demand was used to estimate the required biofuel input.

The amount of biofuel needed was calculated using the net calorific value (NCV) of the fuel 40.1 MJ/kg. This value reflects the lower heating value of the biofuel, accounting for energy losses during combustion. For each scenario, the total energy demand was divided by the NCV to determine the mass of biofuel required to meet the building's annual energy needs.

Estimation of CO_2 Emissions from Biofuel Combustion

To assess the climate impact of biofuel use, CO_2 emissions were estimated using the IPCC methodology for stationary combustion[1]. The following formula was applied:

$$C = Q \times NCV \times EF \times OF \times 44/12$$

Where:

C= CO_2 emissions (kg)
Q= Quantity of biofuel used (kg)
NCV= Net calorific value of the fuel (MJ/kg)
EF= Emission factor (carbon content 0.88)
OF= Oxidation factor (assumed 0.99)
44/12= Molecular weight ratio of CO_2 to carbon

This calculation yields approximately 3.20 kg of CO_2 per kg of biofuel combusted. The resulting emissions vary across scenarios depending on the energy demand and building characteristics, providing a basis for evaluating the environmental performance of the mGT system in different European contexts. Beyond the initial feedstock input, processes such as fast pyrolysis, stabilization, and hydrotreatment generate various

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[1] Eggleston, H. S., ed. 'Chapter 2 Stationary'. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Institute for Global Environmental Strategies, 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html.

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by-products and involve production losses that contribute to overall carbon emissions. The emissions related to the biofuel production calculated based on the assumptions summarised above and the mass balance of the production process is summarised below in Table 8.

Additionally, the modelling of excess electricity production through system expansion (accounting for avoided electricity generation) has been implemented, which offsets some of the carbon emissions from the system.

The emissions from burning the biofuel have been added to the emissions associated with each feedstock scenario, providing a more complete picture of the climate impact during the use phase of the micro gas turbine (mGT) system (Table 9). These results account for the full production process of the biofuel itself.

In the current modelling, the adiabatic and compression cooling components of the system have not yet been included. This aspect will be addressed in the next version of the assessment report (deliverable 6.5).

Table 8 Emissions from biofuel production distributed the three main production steps. The main emissions are here connected to the fast pyrolysis process, and the combustion of byproducts fort the production of heat and power used mainly for reducing water content of the feedstock down to 5% prior to fast pyrolysis. The byproducts may be used for other purposes if drying need is reduced and may then improve system performance through avoided production outside of the system investigated.

	FPBO step		**SPO step**		**HPO step**		**HPO production**
	Bio-feedstock → FPBO		FPBO → SPO		SPO → HPO		Bio-feedstock → HPO
Feedstock scenario A1-A3	Process losses	Byproducts → heat & power used in plant-processes	waste water (excl WWTP)	Byproducts → heat & power used in plant-processes	waste water (excl WWTP)	Byproducts → heat & power used in plant-processes	Byproduct combustion to process-heat and -power + process losses to fluegas
	kg CO_2/kg HPO		kg CO_2/kg HPO		kg CO_2/kg HPO		**kg CO_2/kg HPO**
A1: Forest residue	0,74	2,21	0,24	0,13	0,03	0,49	**3,84**
A2: Contaminated wood	0,98	3,44	0,24	0,13	0,03	0,49	**5,32**
A3: Wheat straw	0,80	3,20	0,24	0,13	0,03	0,49	**4,90**

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Table 9 The carbon footprint performance of the mGT system (excluding cooling) in the 18 specific scenarios combined with the three specific HPO feedstock scenarios.

Use scenario location	**Use cases**	**Energy required for heat (GJ)**	**Heat (GJ)**	**Electricity (GJ)**	**Amount biofuel required (t)**	**CO2 emissions (t) excl. feedstock scenario**	**scenario A1: CO2 emissions (t) incl. feedstock**	**scenario A2: CO2 emissions (t) incl. feedstock**	**scenario A3: CO2 emissions (t) incl. feedstock**
Helsinki	**MFH Helsinki 90’s standard**	721	480	240	18	57	81	104	165
	MFH Helsinki highly efficient standard	621	414	207	15	49	70	89	142
	Office Helsinki 90’s standard	519	346	173	13	41	59	75	119
	Office Helsinki highly efficient standard	412	274	137	10	33	46	59	94
Athens	**MFH Athens 90’s standard**	663	442	221	17	53	75	96	152
	MFH Athens S90	469	312	156	12	37	53	68	107
	MFH Athens highly efficient standard	598	399	199	15	48	67	86	137
	Office Athens 90's standard	469	312	156	12	37	53	68	107
	Office Athens S90	334	222	111	8	27	38	48	76
Strasbourg	**MFH Strasbourg 90’s standard**	712	474	237	18	57	80	103	163
	MFH Strasbourg highly efficient standard	552	368	184	14	44	62	80	126
	Office Strasbourg 90’s standard	552	368	184	14	44	62	79	126
	Office Strasbourg highly efficient standard	269	179	90	7	21	30	39	62
Potsdam	**Health before 1979**	946	631	315	24	75	107	136	217
	Health 1980-2009	946	631	315	24	75	107	136	217
	Health After 2009	946	631	315	24	75	107	136	217
	Lodging before 1979	946	630	315	24	75	106	136	216
	Lodging 1980-2009	946	630	315	24	75	106	136	216
	Lodging After 2009	946	630	315	24	75	106	136	216

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5. Interpretation and Conclusion

The LCA results demonstrate that the environmental performance of the micro gas turbine (mGT) system is highly dependent on the choice and treatment of biofuel feedstock. Using a consequential modelling approach, the study shows that climate impact is influenced not only by emissions from combustion and operation, but also by the alternative use of the feedstock and the substitution effects when it is diverted from conventional applications.

For example, forest residues (Scenario A1) and contaminated wood (Scenario A2) yield net negative GWP100 values, though via different mechanisms—biogenic carbon uptake in A1 and avoided incineration emissions in A2. In contrast, wheat straw (Scenario A3), when sourced from regions with fossil-intensive heat substitution, results in net positive GWP100, underscoring the importance of regional energy contexts (see table 8).

The analysis highlights the role of induced production, which may be heat production. Scenarios where the bio resource used for feedstock to FPBO alternatively would be used for heat production, the 'missing' bio resource is substituted via heat pumps powered by renewable electricity. In this case we see significantly improved climate performance of the mGT & biooil system. This suggests that sourcing feedstocks from regions e.g. with low-impact energy systems can substantially enhance the sustainability of the mGT system, compared to sourcing feedstock that may be substituted by higher impact ressources and technologies. The regional sourcing aspect is relevant for bulky feedstocks where a low value to volume ratio mean that the resource only is likely to be transported shorter distances.

Moreover, the variation across building types, standards, and geographic locations confirms that use-case-specific modelling is essential. The mGT system's performance depends not only on feedstock but also on the local energy grid and heating supply, reinforcing the need for nuanced scenario development. This furthermore imply that the mGT system if implemented in a off grid context likely will perform better if alternatives are based on more emission heavy technologies, which often are seen in off grid applications.

These findings emphasize that biofuel production must be evaluated within its broader system context—considering regional energy mixes, building energy demands, and substitution technologies. Feedstock scenarios where the feedstock for FPBO production is substituted by heat from heat pumps powered by renewable electricity show strong potential.

In the next version of this report, we will expand the scope to include a full range of use scenarios, each linked to specific future business-as-usual alternatives for heating, cooling, and hot water. Furthermore, the modelling will include aspects related to timing of emission and uptake, which will decrease the effect of CO2 uptake in woody biomass. This will support a more comprehensive understanding of environmental trade-offs, importance of biomass feedstock selection, and guide the strategic deployment of the mGT system in contexts where it offers the greatest sustainability advantage.

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