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SIMPLY Project
Pyrolysis plant cases

Report

SIMPLY WP1.2-1
Giacomo Butera, 01-08-2024

Revision History

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Contents

1 Introduction

The SIMPLY project aims to investigate the potential of pyrolysis and biomass utilization from a lifecycle assessment (LCA) perspective. Basic mass and energy balance from thermodynamic modeling are required to carry out an LCA.

1.1 Scope of Report

The scope of this report is to present an overview of the pyrolysis plant cases chosen to be investigated within the SIMPLY project, together with an overview of the mass and energy balance achieved via thermodynamic modeling.

2 Pyrolysis plant cases

In this section, the different pyrolysis plant cases are presented and an overview of the mass and energy balance is provided. The title of each configuration is chosen based on the main products of the single solution.
The reader should observe that in each case, the main product of pyrolysis is biochar, which serves as a structure for carbon sequestration. Since biochar is produced in each configuration it is not included in the title. Block diagrams, Sankey diagrams and the main mass and energy inputs and outputs are shown for each configuration.

2.1 Basic integration pyrolysis-biogas unit: Vrå-type configuration

This configuration is based on a basic integration between a biogas unit and a pyrolysis unit. It is also referred to as Vrå-type configuration, as the SkyClean unit located in Vrå is built exactly based on this type of configuration.
More specifically, compared to a stand-alone biogas unit, the by-product of the digestor (namely the biogas residue fibers) is dried, pelletized and used as feedstock in a pyrolysis unit. In the pyrolysis unit, biochar is produced, as well as pyrolysis gas which is burned to cover for the drying process heat demand. In addition, excess heat from the boiler and from the condensation of the moisture removed during the drying process is used to drive the biogas upgrading process (CO_2 removal) to upgrade biogas to methane. Figure 1 represents a block diagram of the Vrå-type configuration.
Figure 2 shows a Sankey diagram for the Vrå-type configuration. Here, it can be noted that the heat produced by the combustion of pyrolysis gas is used for (1) drying the biogas residue fibers and (2) upgrade the biogas to methane, together with cascaded heat from steam produced during the drying process. From Figure 2 it can be observed that a 20 MW_{th} pyrolysis plant would produce up to 6.9 MW_{th} of heat for the amine-based biogas upgrading process. In case the heat demand for the amine process is lower, the amount of pellets used for the pyrolysis could be decreased and extra pellets could be saved or sold for use in other pyrolysis plants running on dry feedstocks. Despite not shown in the Sankey diagram, the excess heat released from the stripping column of the amin process could be used for district heating or for the anaerobic digestion process.
Table 1 presents the main data regarding mass and energy flows for this configuration.

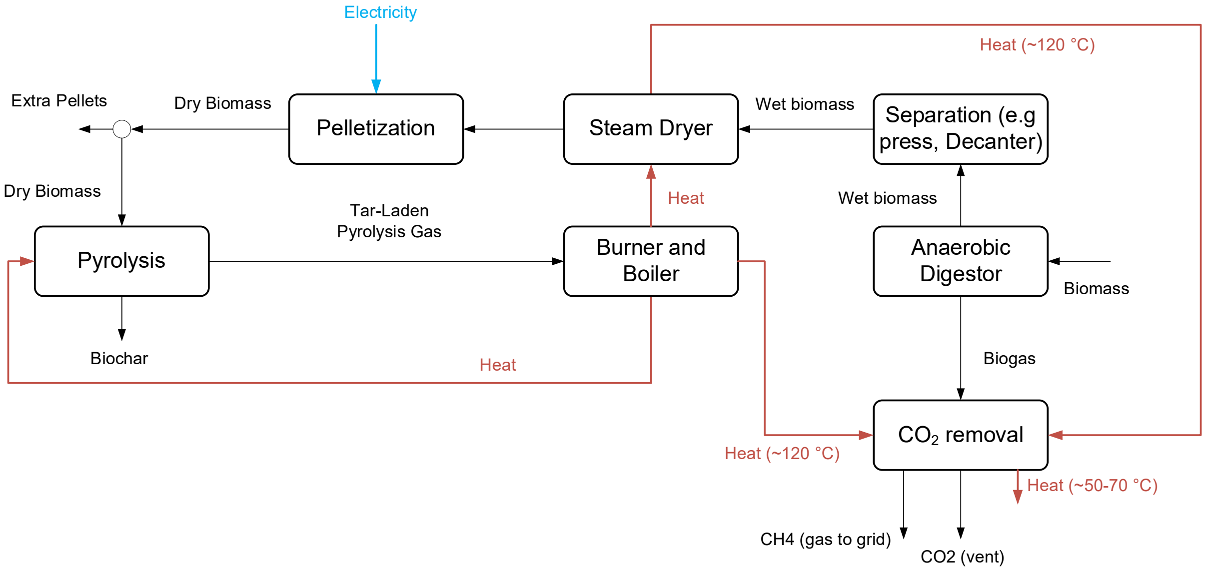

Figure 1 – Block diagram for the Vrå-type configuration.

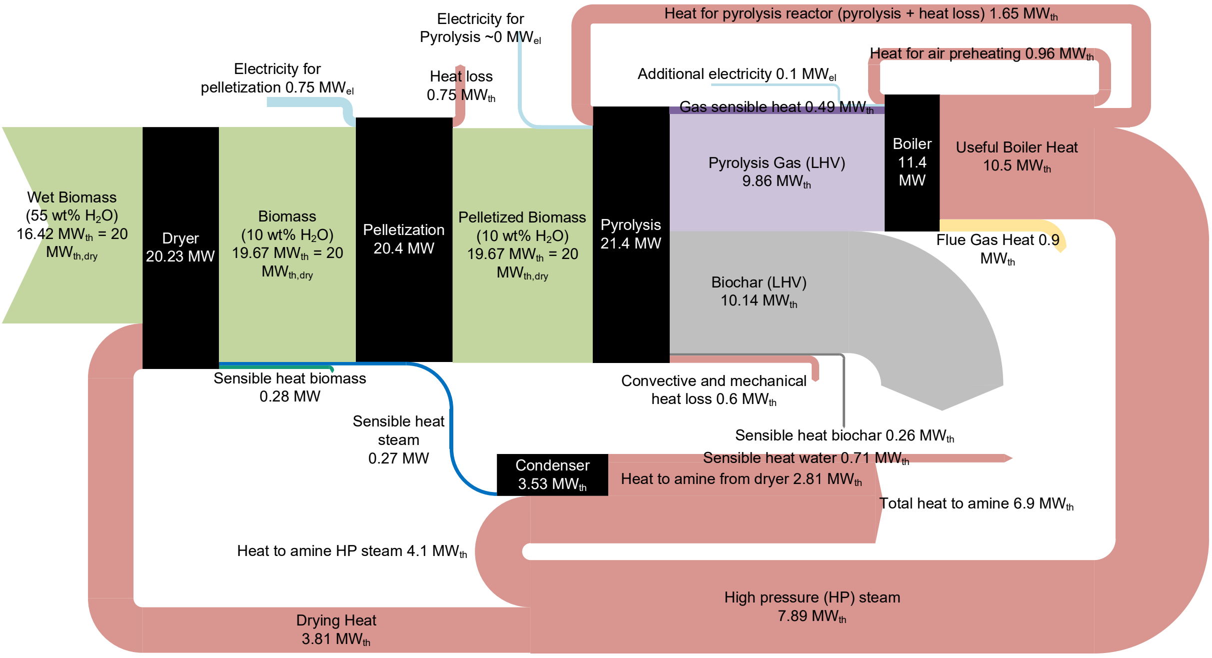

Figure 2 – Sankey diagram for the Vrå-type configuration

		Basic Pyrolysis + Biogas
Biogas residue fibers - As received	ton_AR/h	**9.59**
Biogas residue fibers - 10% moisture	ton/h	**4.79**
Biogas residue fibers - 0% moisture	ton_DM/h	**4.31**
Straw - As received	ton_AR/h	0.00
Straw - 0% moisture	ton_DM/h	0.00
Electricity Consumption	MW	**0.86**
Fuel Consumption - H2	MW	0.00
High-temperature Heat	MW	**6.90**
District heating	MW	**0.71**
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	0.00
Liquid Fuel - Oil	MW	0.00
Biochar	ton_biochar/h	**1.77**
Carbon in Biochar (no permanence factor)	ton_C/h	**1.02**

Table 1 – Main mass and energy flows for the Vrå-type configuration.

2.2 Advanced integration pyrolysis-biogas unit: Agri-Energy configuration

The advanced integration between pyrolysis and a biogas unit is based on the structure of the basic integration shown in 2.1. However, the advanced integration is more complete, and new by-products are present. This configuration is also referred to as Agri-Energy configuration, as it is one of the possible configurations the joint-venture Agri-Energy is investigating.

Compared to the configuration shown in 2.1, CO_2 removed from the biogas via the biogas upgrading is liquefied and serve as CO_2 capture, and is not vented to the atmosphere.

Figure 3 represents a block diagram for the Agri-Energy type configuration. It can be seen combustion of pyrolysis gas produces heat supplied to the digestate drying process, and the biogas upgrading (CO_2 removal), together with the heat from condensation of steam produced in the drying process. It can also be noted a CO_2 liquefaction plant is within the system. Analogously to solution

2.1, excess low temperature heat could be used for district heating or for the anaerobic digestion process.

Figure 4 shows a possible Sankey diagram for the Agri-Energy type configuration (however, not scaled to 20 MW$_{th}$ pyrolysis unit).

Table 2 presents the main data regarding mass and energy flows for this configuration.

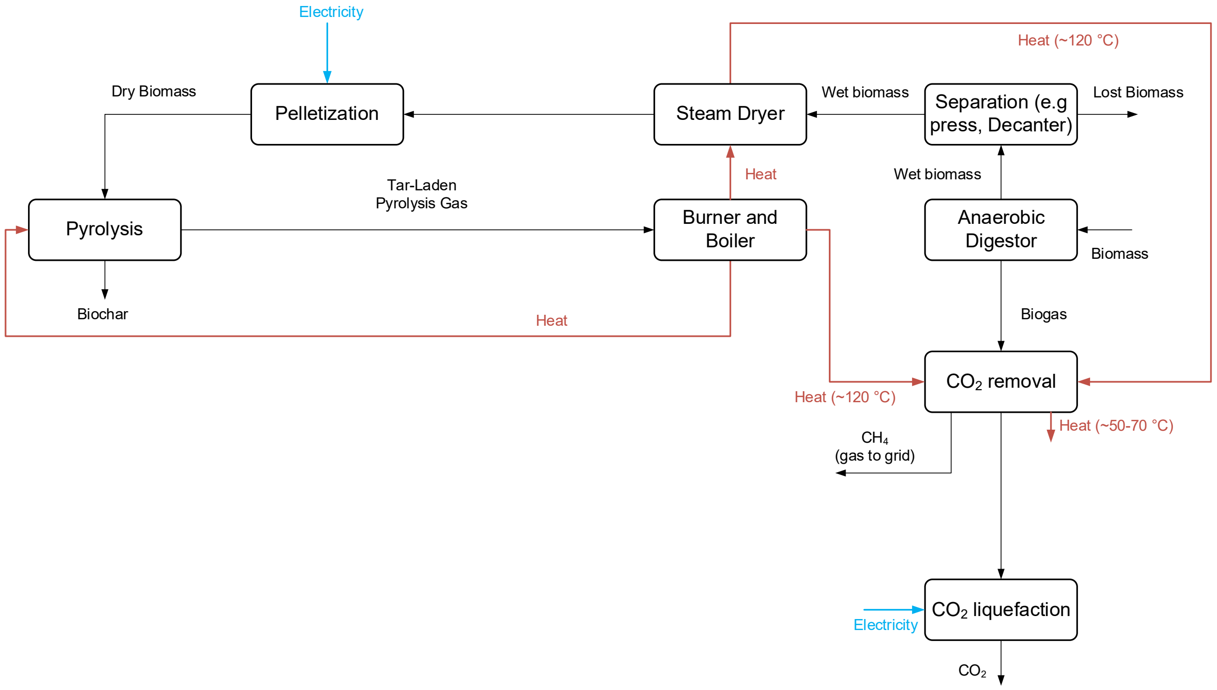

Figure 3 – Block diagram for the Agri-Energy configuration.

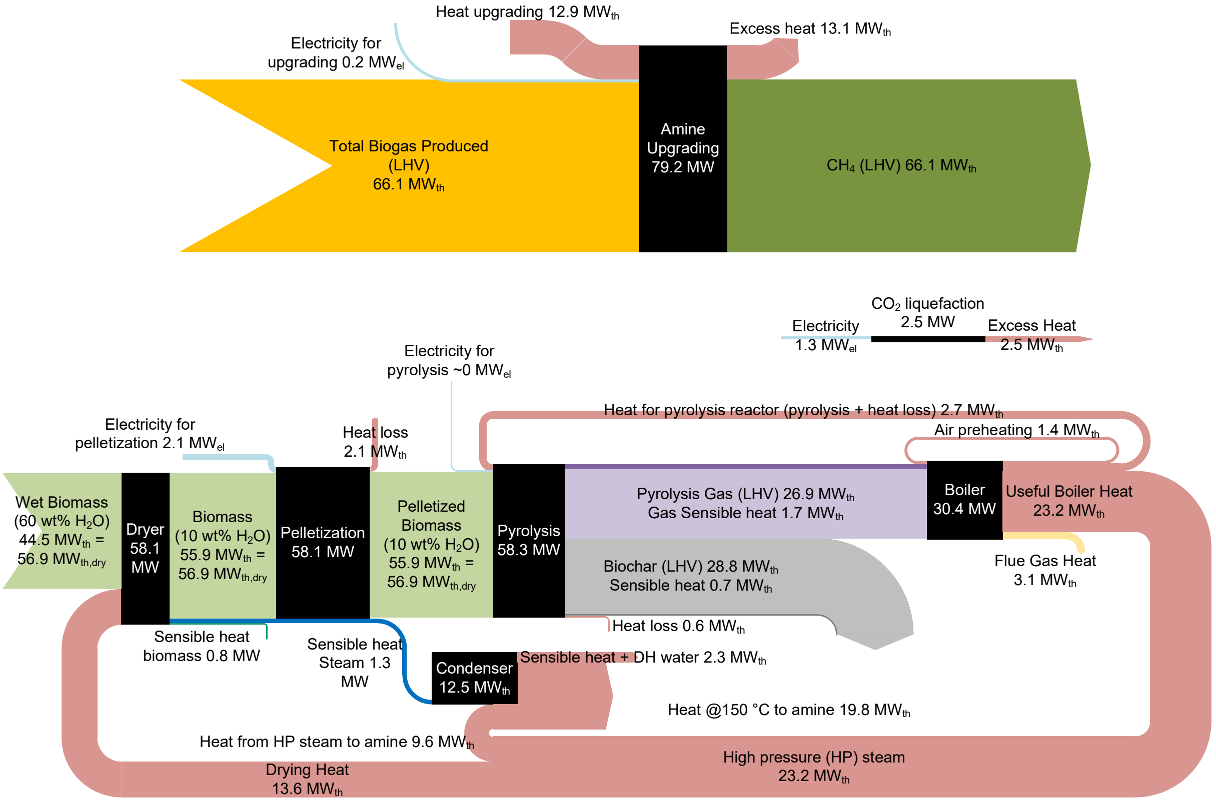

Figure 4 – Sankey diagram for the Agri-Energy configuration. The Sankey diagram is not scaled for a 20 MW$_{th}$ pyrolysis reactor.

		Advanced Pyrolysis + Biogas
Biogas residue fibers - As received	ton_AR/h	**10.78**
Biogas residue fibers - 10% moisture	ton/h	**4.79**
Biogas residue fibers - 0% moisture	ton_DM/h	**4.31**
Straw - As received	ton_AR/h	0.00
Straw - 0% moisture	ton_DM/h	0.00
Electricity Consumption	MW	**1.48**
Fuel Consumption - H2	MW	0.00
High-temperature Heat	MW	**6.96**
District heating	MW	**4.57**
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	0.00
Liquid Fuel - Oil	MW	0.00
Biochar	ton_biochar/h	**1.77**
Carbon in Biochar (no permanence factor)	ton_C/h	**1.02**

Table 2 – Main mass and energy flows for the configuration advanced integration pyrolysis biogas unit.

2.3 Bio-oil and methanation of dry gas without H_2 addition

The configuration bio-oil and methanation of dry gas without H_2 addition is shown in a block diagram in Figure 5.

This configuration is based on a pyrolysis plant fueled with dry pellets, a condensation unit for the condensation of bio-oil, and cleaning section mainly consisting of active carbon filters to ensure the correct living conditions for the micro-organisms in the biological methanation reactor.

Part of the condensed bio-oil can be combusted to provide heat to the pyrolysis unit.

This configuration may be relevant in case of a growing market for bio-oil, together with the injection of bio-methane into the natural gas grid. Since no addition of H_2 is needed, this configuration may be a stand-alone solution or with limited consumption of electricity.

Figure 6 presents a Sankey diagram for the configuration having as products bio-oil and methane produced via biological methanation without addition of electrolytic H_2. It can be observed that a 20 MW_{th} pyrolysis unit produces 4.9 MW_{th} of methane, 1.5 MW_{th} of low temperature excess heat, and 2.4 MW_{th} of bio-oil. Additional heat from the condensation of bio-oil could be used for district heating. Table 3 presents the main data regarding mass and energy flows for this configuration.

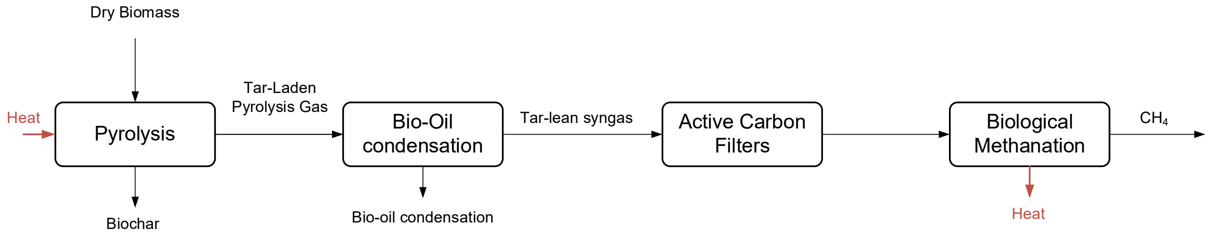

Figure 5 – Block diagram for the bio-oil and methanation of dry gas without H_2 addition.

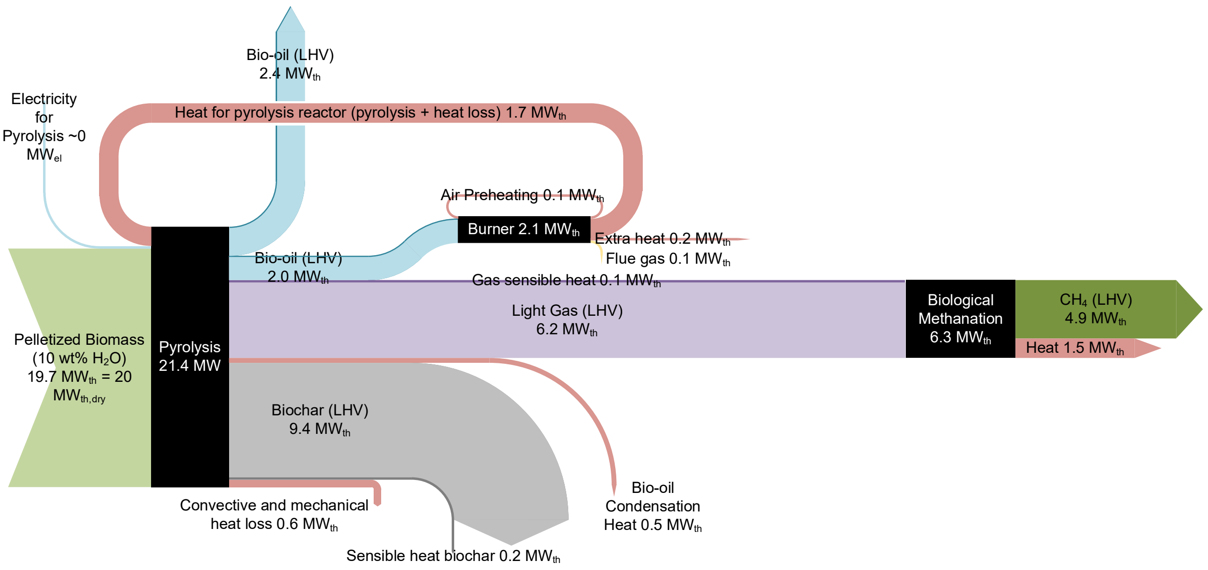

Figure 6 – Sankey diagram for the bio-oil and methanation of dry gas without H_2 addition.

		Bio-oil + Bio-methane
Biogas residue fibers - As received	ton_AR/h	0.00
Biogas residue fibers - 10% moisture	ton/h	0.00
Biogas residue fibers - 0% moisture	ton_DM/h	0.00
Straw - As received	ton_AR/h	**4.69**
Straw - 0% moisture	ton_DM/h	**4.22**
Electricity Consumption	MW	**0.78**
Fuel Consumption - H2	MW	0.00
High-temperature Heat	MW	0.00
District heating	MW	**1.47**
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	**4.86**
Liquid Fuel - Oil	MW	**2.36**
Biochar	ton_biochar/h	**1.23**
Carbon in Biochar (no permanence factor)	ton_C/h	**0.88**

Table 3 – Main mass and energy flows for the configuration bio-oil and methanation without H_2 addition.

2.4 Bio-oil and methanation of dry gas with H_2 addition

The configuration bio-oil and methanation with H_2 addition is based on the base-case described in 2.3. The main difference is that this configuration involves addition of electrolytic H_2 to maximize the production of methane by converting all or almost all the carbon in the syngas from the pyrolysis plant.

Figure 7 represents the block diagram for this configuration, while Figure 8 shows a Sankey diagram for this solution with optimized bio-methane production. While the pyrolysis section is the same as for the configuration described in section 2.3, the biological methanation is improved by injecting 9.3 MW$_{th}$ of H_2. The methane production is increased from the 4.9 MW$_{th}$ to 12.1 MW$_{th}$, as well as the excess low temperature from the biological methanation (from 1.5 to 3.4 MW$_{th}$)

This configuration will not be a stand-alone solution, as it should be somehow coupled with an electrolysis plant providing hydrogen, together with an hydrogen storage, if deemed necessary.

Table 4 presents the main data regarding mass and energy flows for this configuration.

Figure 7 – Block diagram for the configuration bio-oil and methanation with H_2 addition

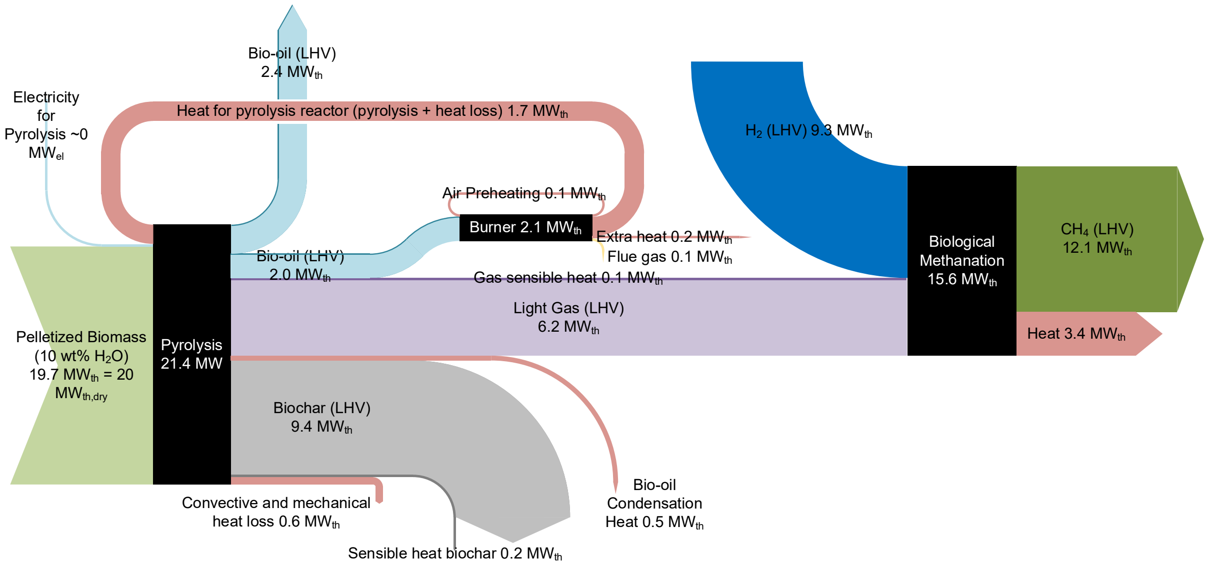

Figure 8 – Sankey diagram for the configuration bio-oil and methanation with H_2 addition.

		Bio-oil and Bio-methane with H2
Biogas residue fibers - As received	ton_AR/h	0.00
Biogas residue fibers - 10% moisture	ton/h	0.00
Biogas residue fibers - 0% moisture	ton_DM/h	0.00
Straw - As received	ton_AR/h	**4.69**
Straw - 0% moisture	ton_DM/h	**4.22**
Electricity Consumption	MW	**0.78**
Fuel Consumption - H2	MW	**9.25**
High temperature Heat	MW	0.00
District heating	MW	**3.39**
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	**12.09**
Liquid Fuel - Oil	MW	**2.36**
Biochar	ton_biochar/h	**1.23**
Carbon in Biochar (no permanence factor)	ton_C/h	**0.88**

Table 4 – Main mass and energy flows for the configuration bio-oil and methanation with H_2 addition.

2.5 Bio-oil and process heat: Mærsk configuration

The configuration bio-oil and process heat aims at producing bio-oil for e.g. the maritime shipping sector, and to produce excess heat for either (1) high temperature processes or (2) district heating.

It is also referred to as Mærsk configuration, as Mærsk could represent a potential customer, as they need large amounts of bio-oil to substitute their fossil fuel oil.
Figure 9 shows a block diagram for the bio-oil and process heat configuration. Bio-oil is condensed after the pyrolysis reactor, while the combustion of pyrolysis gas in the burner and boiler block is used to provide high temperature heat to a potential user.
The partial oxidation process shown in the block diagram is optional, and should be seen as a simplification to provide heat to the pyrolysis process directly without using heat from the burner. In this way, the pyrolysis plant and the user plant, where the final combustion of pyrolysis gas takes place, are fully separated.
Figure 10 presents a Sankey diagram for the bio-oil and process heat configuration.
Table 5 presents the main data regarding mass and energy flows for this configuration.

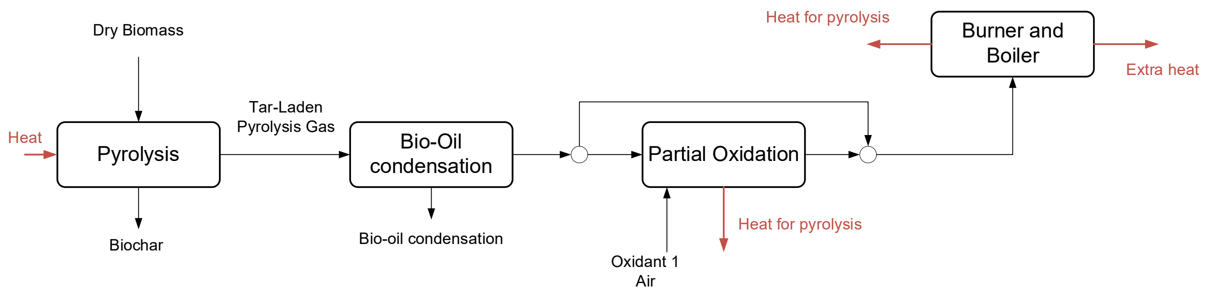

Figure 9 – Block diagram for the configuration bio-oil and process heat.

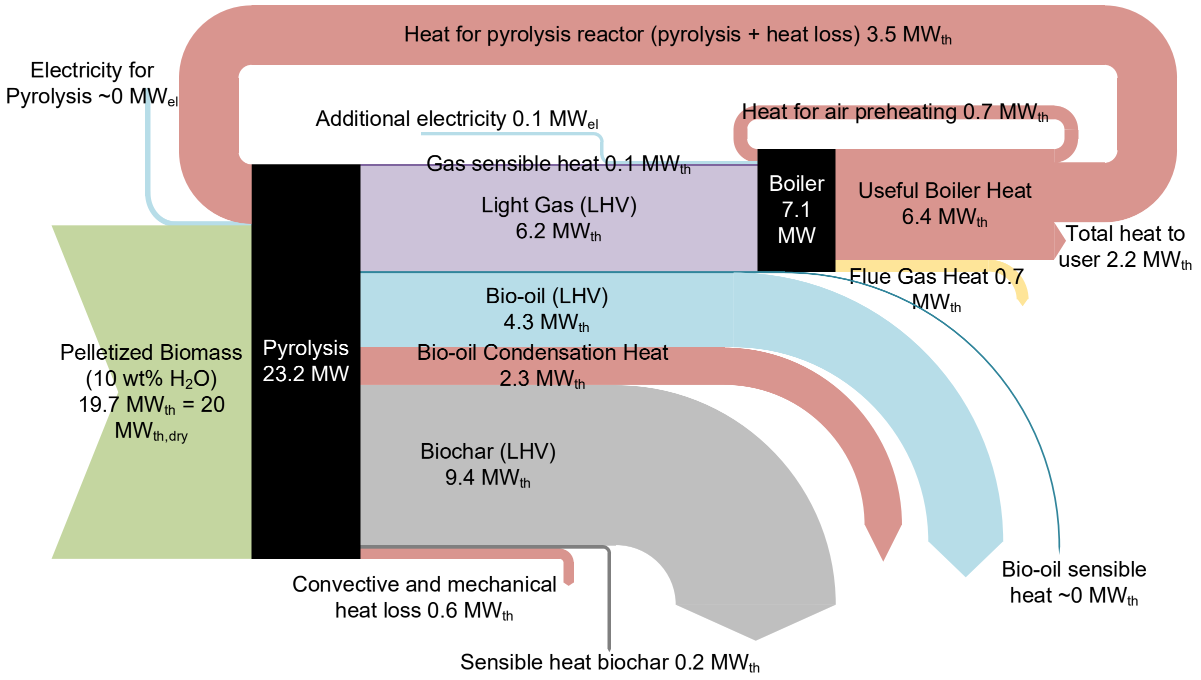

Figure 10 – Sankey diagram for the configuration bio-oil and process heat.

		Bio-oil and process heat
Biogas residue fibers - As received	ton_AR/h	0.00
Biogas residue fibers - 10% moisture	ton/h	0.00
Biogas residue fibers - 0% moisture	ton_DM/h	0.00
Straw - As received	ton_AR/h	**4.69**
Straw - 0% moisture	ton_DM/h	**4.22**

Electricity Consumption	MW	**0.83**
Fuel Consumption - H2	MW	0.00
High temperature Heat	MW	**4.51**
District heating	MW	0.00
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	0.00
Liquid Fuel - Oil	MW	**4.33**
Biochar	ton_biochar/h	**1.23**
Carbon in Biochar (no permanence factor)	ton_C/h	**0.88**

Table 5 – Main mass and energy flows for the bio-oil and process heat configuration.

2.6 Process heat: Aalborg Portland configuration

The configuration process heat is conceived to deliver high temperature heat to processes such as cement production. For this reason, this configuration is referred to as Aalborg Portland configuration, as the cement production company Aalborg Portland may represent a potential customer. However, the use of this configuration is not limited to cement production, but can supply high temperature heat to any user requiring high temperatures. Figure 11 represents the block diagram for this configuration. As described in section 2.5, the partial oxidation process shown in the block diagram is optional and is a potential way to decouple the pyrolysis and the user requiring high temperature heat from the burner and boiler block. However, it is not a requirement for the plant. Figure 12 represents a Sankey diagram for the configuration Process heat. Up to 8.5 MW_{th} can be available as steam, hot water or directly as high temperature flue gases for an industrial process. Table 6 presents the main data regarding mass and energy flows for this configuration.

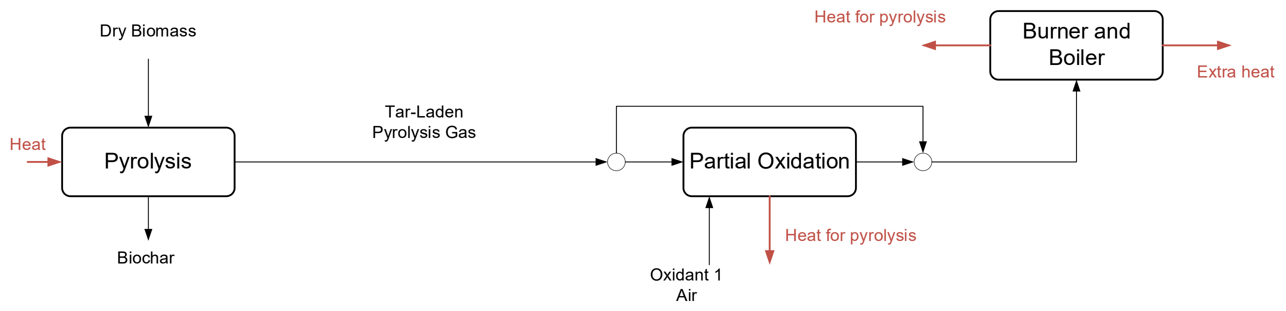

Figure 11 – Block diagram for the process heat configuration.

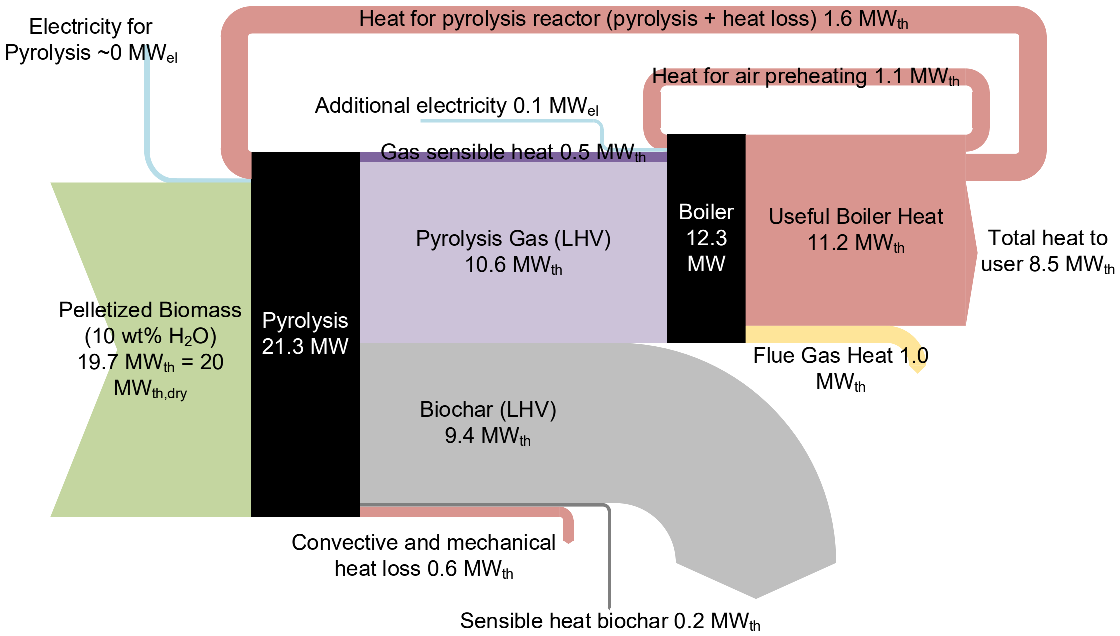

Figure 12 – Sankey diagram for the process heat.

		Process Heat
Biogas residue fibers - As received	ton_AR/h	0.00
Biogas residue fibers - 10% moisture	ton/h	0.00
Biogas residue fibers - 0% moisture	ton_DM/h	0.00
Straw - As received	ton_AR/h	**4.69**
Straw - 0% moisture	ton_DM/h	**4.22**
Electricity Consumption	MW	**0.86**
Fuel Consumption - H2	MW	0.00
High temperature Heat	MW	**8.54**
District heating	MW	0.00
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	0.00
Liquid Fuel - Oil	MW	0.00
Biochar	ton_biochar/h	**1.23**
Carbon in Biochar (no permanence factor)	ton_C/h	**0.88**

Table 6 – Main mass and energy flows for the process heat configuration.

2.7 Methanation without H_2 addition via partial oxidation

The configuration based on partial oxidation for biological methanation without H_2 addition aims at converting all the pyrolysis gas, including the tars in vapor phase, to a syngas that can be further converted in a biological methanation reactor, without need for additional electrolytic H_2. In this case, no bio-oil is produced and would represent a case where CH_4 represents an important fuel or energy carrier for the energy sector, while the bio-oil has little market.

Figure 13 shows a block diagram for this configuration. In this case the partial oxidation is a required process to convert all the tars and higher hydrocarbons into CO and H_2 for subsequent synthesis of methane. Additional cleaning with active carbon filters may be needed.

Figure 14 represents a Sankey diagram for the configuration methanation without H_2 addition via partial oxidation, while Table 7 presents the main data regarding mass and energy flows for this configuration.

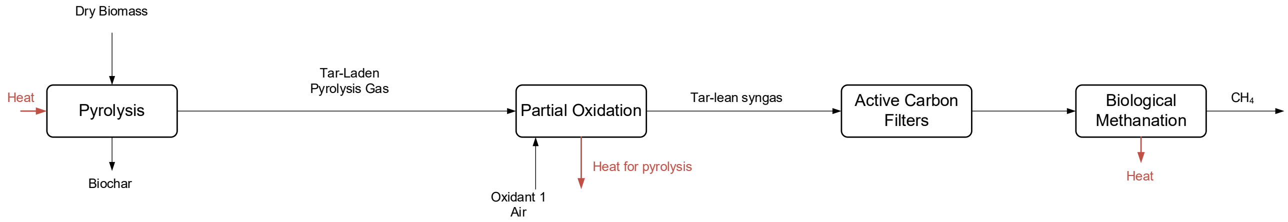

Figure 13 – Block diagram for the configuration biological methanation via POX without H_2 addition.

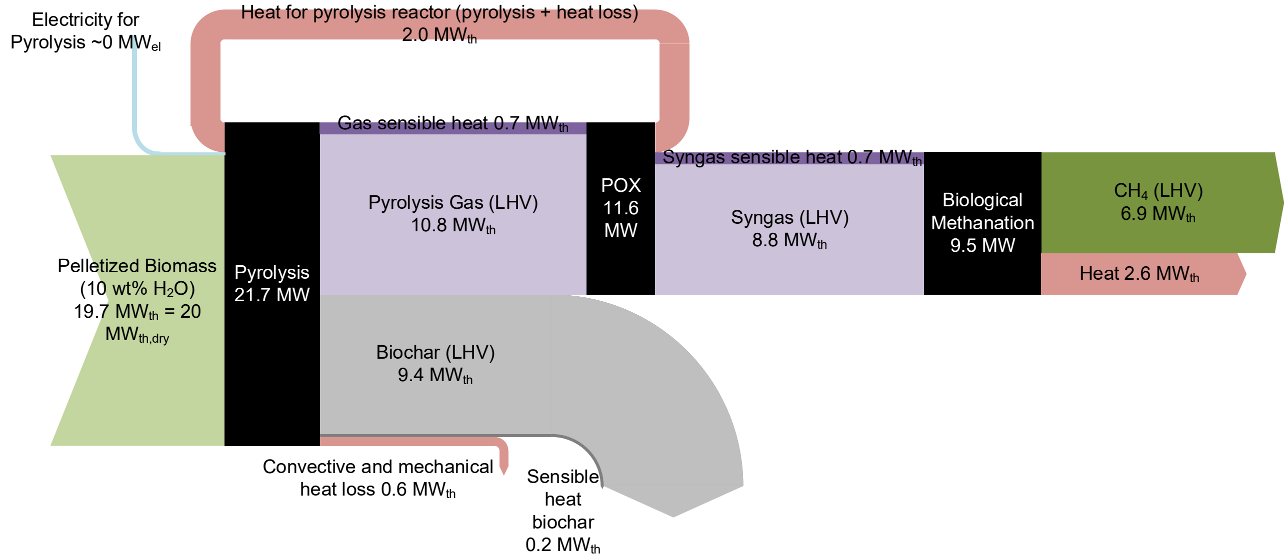

Figure 14 – Sankey diagram for the configuration biological methanation via POX without H_2 addition.

		Bio-methane via POX
Biogas residue fibers - As received	ton_AR/h	0.00
Biogas residue fibers - 10% moisture	ton/h	0.00
Biogas residue fibers - 0% moisture	ton_DM/h	0.00
Straw - As received	ton_AR/h	**4.69**
Straw - 0% moisture	ton_DM/h	**4.22**
Electricity Consumption	MW	**0.78**
Fuel Consumption - H2	MW	0.00
High temperature Heat	MW	0.00
District heating	MW	**2.64**
Gaseous Fuel - Pyrolysis Gas	MW	0.00
Gaseous Fuel - Methane	MW	**6.85**
Liquid Fuel - Oil	MW	0.00
Biochar	ton_biochar/h	**1.23**
Carbon in Biochar (no permanence factor)	ton_C/h	**0.88**

Table 7 – Main mass and energy flow for the methanation via POX without H_2 configuration

List of References