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Sustainable value methodology to compare the performance of conversion technologies for the production of electricity and heat, energy vectors and biofuels from waste biomass

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A R T I C L E I N F O

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A B S T R A C T

The Sustainable Value methodology was used to compare and rank eight combinations of waste biomass types and conversion technologies on a common assessment basis to produce energy, energy vectors and advanced biofuels. The studied combinations included agricultural and agro-industrial residues, slurries and effluents, pulp and paper mill sludge, piggery effluents and organic fractions of municipal solid waste, to produce biodiesel by (trans)esterification, biogas by anaerobic digestion, ethanol by fermentation, hydrogen by dark fermentation, electricity and heat by combustion, biogas and synthesis gas by gasification, and bio-oils by pyrolysis or hydrothermal liquefaction. The numerator “Functional Performance” of the Sustainable Value indicator was estimated according to 14 criteria of process technology, material and energy inputs and outputs, and acceptance by the stakeholders. The performance of the technologies was classified based on the values of relative importance (φ) and level of satisfaction (*S*) attributed to each criterion. The gasification of residues from the olive-oil industry reached the highest “Functional Performance”, followed by anaerobic digestion of chestnut processing residues and pig-rearing effluents. The Sustainable Value denominator “Costs” depended mainly on the degree of maturity of the technologies, which penalised pyrolysis, hydrothermal liquefaction and dark fermentation. The final ranking of the Sustainable Value indicator was gasification > combustion > anaerobic digestion > (trans)esterification > pyrolysis and fermentation to ethanol > hydrothermal liquefaction > dark fermentation, respectively for the most adequate waste biomass types under study. Thermochemical conversions were mainly impacted by process and input criteria, while output and social acceptance criteria were more decisive for the biochemical conversions.

1. Introduction

The Paris Agreement was signed in 2015 with the aim of establishing a framework to limit global warming to significantly below 2 ⁰C relative to pre-industrial levels and strive to limit it to 1.5 ⁰C in order to avoid dangerous climate change (Intergovernmental Panel on Climate Change, Conference of the Parties COP 21). At this time, the contribution determined by the European Union (EU) was to reduce the greenhouse gas (GHG) emissions by at least 40 % by 2030 compared to 1990. The GHG emissions include emissions of various gases, such as carbon dioxide (CO_2), methane, nitrous oxide, and other trace gases like hydrofluorocarbons and sulphur hexafluoride. Being the second gas responsible for global warming (the first is water vapour), CO_2 is, in part, associated with human activities (Londono-Pulgarin et al., 2021).

Since the Paris Agreement, the EU has established more ambitious climate ambition program for 2030 and beyond. The European Green Deal has raised the main target of reducing GHG emissions and removals to at least 55 % below 1990 by 2030, and set the target of Europe becoming the world's first climate neutral continent in 2050. To face these challenges, a commitment to increasingly low carbon practices in all

Abbreviations: EROI, Energy Return on Investment; FAME, Fatty acid methyl esters; GHG, Greenhouse gases; H, Hazard statement; PNAER 2020, Portuguese National Action Plan for Renewable Energies 2020; PNEC 2030, National Plan for Energy and Climate 2030; R&D, Research and development; S, Level of satisfaction; SV, Sustainable Value; WBtoE, Waste biomass-to-energy; φ, Relative importance

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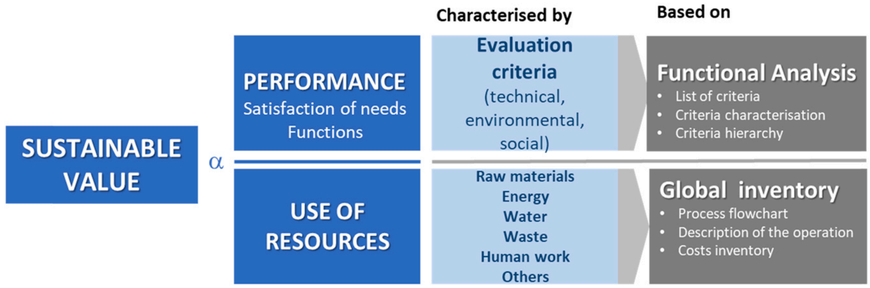

Fig. 1. The Sustainable Value concept.

sectors of activity is essential, and fortunately, these practices are already underway. Among the actions that nations are strengthening implementation, renewable energies such as wind energy, solar energy, hydraulic energy, geothermal energy, tidal energy and biomass to energy are the most impacted (Londono-Pulgarin et al., 2021).

According to the review of the Portuguese National Action Plan for Renewable Energies 2020 (PNAER 2020) launched in April 2013, biomass should contribute up to 93 % of all Renewable Energy Sources (RES) for the heating / cooling sector and 87 % for the transport sector (as biofuels) by 2020. Although with a less significant contribution in the context of different RES, biomass should also contribute to the renewable electricity within the national target of 49.6 %, through cogeneration plants or dedicated plants using biomass. Biomass is defined by the European Technical Specification CEN/TS 14588 as "all material of biological origin excluding those that have been encompassed in geological formations undergoing a process of mineralisation". Biomass for bioenergy includes organic matter of vegetal origin and the materials that come from their natural or artificial transformation, like the waste coming from agricultural and forestry activities and by-products of the food industries and the transformation of wood, as well as municipal bio-degradable waste (Gold and Seuring, 2011).

More recently, the Portuguese National Plan for Energy and Climate 2030 (PNEC 2030) included as its first objective the decarbonisation of the national economy, in which the path to ensure the reduction of the national GHG emissions in all sectors of activity, namely energy and industry, mobility and transport, agriculture and forests, and waste and wastewater was established, and to promote the integration of mitigation objectives in sectoral policies. PNEC 2030 details the promise of greater efficiency and less usage of resources in the industry sector, optimising as much as possible the nexus of energy, water and material's efficiency in terms of production processes, while ensuring increased productivity and competitiveness. The plan also proposed renewable gases, in particular biomethane and green hydrogen, as viable alternatives for the replacement of fossil fuels.

The use of different categories of biowaste, that include woody biomass, agricultural waste, municipal waste, sewage sludge, algae and aquatic plants, as low-cost raw resources for the production of renewable energy would help to solve clean energy problems, while also avoiding landfilling and creating an income (Abdel-Basset et al., 2021, Awasthi et al., 2021). In terms of waste resources overview, the sector of olive oil sector achieved a production of 2.25 millions hL in Portugal in 2021, and represents one of the most important agro-industrial sector in the country (Statistics Portugal). The olive oil extraction generates huge amounts of olive pomace as main residue, which, due to the quantities generated and the toxic composition, represents an important asset for valorisation. The importance of the pulp and paper sector Portugal was also expressed by its ranking in the 3rd and 11th European position in the production of pulp and of paper and board, respectively, in 2021 (CELPA, 2021). From the primary sedimentation of solid matter (fibers, wood residues, etc.) that is dragged in the effluent of the pulp production process, primary sludge is generated as a residue with great potential for conversion, particularly in the Portuguese industrial context.

In Portugal, in recent decades, important progress has been made in the management of waste resources, in line with the objectives and guidelines of the European Union. The case of urban waste and biowaste is, in a way, a success, as the developing effort has created tools for the prevention, control, recovery and treatment of a considerable amount of generated waste. However, a systematic assessment of the suitability of waste biomass types for specific energy conversion technologies is still scarce. Those types include the biogenic fraction of municipal solid waste from households, restaurants, caterers and retail premises, garden and park waste, agricultural and agro-industrial residues and by-products, and manure, industrial and sewage sludge. The Portuguese R&D project CONVERTE (https://converte.lneg.pt/) addressed this challenge and evaluated the best possible application of energy crops and waste biomass types generated in mainland Portugal in viable technological solutions to produce energy and heat, energy vectors and advanced biofuels (Abreu et al., 2020). The focus was the use of low-ILUC biomass and with high potential of GHG emission savings, to comply as much as possible with identified synergies and/or trade-offs for the biofuel transition under the scope of the Sustainable Development Goals (Ronzon and Sanjuan, 2020). At the same time, an analysis of conversion technologies with different degrees of maturity and the respective energy products was performed, to assess the sustainability of the value chain for the recommended solutions, in order to guarantee compliance with national and European legislation.

In the present study, eight selected combinations of waste biomass types x conversion technology and respective energy product were evaluated according to the Sustainable Value methodology. According to the EN 1325 standard (EN 1325:2014), the value of a study subject can be described as the relationship between the satisfaction of needs (performance) and the resources used in achieving that satisfaction: Value α Satisfaction of needs/Use of resources (Fig. 1). The Sustainable Value for each combination of waste biomass type x conversion technology was obtained by quantifying the Performance (the satisfaction of needs was characterised by criteria of technical, environmental and social performance) and the Resources involved to obtain this performance (e.g. energy, water, human resources, costs), in the form of a quotient. This approach admits the integration of solutions that may increase the value of the object of study, for example by efficiency improvement of existing processes, products and technologies or by considering the integration of other renewable energy technologies (Simões et al., 2021).

The types of waste biomass of this study included residual biomass generated in mainland Portugal from agricultural and agro-industrial activities, pulp and paper mill sludge from one industrial unit, manure and effluents from poultry and pig farming, and organic waste from separated collection of municipal solid waste. The energy product and the respective conversion technologies under investigation were i) biodiesel (fatty acid methyl esters - FAME) by (trans)esterification, ii) biogas by anaerobic digestion, iii) ethanol by fermentation, iv) hydrogen by dark fermentation, v) electricity and heat by combustion, vi) biogas and synthesis gas by gasification, vii) bio-oils by pyrolysis, and viii) bio-oils by hydrothermal liquefaction. The methodology used in CONVERTE project intended to develop a tool that would reduce the evaluation complexity and respective decision making in the process of

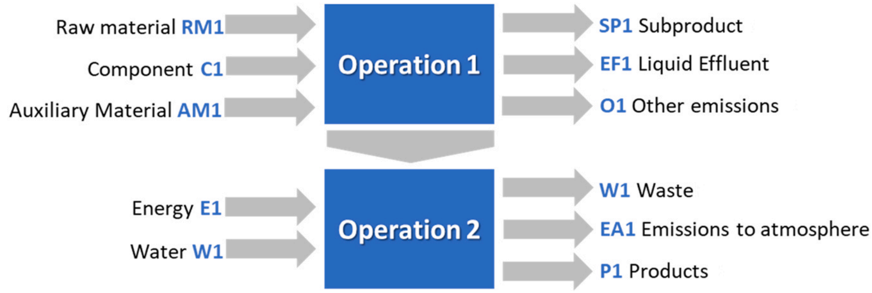

Fig. 2. Example of a process flowchart and identification of the respective inputs and outputs.

allocating available waste biomass resources for energy. A total of 55 samples of different waste biomass types were obtained from 28 industrial and waste management stakeholders. They were submitted to extensive physical and chemical characterisation before being used to support the 27 case studies of combined waste biomass type x conversion technology to energy. This information served as the basis for establishing a classification grid of the waste biomass types for energy, which included sustainability indicators by the estimation of the Sustainable Value.

2. Methodology

2.1. Sustainable value indicator

In CONVERTE project the indicator chosen to compare the different technologies was the "Sustainable Value" and resulted from the application of the Sustainable Value Methodology (Catarino et al., 2011), with adaptation of the conventional methodology phases to the specificities of the study subject.

To evaluate the performance considered in the numerator of the Sustainable Value quotient, a set of performance evaluation criteria applicable to the eight technologies involved was identified and the relative importance of each criterion was established. Then it was determined how each technology met each criterion, according to a previously defined scale. The process flowchart of each technology was the starting point to evaluate the inputs and outputs in each case. Due to discrepancies in the Technology Readiness Level of the studied technologies, the costs estimation was based on relevant data from the literature.

2.2. Sustainable value working teams

The team that developed the Sustainable Value concept (Catarino et al., 2011; Henriques and Catarino, 2015; Henriques and Catarino, 2017) was responsible for the adaptation and application of the Sustainable Value methodology to the objectives of CONVERTE, the guidance in the implementation of the methodology, training the eight technology teams and transposing the information and the specificities of each technology to determine the Sustainable Value indicators. The involvement of the technology teams in the assessment of the Sustainable Value focused in particular the discussion and definition of the following aspects:

- Preparation of the process flowcharts, including the identification of all unitary operations, the material, water and energy inputs and outputs, and GHG emissions;
- Definition of the performance evaluation criteria, as well as definition of the degree of satisfaction associated with each binomial technology x waste biomass type;
- Prioritisation of the importance of the performance evaluation criteria for each technology, using an importance matrix;
- Evaluation of the investment and exploration costs associated with each technology and expressed by energy unit (€/MWh), based on relevant bibliographic data.

The global definition of the performance evaluation criteria and their weighting were decided between the Sustainable Value team and all eight technology teams.

2.3. Base assumptions

The functional unit adopted for this study corresponded to 1 kg dry matter of raw material, i.e. waste biomass used as process feedstock, regardless of the origin considered for the development of the binomial technology x waste biomass type. The scope of the study included the stages of raw material pre-processing, production of the electricity and heat, energy vector or advanced biofuel, and downstream purification. The usage of the energy product was not contemplated and therefore not included in the process flowchart.

The availability of the waste biomass type in question in mainland Portugal was considered as the frontier of the study, that is, the feasibility of combining the technological transformation into energy products of each waste biomass considered would only make sense if the availability, in material terms, turned out to be a reality.

2.4. Definition of the process flowcharts

All conversion technologies under study were characterised by process flowcharts (Fig. 2), in which the main and auxiliary process stages were represented and then numbered sequentially. Eight process flowcharts were obtained, where the main unit operations were identified, as well as the respective inputs (raw materials, energy and water) and outputs (products / by-products, emissions, waste).

2.5. Functional analysis

To estimate the *Performance* shown in the numerator of the Sustainable Value indicator (Fig. 1), the performance evaluation criteria selected by the technology teams were listed, characterised and ranked through a hierarchy matrix that enabled the comparison of the criteria two by two, assigning them specific scores (0.5 for the case of equal importance, 1 for more important and 0 for less important). The respective scores were considered and therefore it was possible to estimate the percentage of the relative importance of each criterion (weighting coefficient - φ) that had established their ranking.

Each technology team defined how each technology fulfilled each criterion, which would then correspond to the level of satisfaction (S). The weighted sum of the various satisfaction factors (ΣφxS) enabled the estimation of the performance of each technology, which was mandatory to determine the Sustainable Value indicator. According to Fig. 1, the ratio obtained between the *Performance* and the associated *Resources* led to the calculation of the Sustainable Value of each technology under study, thus enabling comparisons between them.

Table 1
Studied technologies and respective waste biomass types considered, energy products and co-products.

Technologies		Waste biomass types	Products	Maturity degree	Co-products
T1	(Trans)esterification	Fat-rich agro-industrial residues	Biodiesel (FAME)	Commercial (EU and Portugal)	Non-refined glycerin
T2	**Anaerobic digestion**	Agro-industrial residues, slurries and effluents, piggery effluents	Biogas	Commercial (EU and Portugal)	Fertilizer
T3	**Fermentation**	Agro-industrial residues; pulp and paper mill slurries	Bioethanol	Industrial/ Demonstration (EU) R&D (Portugal)	Lignin
T4	**Dark fermentation**	Agro-industrial residues; catering and restaurant waste	Bio-hydrogen	Demonstration (Taiwan) R&D (Portugal)	Organic acids
T5	**Combustion**	Agro-industrial residues; harvest and pruning residue	Heat and Power	Commercial (EU and Portugal)	–
T6	**Gasification**	Agro-industrial residues; harvest and pruning residue	Biogas and synthesis gas	Commercial (EU and Portugal)	Biochar
T7	**Pyrolysis**	Fat-rich agro-industrial residues and slurries	Bio-oils	Commercial (EU) R&D (Portugal)	Biogas Biochar
T8	**Hydrothermal liquefaction**	Green waste	Bio-oils	R&D (EU and Portugal)	Biogas Biochar

2.6. Brief description of the technologies under study

The information about technologies, energy products, the biomass resources tested in each technology and their degree of maturity is aggregated in Table 1 and detailed below.

2.6.1. Technology 1. (Trans)esterification for biodiesel

Biodiesel production, most specifically FAME, is carried out through a (trans)esterification reaction, in which the glycerides and/or free fatty acids present in a given raw material are converted into esters, in the presence of an alcohol and a catalyst. Biodiesel has been increasingly produced from residual raw materials, such as waste cooking oil as an organic waste (Awasthi et al., 2021), as well as animal fats (Hajjari et al., 2017). Biodiesel can also be produced from lipids of microbial origin, such as algae or yeast, obtained by biological conversion (fermentation) of residues with a high sugar content.

2.6.2. Technology 2. Anaerobic digestion for biogas

Anaerobic digestion is the utmost favourable technology to treat biological wastes (Awasthi et al., 2021). Anaerobic digestion is a biological process that degrades complex organic matter in the form of proteins, carbohydrates and lipids, using several categories of microorganisms and enzymes, until it generates a gaseous product named biogas, consisting essentially of methane (CH_4) and carbon dioxide (CO_2). It also contains other compounds in lower concentrations, such as water (H_2O), carbon monoxide (CO), hydrogen (H_2), hydrogen sulphide (H_2S), mercaptans, siloxanes and halogenated compounds. This degradation process is quite complex and can be briefly described as consisting of three distinct phases: hydrolysis of the molecules, acidification and methanation, which coexist at the same time in the digester (Horváth et al., 2016). The different microbial groups involved in each phase act together in a symbiotic and synergistic relationship, which makes the process complex and sensitive to environmental variations.

The main outputs of anaerobic digestion are the energy-rich biogas, the final slurry and the digestate residue. Normally, the residue can be landfilled, incinerated, composted or directly spread on land as fertiliser. However, the dewatered digestate and the press water from anaerobic digestion may contain abundant pollutants in the form of chemical oxygen demand (COD), and heavy metal (Awasthi et al., 2021).

The waste biomass commonly used for the production of biogas corresponds to effluents and organic waste, e.g. the flows from animal production, grasses and green waste, food waste, industrial wastewaters and slurries.

2.6.3. Technology 3. Fermentation for bioethanol

Bioethanol is produced by the biological conversion of a carbohydrate-rich biomass by the action of fermentative yeasts. The yeast *Saccharomyces cerevisiae* is commonly employed due to its high ethanol productivity, high ethanol tolerance and ability to ferment a wide range of sugars. The bioconversion process can use a variety of feedstock, either rich in directly fermentable sugars (e.g.: sugar cane, sugar beet, carob), rich in starch (e.g.: corn, wheat) or non-saccharine biomass, consisting of lignocellulose material (e.g. wood scraps, waste from the pulp and paper industry and energy crops such as *Miscanthus*) (Marques et al., 2008). The conversion of lignocellulosic materials, namely the cellulose and hemicellulose components, requires the use of suitable feedstock pretreatments, enzymes and adapted fermentation technologies.

2.6.4. Technology 4. Dark fermentation for hydrogen

Dark fermentation consists in the biological conversion of carbohydrate-rich biomass by strict or facultative anaerobic microorganisms, with the production of H_2, CO_2 and organic acids. Given the versatility of the biocatalysts, there is a wide variety of waste biomass types that can be used as a substrate for dark fermentation: the by-products of biodiesel production containing glycerol, hydrolysates obtained by enzymatic treatment of waste from the pulp and paper industry; food waste, agricultural and agro-industrial byproducts or residues, such as brewery spent grain, corn cob and carob pulp, and spent microalgal biomass (Ortigueira et al., 2018, 2020).

2.6.5. Technology 5. Combustion for heat and power

The thermochemical technologies such as combustion, gasification and pyrolysis are processes that use a high temperature to convert feedstock into electricity, heat, energy vectors, biofuel precursors and value-added products (Awasthi et al., 2021). Combustion, in particular, converts the chemical energy contained in the biomass into other energy types, such as thermal energy (in the form of heat, through equipment intended for this purpose, such as steam generators, boilers, furnaces, stoves, amongst others), and mechanical energy (in the form of electricity, using turbo generators such as steam and gas turbines, alternative engines, amongst others) (Ferreira et al., 2017). A wide variety of solid biomass types can be considered for this thermochemical process, including several forest and short-cycle forest species (e.g. firewood, wood chips, chips, pellets, briquettes), residues from the timber industry, from forestry crops and agriculture, and agro-industrial residues, like sugarcane bagasse residues, olive pomace and olive stone. For all these possibilities the solid residues must meet the initial requirements for their burning, namely having or being able to be brought to a low moisture content, which would not exceed 20 % (w/w) (Ferreira et al., 2017).

2.6.6. Technology 6. Gasification for biogas and synthesis gas

Biomass gasification is a thermochemical conversion process that makes it possible to obtain a gas, which can be used as gaseous biofuel or as raw biomaterial. The gasification products are mostly gaseous, although a small fraction of solids that contains the mineral matter of the processed waste and some unconverted carbonaceous matter is also produced. Thus, gasification produces a gas of which its main constituents are H_2, CO_2, CO, CH_4 and other gaseous C2- and C4-hydrocarbons. The gas produced by gasification can be burned directly to produce energy, be used in combustion engines or turbines, used in fuel cells if enriched with hydrogen, or used in chemical synthesis to produce ethanol, methanol or dimethyl ether.

Gasification has been applied to several types of biomass, which must have a moisture content of less than 20 % (w/w). Dry wood shavings, agricultural and agro-industrial residues (e.g. coconut, palm, sawdust, corncobs and fruit husks, olive stone and olive pomace) and municipal solid waste are some of the biomass types that have been used as gasification feedstock (Pinto et al., 2011).

2.6.7. Technology 7. Pyrolysis for bio-oils

Pyrolysis is a thermochemical process that consists of the decomposition of biomass in an oxygen-free atmosphere, at medium or high temperatures (depending on the type of products required). For the production of bio-oils it is necessary to apply rapid pyrolysis, a process with a high heating speed, where the biomass must be initially dried to decrease the moisture that may be present, up to a value between 10 % and 15 % (w/w) of water content. The dried biomass must be crushed to reduce the particle size in order to ensure a rapid reaction in the reactor, which favours the formation of liquid products.

Bio-oils can be obtained from various types of biomass including several species of softwoods (e.g. cedar, redwood, firs and pine), hardwoods (e.g. cypress, chestnut, oak, beech, eucalyptus), residues from industrial activities of wood and biomass processing, energy crops (e.g. *Miscanthus*, Thistle) and residues from agricultural and agro-industrial activities (Dhyani and Bhaskar, 2017).

2.6.8. Technology 8. Hydrothermal liquefaction for bio-oils

Hydrothermal liquefaction is a thermochemical process used to convert raw materials with high moisture content into bio-crude and value-added chemicals. Currently, the main objective of this technology is the production of a bio-oil, a liquid with high viscosity, usually black in colour and with a calorific value of about 30–38 MJ/kg (Tian et al., 2014). One of the major benefits of using hydrothermal liquefaction over conventional pyrolysis technology is that there is no need to dry the biomass before the thermal conversion. This enables the use of a wide variety of materials, such as lignocellulosic biomass, agricultural wastes (corn, sorghum and barley straw), municipal waste (primary sewage sludge from wastewater), agro-food waste from tree crops (from vineyards and fruit trees), industrial waste from the forestry sector and microalgae and macroalgae biomass without previous drying.

2.7. Definitions

Sustainable Value concept - according to the EN 1325 standard (EN 1325:2014), the value of a study subject can be described as the relationship between the satisfaction of needs (performance) and the resources used in achieving that satisfaction: Value α Satisfaction of needs/Use of resources, which may change with context and time. When the terms of this relationship take into account environmental and social aspects besides the economic ones we are referring to Sustainable Value.

Sustainable Value – the quotient (Value α Satisfaction of needs/Use of resources) where the numerator is quantified by means of technical, environmental and social evaluation criteria that are considered relevant for the performance of the studied product and/or process, and the denominator is determined by the quantification of expenditures in energy, water, human resources, time, amongst others.

Sustainable Value methodology – a systematic and function-based approach to improve the sustainable value of products, projects or processes. It uses a combination of creative and analytical techniques.

Functional analysis – a systematic process that enables identification, characterisation, classification and evaluation of the functions of the study subject (product and/or process) and the relationship between them.

Relative importance (φ) - weighting coefficient that ranks each performance evaluation criterion according to its importance for the fulfilment of the product and/or correct process performance.

Level of Satisfaction (S) - how the product and/or process behaves concerning the satisfaction of the defined performance evaluation criteria.

3. Results

3.1. Definition of the process flowcharts

The technologies for the production of electricity and heat, energy vectors and advanced biofuels of the present study included four biochemical and four thermochemical conversion paths:

T1. (Trans)esterification for biodiesel,
T2. Anaerobic digestion for biogas,
T3. Fermentation for bioethanol,
T4. Dark fermentation for hydrogen,
T5. Combustion for electricity and heat,
T6. Gasification for biogas and synthesis gas,
T7. Pyrolysis for bio-oils,
T8. Hydrothermal liquefaction for bio-oils.

Consequently, eight process flowcharts were defined, one for each conversion process under study. Fig. 3 is the exemplary flowchart of hydrothermal liquefaction. The unitary operations considered in each case corresponded to those necessary for the admission of the respective waste biomass type considered (Table 1) and to the possible pretreatment steps required.

3.2. Performance evaluation criteria

The evaluation criteria defined to assess the performance of the conversion processes considered in the present study are shown in Table 2. These criteria were selected in order to integrate aspects of sustainability related to the technical conversion process (efficiency and flexibility) and its management (execution time and maturity), the processes inputs and outputs, and aspects associated with social acceptance. The basis for the process inputs included the eco-efficiency parameters, materials and energy intensity, toxicity dispersion, scarcity of resources, with emphasis on water availability. For process outputs, the basis included toxicity dispersion, principles of circularity, air quality and climate action.

For a better understanding of the listed criteria, the meaning associated with each of them is briefly explained.

- Overall mass efficiency - Refers to the overall efficiency in converting waste biomass to energy for the various energy products considered in the process flowcharts (or calorific value for combustion), in effective percentages.
- Flexibility of the raw material allowed as input - considers the admissible concentration range of the waste biomass at the beginning of the process, for each technology. In biochemical processes it is

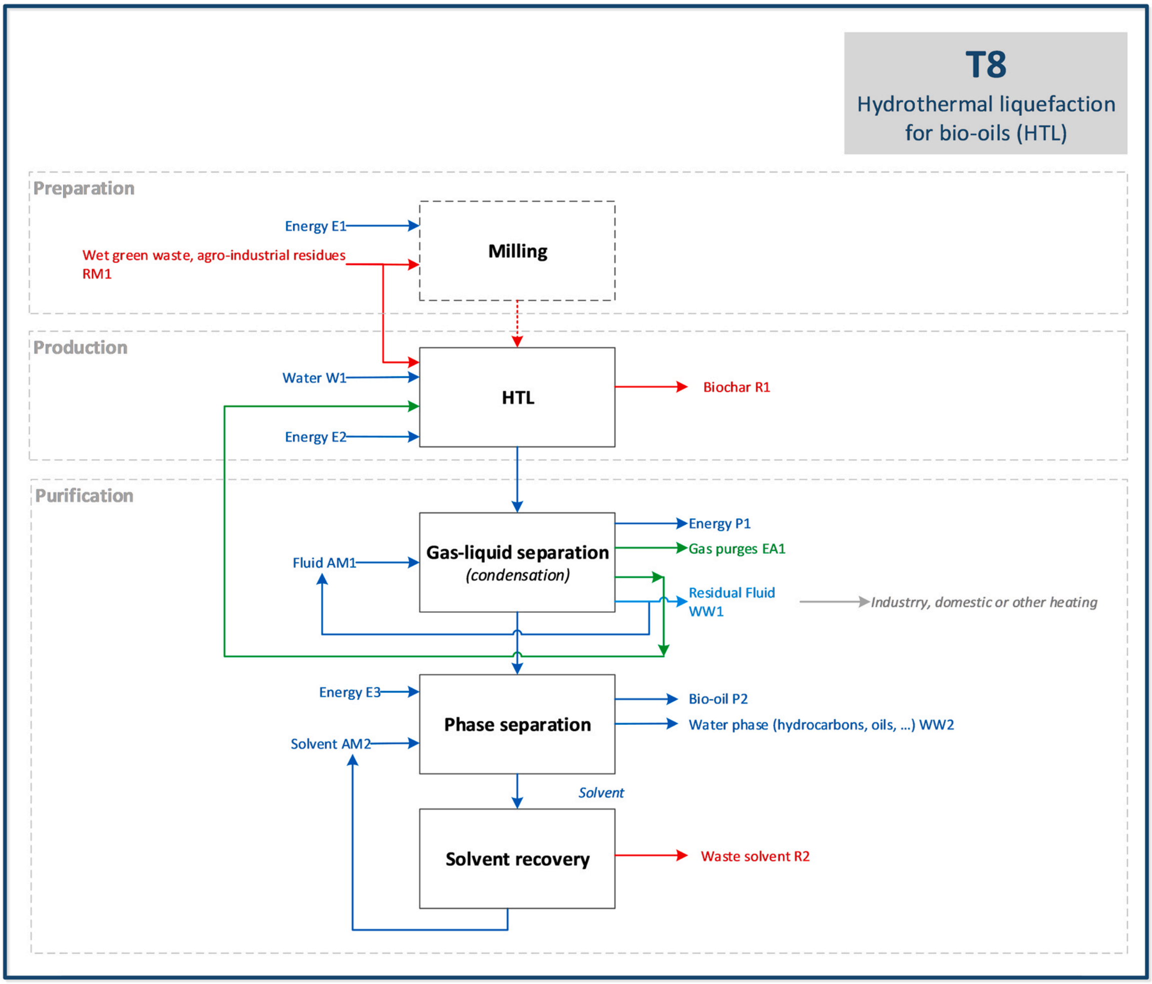

Fig. 3. Process flowchart of hydrothermal liquefaction for bio-oils.

Table 2
Criteria used to assess the Sustainable Value and respective contemplated basis.

Basis		Criteria
Process	Conversion process	Overall mass efficiency
		Flexibility regarding the waste material allowed as input
	Process management	Execution time
		Maturity according to the *Technological Readiness Level* (TRL) scale
Inputs	Material intensity	Materials incorporation
	Toxicity dispersion	Hazardous materials (hazard of the embedded materials)
	Resources scarcity	Use of non-renewable resources
	Energy intensity	Ratio between energy released or produced and energy consumed in the process
	Water availability	Water usage
Outputs	Toxicity dispersion	Hazard of waste
	Circularity	Waste generation
	Air quality	Particulate emissions to the atmosphere
	Climate change	Contribution to the greenhouse effect
Society	Social acceptance	Acceptance by the stakeholders (e.g. population in general, technology players, waste management systems)

associated with the concentration of raw material that can enter the reactor; in the thermochemical processes it is mostly associated with the water concentration in the raw material, that determines if, or after which pretreatment, the conversion process can take place. It can also be understood as a measure of the widest or narrowest admissible range of the feedstock intake spectrum at each process entrance.

- Materials incorporation - refers to the amount of auxiliary materials used in the conversion process. Water incorporation is excluded here, because it will be the object of a specific analysis below. The results were expressed in kg/kg of dry matter of the waste biomass used as feedstock in the conversion processes.
- Hazardous materials - refers to the hazard statements associated with each auxiliary material incorporated in the conversion process (hazard statements H are part of Regulation (EC) No. 1272/2008 of

Table 3
Relative importance adopted for the performance evaluation criteria used in calculating the Sustainable Value for the various binomial waste biomass types x technologies under study.

Relative importance (φ)	Criteria
5	Overall mass efficiency
1	Flexibility regarding the raw material allowed as an input
1	Materials incorporation
3	Hazardous materials
5	Use of non-renewable resources
5	Ratio between the energy released or produced and the energy consumed
5	Water usage
1	Waste generation
3	Hazardous waste
5	Particulate emissions to the atmosphere
5	Contribution to the greenhouse effect
5	Acceptance by the stakeholders

the European Parliament and of the Council, of 16 December 2008) ((EC) No. 1272/2008). Since not all entries represent the same level of danger, 3 groups were considered: A) H200 to H299 - physical hazard; B) H300 to H399 - health hazard; C) H400 to H499 - danger to the environment.

- Use of non-renewable resources - refers to the use of non-renewable materials or fossil energy in the conversion processes. It is related to resource depletion.
- Ratio between the amount of energy released or produced and the amount of energy consumed – considers the ratio between the energy content of the products generated or the energy produced, and the energy consumed in the process. It corresponds to the Energy Return on Investment (EROI), the ratio of the amount of usable energy obtained from a resource to the amount of energy expended to produce that net amount of energy.
- Water usage - refers to the water expenditure in the conversion processes, in l/kg of dry matter of the waste biomass used as feedstock in the conversion process. It does not account for recycled water, only process water in absolute terms. Due to the special character that water represents in environmental terms (scarcity, quality, others) this criterion was defined as independent from other auxiliary materials. On the other hand, it is not representative in terms of costs, as a significant value is still not attached to the use of water.
- Waste generation - refers to the amount of solid waste generated in the conversion process, in kg of dry waste/kg dry matter of the waste biomass type used as feedstock.
- Hazardous waste - refers to the number of hazardous characteristics of the waste generated as process output, as defined in Annex III of Regulation (EU) No. 1357/2014 ((EC) No. 1357/2014).
- Particulate emissions to the atmosphere - refers to the emission of particles to the atmosphere in mg/kg dry matter of the waste biomass used as feedstock in the process.
- Contribution to the greenhouse effect - refers to the ratio between the amount of greenhouse gases generated in the conversion processes, in kg CO_2 eq. released into the atmosphere / stoichiometric CO_2 from kg of dry matter from the waste biomass used as feedstock in the process.
- Acceptance by the stakeholders - associated with the reaction of stakeholders towards the technology in question, in which full acceptance is more valued, followed by simple acceptance, indifference, difficult acceptance or explicit rejection. For this purpose, it is required that the stakeholders correspond in general terms to the producers and operators of the technology and to the population in general. The general opinion expressed in the media was also considered.

Table 4
Classification ranges of the defined performance evaluation criteria to enable the quantitative analysis of the Level of Satisfaction.

Criteria	Units	Range				
Overall mass efficiency	%	90 – 100	75–89	50–74	25–49	< 25
Flexibility regarding the raw material allowed as an input	–	Indifferent	Wide range	High	Limited	Very Limited
Materials incorporation	*kg/kg dry matter of raw material*	0	< 0.10	0.10–0.25	0.25 – 0.50	> 0.5
Hazardous materials	*Hazard of embedded materials*	No danger item	1 item class A	1 item class A and another B or C	2 items class B or C	> 2 items class B or C
Use of non-renewable resources	–	No use	–	–	–	Use
Ratio between energy released or produced and energy consumed in the process	*EROI (= energy gathered /energy invested)*	> 1	–	1	–	< 1
Water usage	*L/kg dry matter of raw material*	0	0–1	1–2	2–3	> 3
Waste generation	*kg dry residue/kg dry matter of raw material*	0	< 0.25	0.25 – 0.5	0.5–0.75	> 0.75
Hazardous waste	*Number of hazardous items*	0	1	2	3–10	11–15
Particulate emissions to the atmosphere	*mg/kg of dry matter of raw material*	0	–	–	–	1
Contribution to the greenhouse effect	*kg CO_{2eq} released /kg dry matter of raw material*	0	< 0.25	0,25–0.5	0.5–0.90	> 0.90
Acceptance by the stakeholders	–	Fully	Acceptable	Indifferent	Difficult acceptance	Rejection
Execution time	*Associated to the conversion rate or reaction time*	Seconds	Minutes	Hours	Days	Weeks
Maturity	*Scale of Technological Readiness Level (TRL)*	Marketing (TRL 8–9)	Demonstration (TRL 6–7)	Pilot (TRL 4–5)	R&D (TRL 2–3)	Idea (TRL 1)
Classification		5	4	3	2	1

Table 5
Technologies' performance based on the classification of the Level of Satisfaction.

Criteria	Level of Satisfaction, S								
	T1	T2	T3	T4	T5	T6	T7	T8	Relative importance, φ
Overall mass efficiency	5	3	2	2	5	5	3	3	**5**
Flexibility regarding the raw material allowed as an input	4	3	2	3	5	5	3	3	**1**
Materials incorporation	2	4	3	3	5	5	5	4	**1**
Hazardous materials	1	4	3	5	5	5	5	5	**3**
Use of non-renewable resources	1	4	1	5	5	5	5	5	**5**
Ratio between energy released or produced and energy consumed	5	5	5	1	5	5	5	5	**5**
Water usage	4	5	1	4	5	5	5	4	**5**
Waste generation	4	4	4	4	4	4	3	3	**1**
Hazardous waste	5	4	5	5	3	3	2	2	**3**
Particulate emissions to the atmosphere	5	5	5	5	1	5	5	5	**5**
Contribution to the greenhouse effect	5	5	4	4	1	5	5	5	**5**
Acceptance by the stakeholders	5	5	5	4	2	4	4	3	**5**
Performance (ΣφxS)	**177**	**195**	**147**	**166**	**158**	**208**	**192**	**181**	–

T1, (trans)esterification; T2, anaerobic digestion; T3, fermentation (to ethanol); T4, dark fermentation; T5, combustion; T6, gasification; T7, pyrolysis; T8, hydrothermal liquefaction.

Table 6
Total costs considered for each technology and product.

Technology and product	Cost [€/MWh]	Reference
T1. (Trans)esterification for biodiesel	68–104	(Maniatis et al., 2018)
T2. Anaerobic digestion for biogas	71–91	(Maniatis et al., 2018)
	40–120	(Bioenergy in Germany facts and figures, 2017)
Biogas production - codigestion	28.8	(Kampman et al., 2017)
Biogas production - conventional	50.4	(Kampman et al., 2017)
Biogas production - monodigestion	79.2	(Kampman et al., 2017)
Biogas production – from WWTP sludge	108	(Kampman et al., 2017)
T3. Fermentation for bioethanol	67–87	(Maniatis et al., 2018)
T4. Dark fermentation for hydrogen	50	(Hay et al., 2013)
	146–417	(Randolph and Studer, 2017)
T5. Combustion for heat and power	26.6–62.6	(Bruckner et al., 2011; EUROSTAT, 2019)
T6. Gasification for syngas	50.9	(Maniatis et al., 2018; Hannula and Kurkela, 2013)
T7. Pyrolysis for bio-oils	83–118	(Maniatis et al., 2018)
T8. Hydrothermal liquefaction for bio-oils	81–128	(Magdeldin et al., 2018)

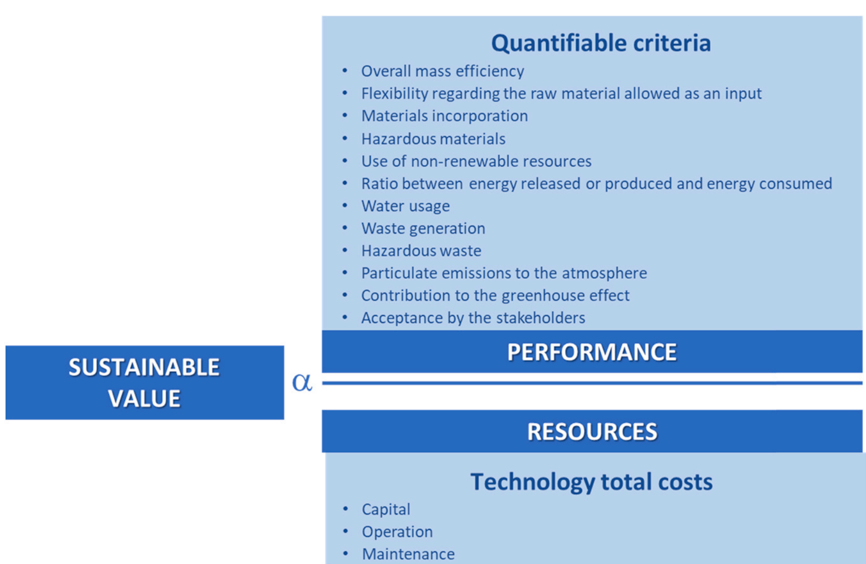

Fig. 4. Sustainable Value evaluation in the present study.

Table 7
Performance, costs and Sustainable Value indicators of each studied conversion process.

		Technology							
		T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
Performance	*(ΣφxS)*	177	195	147	166	158	208	192	181
Cost	*max.*	104	120	87	417	63	51	118	128
[€/MWh]	*min.*	68	29	67	50	27	51	83	81
	average	86	75	77	234	45	51	101	105
Sustainable Value	*max.*	2.60	6.76	2.20	3.32	5.85	4.09	2.31	2.23
	min.	1.70	1.62	1.69	0.40	2.51	4.09	1.63	1.41
	average	2.06	2.62	1.91	0.71	3.51	4.09	1.91	1.73

T1, (trans)esterification; T2, anaerobic digestion; T3, fermentation (to ethanol); T4, dark fermentation; T5, combustion; T6, gasification; T7, pyrolysis; T8, hydrothermal liquefaction.

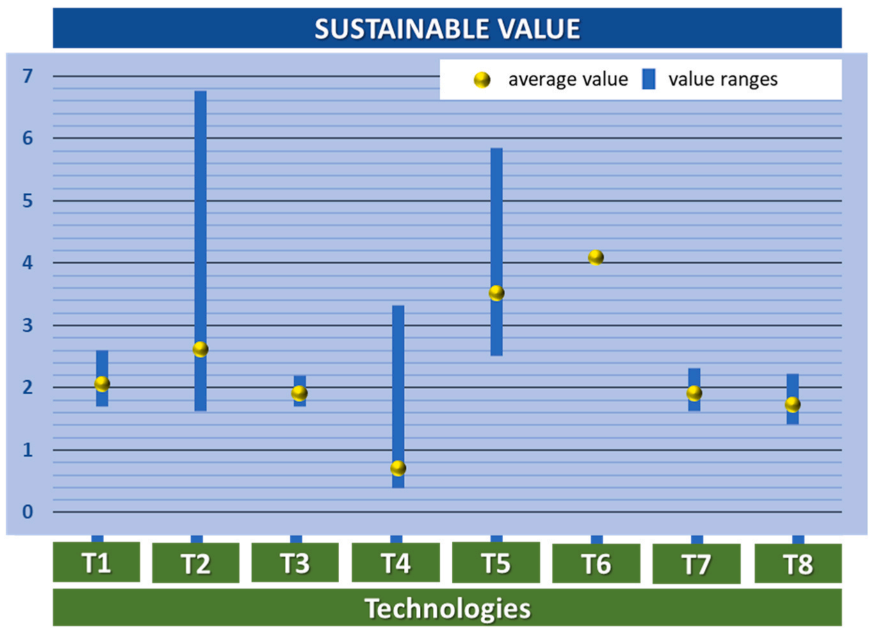

Fig. 5. Sustainable Value calculated for the conversion processes under study in the CONVERTE Project (T1, (trans)esterification; T2, anaerobic digestion; T3, fermentation (ethanol); T4, dark fermentation; T5, combustion; T6, gasification; T7, pyrolysis; T8, hydrothermal liquefaction).

The possibility of including two additional criteria for the performance evaluation, namely the process runtime and the technologies' maturity degree, was considered. However, the disparity between the normal execution time of the biochemical and thermochemical conversion processes, as well as the much lower degree of maturity of dark fermentation for hydrogen and hydrothermal liquefaction for bio-oils when compared to the other technologies, would make it more difficult to compare between functional performances. The influence of the maturity criterion was considered to be partly embedded in the respective capital costs.

- Execution time - this parameter was not used to determine the processes performance. It relates with the speed with which the conversion reaction occurs, and it can be associated with the length of the conversion in biochemical processes or with the reaction time in thermochemical processes.
- Maturity - this parameter was not used to determine the processes performance. It refers to the degree of development of the technology in question, distinguishing the higher Technology Readiness Level technologies from those of less mature stages, which still only refer to initial research or laboratory to pilot scale research.

3.3. Weighting of the performance evaluation criteria

Since not all the performance evaluation criteria presented the same level of importance, the next step was to use weighting matrices to establish the former level. The criteria were compared two by two, thus allowing to determine a hierarchy between them. After this comparison and according to the results, three levels of relative importance (φ) were considered: 5 = high importance, 3 = medium importance and 1 = low importance. The results are shown in Table 3.

3.4. Assessment of the technology performance

In order to assess the performance of each technology (ΣφxS), the parameter level of satisfaction (S) was used. This parameter indicates the way in which each technology behaves concerning the defined evaluation criteria (Table 2), and it can be quantified on a scale of 1–5, according to the interpretation shown in Table 4, which contains the 14 criteria used for the quantitative analysis. The last two criteria in Table 4, execution time and maturity, were considered only qualitatively.

Once each level of satisfaction (S) was classified, it was possible to evaluate the performance of the eight different combinations of waste biomass type x technology (Table 5).

3.5. Assessment of the costs associated with the conversion processes

The conversion processes were economically evaluated using the capital, operation and maintenance costs referred to in the literature. Table 6 shows the costs considered for the estimation of the Sustainable Value.

3.6. Sustainable value assessment

Using functional analysis, the evaluation criteria were set and ranked in a score of 1, 3 or 5 of relative importance (φ), the levels of satisfaction (S) were established and the performances of the conversion processes were estimated (Σφxs) (Table 5). The Sustainable Value of each combination of waste biomass type x technology was determined as the quotient of the performance by the technology total costs (Fig. 4).

The Sustainable Value calculated for the eight different waste biomass type x technology is shown in Table 7.

From the information in Table 7, it was possible to determine the Sustainable Value, which enabled the comparison of the combinations of waste biomass types and conversion technologies for energy products involved in the present study, based on a single indicator. Since it was not possible to allocate the real process costs, the values considered for each technology and product were those in Table 6, obtained from the literature. They were estimated as closely as possible in accordance to each process flowchart. Fig. 5 shows the range between the maximum and minimum values calculated, as well as the average values considered for each Sustainable Value indicator. Gasification and combustion achieved the best Sustainable Value results (Table 7). In terms of process performance, gasification of olive pomace and anaerobic digestion of piggery effluents showed the highest scores of 208 and 195, respectively. The contribution to the high performance of gasification was mainly due to the process and inputs categories of criteria, while in anaerobic digestion the contribution of the outputs and social acceptance criteria were the most decisive. The average Sustainable Value of gasification was higher than that of anaerobic digestion due to the value of the average cost of the technology (Table 7). However, if the minimum value of the anaerobic codigestion process cost of 29€/MWh is considered, then it would be possible to reach the highest Sustainable Value score of 6.76 for this technology. (Trans)esterification of fat-rich olive-oil industrial residues, fermentation of pulp and paper mill slurries to ethanol and pyrolysis of fat-rich olive-oil slurries to bio-oils achieved intermediate Sustainable Value indicators, with medium performance levels and cost estimation. The criteria that were considered to evaluate the performance of the technologies influenced the results differently, depending on whether the conversion processes were biochemical or thermochemical based. In general, the input and processes basis criteria influenced more the performance of the thermochemical technologies, whereas the criteria associated with process outputs and social acceptance were more determinant for the biochemical ones. The results obtained for the technologies with the lowest Technology Readiness Level, namely dark fermentation to bio-hydrogen and hydrothermal liquefaction to bio-oils, in which the uncertainty regarding costs is still very high, achieved a lower Sustainable Value indicator, especially in what concerns dark fermentation with the highest cost estimation. The fermentation to ethanol with a maturity degree at the industrial or demonstration level in the European Union but still in the R&D phase in Portugal followed the trend of low Sustainable Value indicator, not only because of the costs but also due to the technology performance when compared with the thermochemical conversion processes. Pyrolysis for bio-oils showed a high performance result, but the average cost of circa 101€/MWh brought this technology to a moderately ranked value of Sustainable Value (Table 7). Although this technology is already industrially developed in the European Unit, it is only in R&D phase in Portugal.

In synthesis, the Sustainable Value Methodology contributed to the comparing of the studied combinations of waste biomass and conversion technologies. The findings of this study suggest a clear correlation between the Sustainable Value indicator and the Technology Readiness Level of the conversion technologies, as seen with other studied technologies (Barry and Ramachandran 2010). The combustion and gasification of agro-industrial residues or harvest and pruning residues for the production of electricity and heat and synthesis gas, respectively, achieved the highest Sustainable Value rating. Although less averagely scored, the conversion of agro-industrial residues, e.g. from chestnut peeling, and pig-rearing effluents by anaerobic digestion presented the potential to reach a higher level of Sustainable Value. In line with recent studies (Kargbo et al., 2021), the technologies pyrolysis and hydrothermal liquefaction offer a promise as future solutions for energy products from waste biomass provided that the process costs decrease with the respective Technology Readiness Level increase.

The estimation of the Sustainable Value incorporates aspects related to the cost of the conversion processes, since it integrates an assessment of the amount of resources, water and energy required for each conversion process under study. In terms of technological performance, the most important parameter of Sustainable Value is the execution time of each conversion process, which can be considered as a measure of the process efficiency, and also the amount of particulate matter, waste and GHG generated. However, several techno-economic challenges can be identified, particularly related to case studies with lower Technological Readiness Level and the valorisation of all process flows towards zero waste, as a way to increase economic revenues. This is the case of dark fermentation for hydrogen production and the possibility to valorise all the generated streams besides the gas, e.g. the liquid fraction that is rich in volatile fatty acids for the production of polyhydroxyalkanoates (Saratale et al., 2021). Another example is the co-recovery of the biochar fraction from thermochemical decomposition of waste biomass, for use in the production of biocomposites or for soil amendment (Bartoli et al., 2022; Paneque et al., 2019).

In this work, the Sustainable Value score was validated with real data, obtained from waste biomass samples that were obtained from Portuguese waste management systems and agricultural, agro-industrial and industrial stakeholders. These samples were submitted to biochemical or thermochemical conversion to bioenergy products at laboratorial or pilot scale, after extensive physicochemical characterisation. As the tested waste biomass are not currently used in waste to energy processes in Portugal, it would be worth furthering this study with at least the best scored combination of waste biomass x technology, to include effective process costs after scale-up and obtain a greater detail on the process techno-economic performance.

The Sustainable Value methodology can be adopted in other contexts and in other countries in general. The biggest challenges are the quantification of the real costs associated to the alternatives under study, and the requirement of a deep knowledge of the technological process, product, service or system in which the Sustainable Value methodology is applied. This study involved a multidisciplinary team of senior researchers from different areas of knowledge that identified the main key points for the comparison of the technologies in question. With the bases of the present article, future applications to similar case studies can be carried out without this strong scientific involvement, requiring only the adjustment of values for the different geographies. In a context of greater energy consumption in the next decades, it is important to identify relevant bioenergy alternatives, keeping in mind that a sustainable energy system must satisfy the following elements: meet energy needs, ensure energy justice, and respect environmental limits (Holden et al., 2021), simultaneously with the empowerment of managers with tools that help them in the decision-making process.

4. Conclusions

This work enabled the ranking of eight technologies for converting waste biomass into electricity and heat, energy vectors and advanced biofuels using the Sustainable Value indicator. This indicator considered environmental, social and economic criteria for each of the studied technologies, namely process criteria, inputs, outputs, social concerns and associated process costs.

The various conversion processes showed different behaviours with regards to the Sustainable Value indicator, and seemingly to express a positive relationship with the degree of maturity of the technologies under analysis. This became apparent when the technologies fermentation to ethanol, dark fermentation to hydrogen, pyrolysis and hydrothermal liquefaction to bio-oils, in which the uncertainty regarding costs is still very high and with low Technology Readiness Level, were confronted with more developed technologies.

The more mature technologies under study, i.e. combustion, gasification and anaerobic digestion achieved the best Sustainable Value results. The high performance and low process costs of anaerobic digestion were associated with the outputs and social criteria, whereas process and inputs criteria impacted more on the gasification Sustainable Value score.

The Sustainable Value methodology proved to be a powerful tool to reduce the complexity in the evaluation and decision making of the process of capturing value from waste biomass for energy products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Figs. A.1-A.7.

Process flowcharts T1 to T7 of (trans)esterification for biodiesel, anaerobic digestion for biogas, fermentation for bioethanol, dark fermentation for bio-hydrogen, combustion for electricity and heat, gasification for biogas and synthesis gas, and pyrolysis for bio-oils.

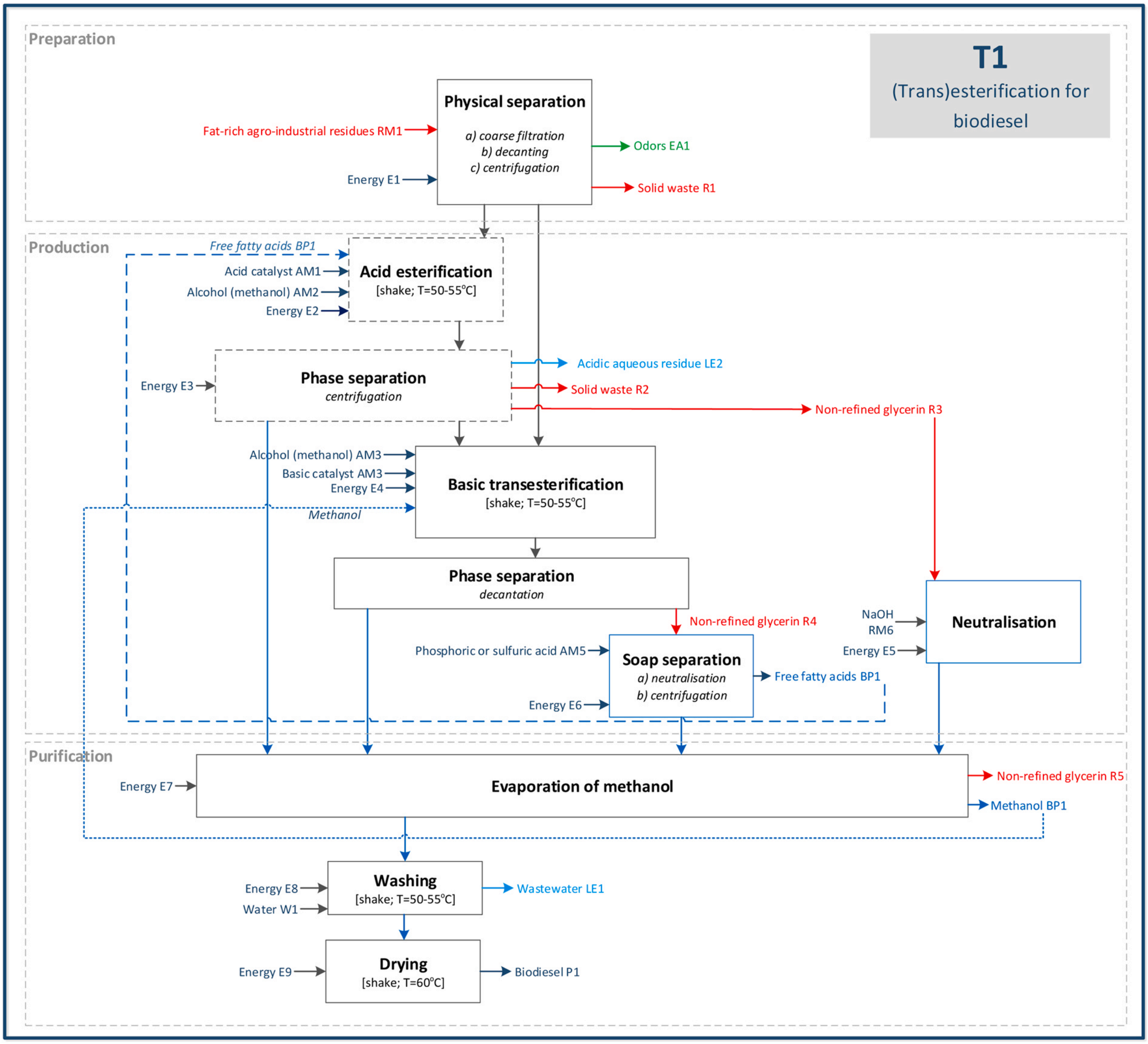

Fig. A.1. Process flowchart of (trans)esterification for biodiesel.

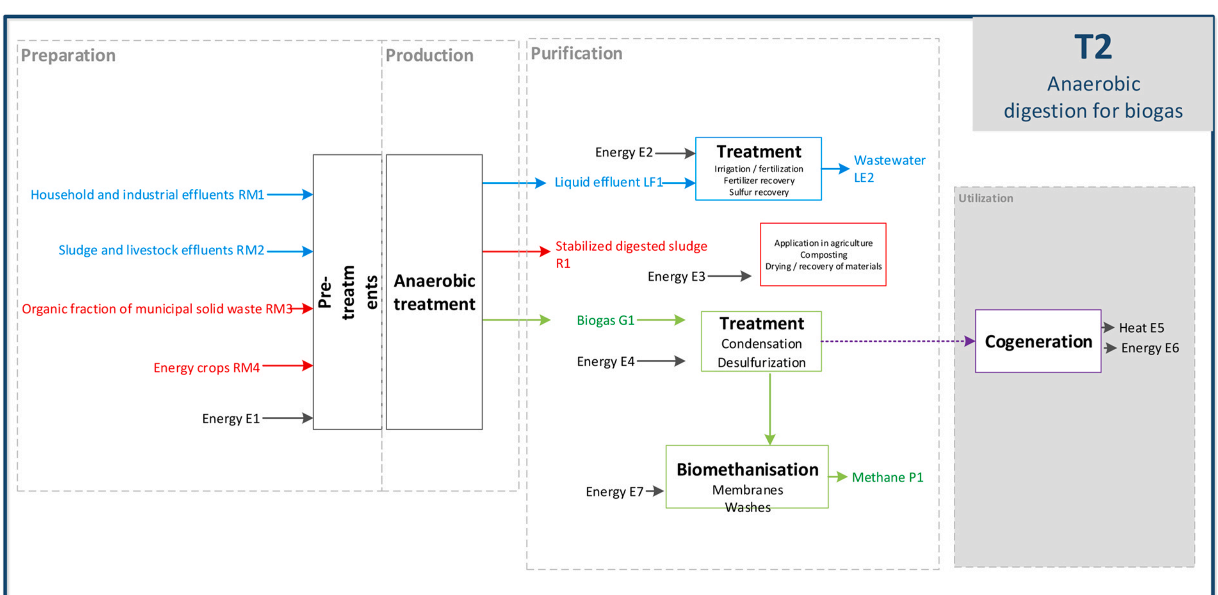

Fig. A.2. Process flowchart of anaerobic digestion for biogas.

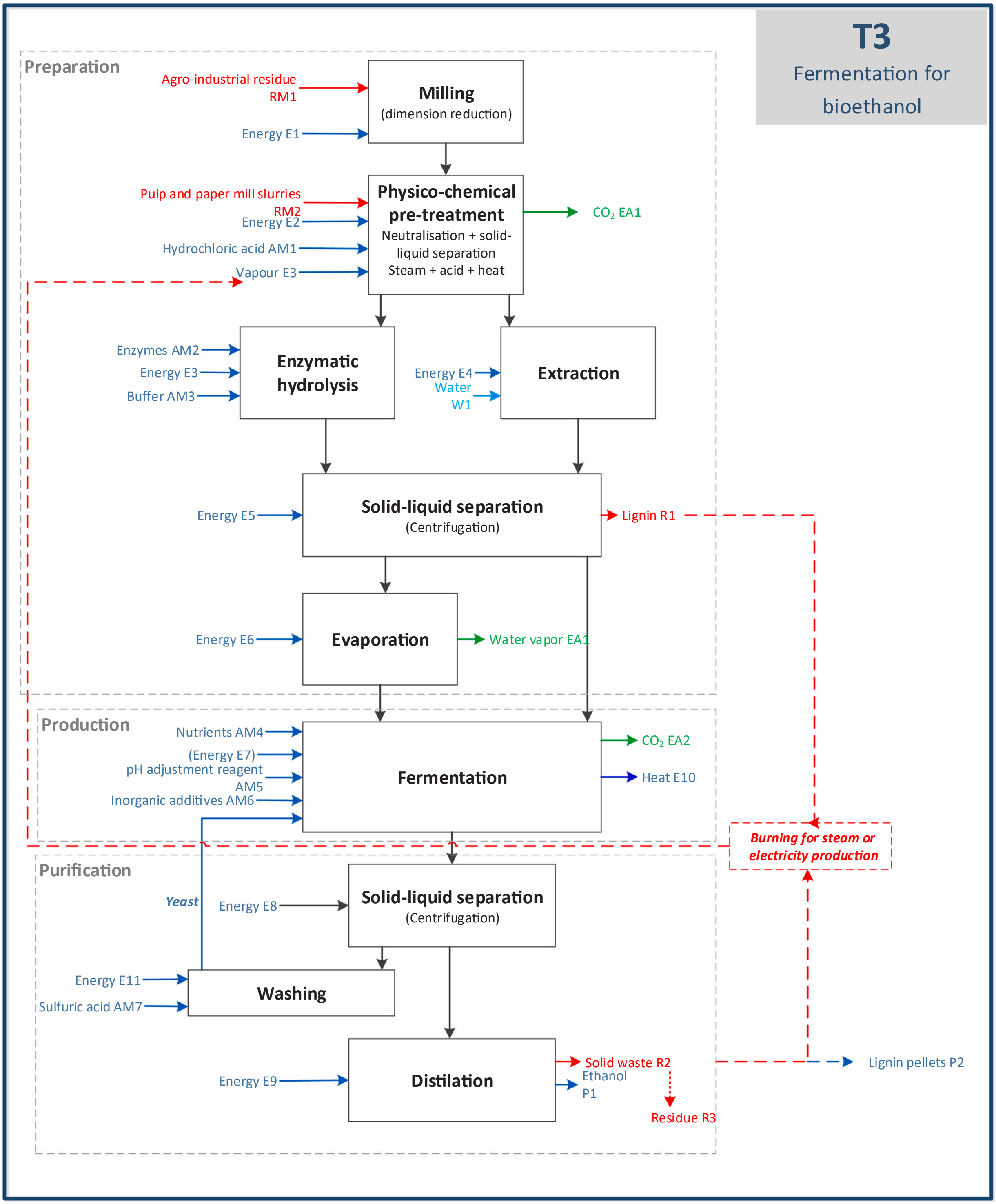

Fig. A.3. Process flowchart of fermentation for bioethanol.

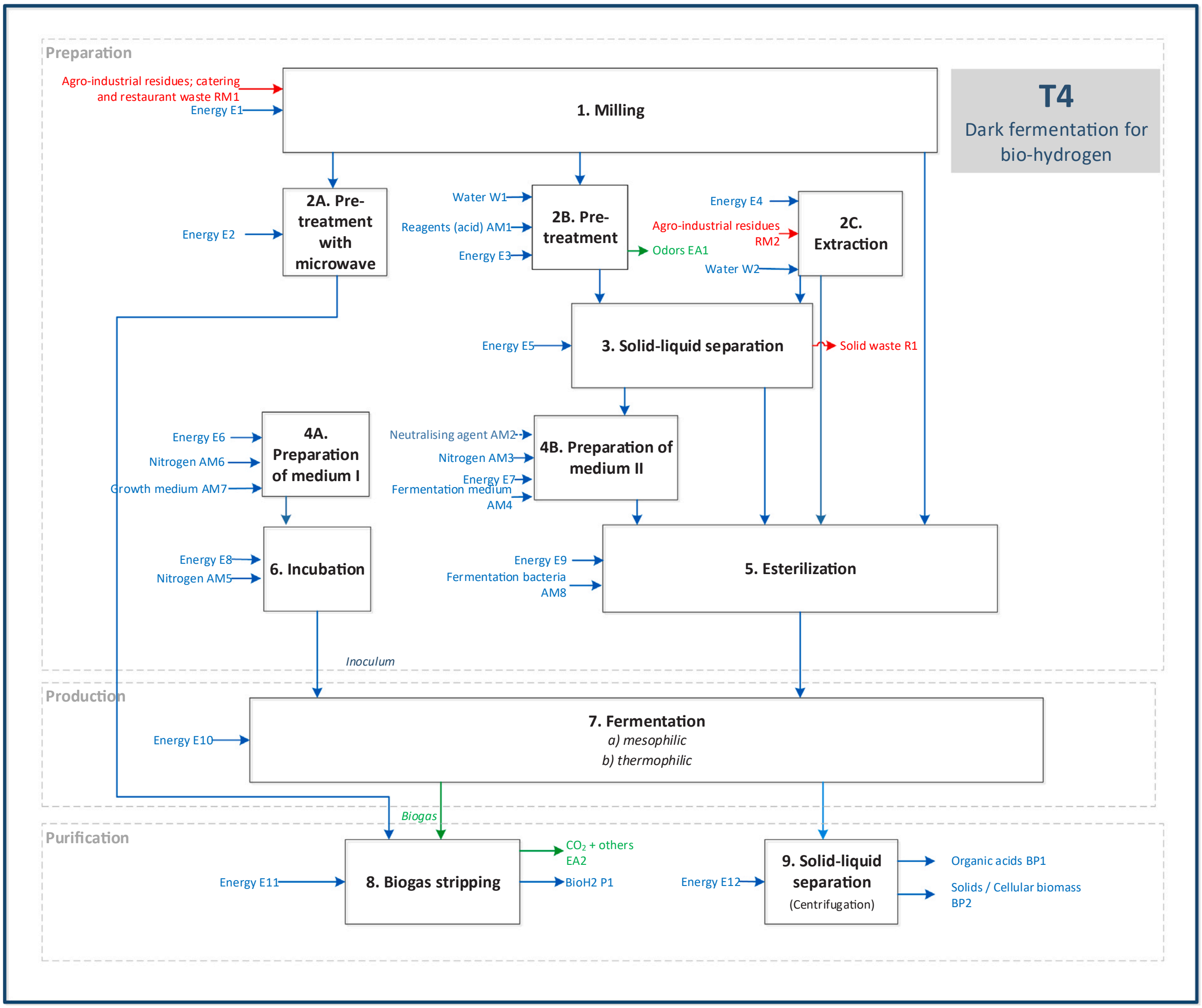

Fig. A.4. Process flowchart of dark fermentation for bio-hydrogen.

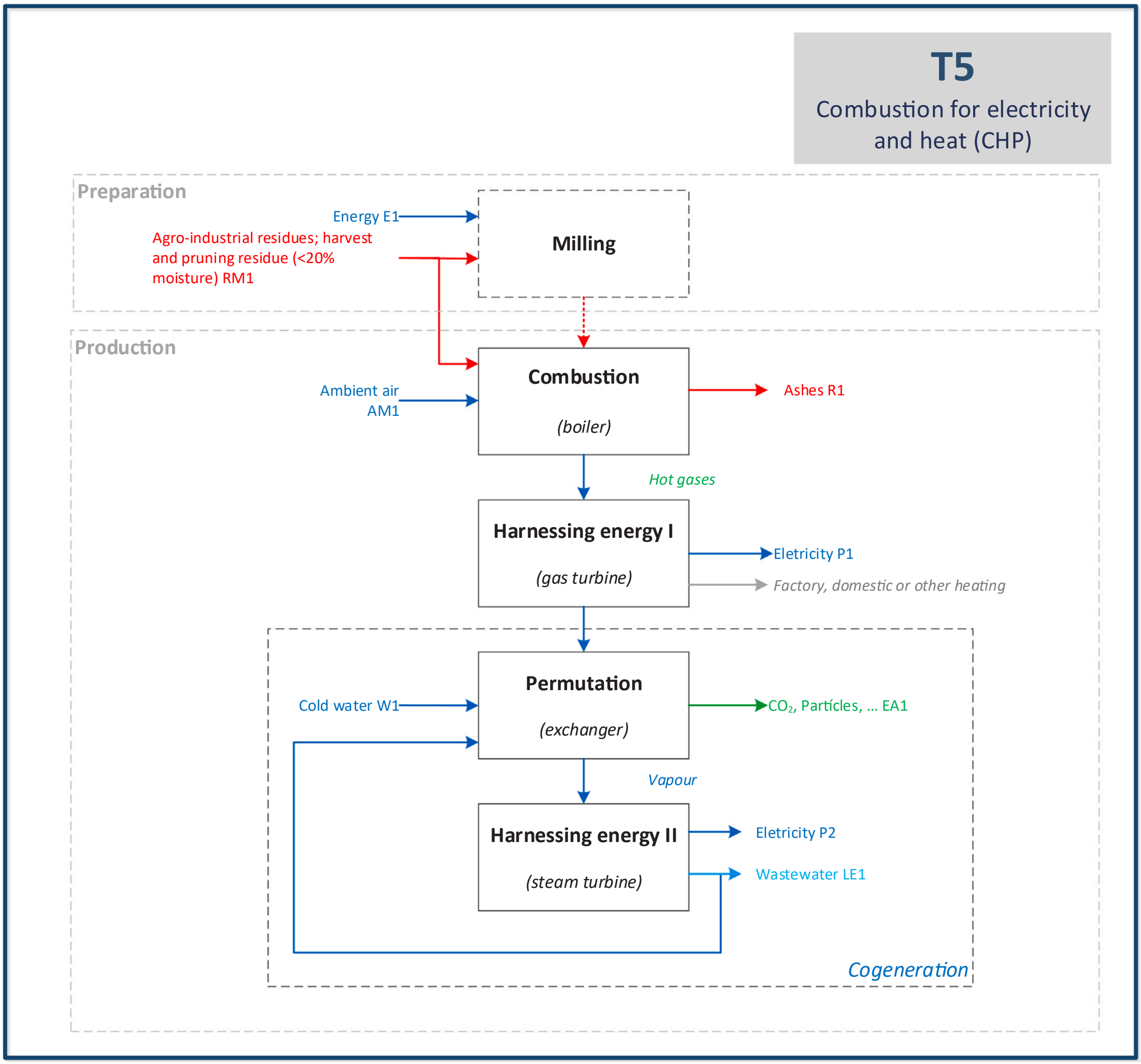

Fig. A.5. Process flowchart of combustion for electricity and heat.

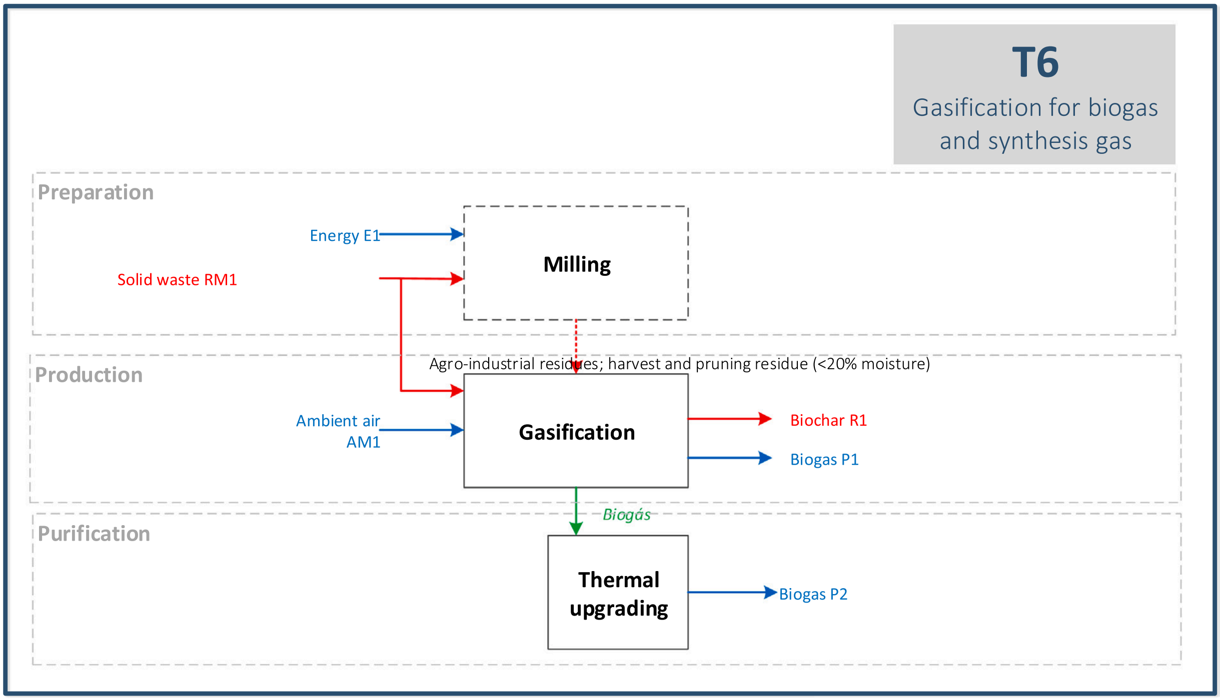

Fig. A.6. Process flowchart of gasification for biogas and synthesis gas.

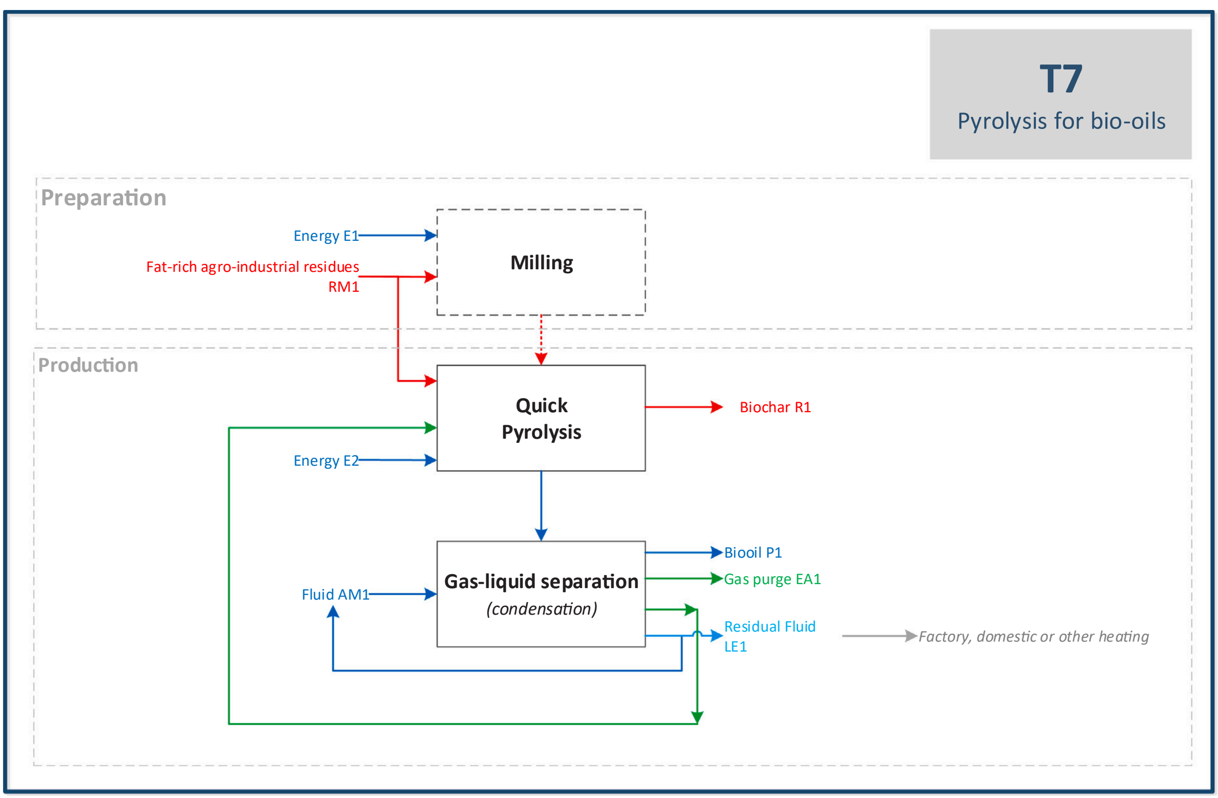

Fig. A.7. Process flowchart of pyrolysis for bio-oils.

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