MULTI-CRITERIA BENCHMARKING OF ENERGY RECOVERY ROUTES FROM WASTES

"WASTE TO ENERGY VALORIZATION"

Lugas Raka ADRIANTO
2nd year student of *Energy and Environment (STEEM)* Graduate Degree program
Ecole Polytechnique

Under the Supervision of:

Sébastien GROS, Industrial Tutor
Claude BASDEVANT, Academic Tutor

Internship at EDF R&D Chatou, MFEE Department
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Abstract

The implementation of energy transition law in France, the emergence of various technologies to treat wastes, and additionally the appearance of fuels which are derived from wastes create a stimulating environment in the country to encourage the sustainable ways of managing wastes. Aligning with the waste hierarchy with different level of priority, France with its diverse waste production has plenty of options to choose in order to have a reliable waste management technique, both for its metropolitan area and overseas territories. The options or schemes to manage waste would depend on the constraints and objectives to accomplish, including the energy performance, economic results, and environmental aspects.

This report presents the multi-criteria analysis with respect to the waste valorization for French metropolitan and overseas territories as the case studies. Critical understanding about wastes and its management techniques should be completed prior to the assessments. Thus, the study is generally divided into three parts:

1. Waste characterization: entailing the concept of waste hierarchy, waste flows, and wastes derived fuels classification in France,
2. Waste valorization and related aspects: discussing relevant valorization pathways with collected information from the recent studies and relevant reports
3. Case studies: Assessing the two main case studies with different context and objectives.

The principal result of this study has shown that in the metropolitan areas, there are numerous schemes that are proposed aside from the conventional incineration technique to eliminate residual wastes. In addition, the production of France's unique waste derived fuel (CSR) can also enable the recycling of certain materials from the raw wastes, which is essential to boost the recoverability of materials and to minimize the necessity for landfilling.

On the other side, with a smaller scope and different boundaries, some sites in the French overseas territories (*DOM*) can substitute their open burning technique with alternative waste valorization schemes. For certain schemes, it provides opportunities for the respective sites to generate its own electricity onsite (energy valorization) in addition to the waste quantity reduction. However, the final choice of technology would be matched accordingly with the demand of outputs, either energy or material depending on the demand.

Keywords: waste valorization, waste management, solid recovered fuel, techno-economic

Table of Content

Abstract **2**
Table of Content **3**
List of Figures **5**
List of Tables **6**
Glossary **7**
1 Introduction **8**
1.1 Context 8
1.2 Objective 8
2 Methodology **9**
3 Waste Characterization **10**
3.1 Waste Management 10
3.2 Flow of Wastes in France 10
3.3 Classification of Waste Derived Fuels 13
3.4 Valorization of CSR in France 16
4 Municipal Waste Management Pathways **17**
4.1 Focus on Sorting and Treatment Options 18
4.2 Thermochemical Conversion Routes for Wastes Valorization 20
5 Environmental Aspects Related to Waste-to-Energy Plants **22**
5.1 Key Pollutants and Impacts 22
5.2 Byproducts from Waste-to-Energy Plants 23
6 Case Studies **24**
6.1 Assessment Methodology 24
6.2 Technical Aspects 26
6.3 Economic Aspects (Hypothesis) 26
6.4 Environmental Aspects 28
6.5 Residual Wastes Valorization in the Metropolitan 29
6.6 Household Wastes Valorization in French Overseas Territories 33
7 Conclusion and Perspectives **39**
List of References **41**
Appendix **45**
Appendix 1 Working Schedule with Checkpoints (Internship Calendar) 45
Appendix 2 CSR and Its Classification proposed by FEDEREC [8] 45
Appendix 3 Common CSR Characteristics in France [9] 47
Appendix 4 Definition of “Technology Readiness Level” or TRL 47

Appendix 5 Waste Composition in France Metropole and DOM [10] and [11] 48
Appendix 6 Various Pathways for Waste to Energy Technologies.....48
Appendix 7 Sharing Session I and Exchange with Internal R&D Team 61
Appendix 8 Sharing Session II and Exchange with Tiru 63
Appendix 9 The Process of Filtering Technologies (pre-selection part of the studies).....65
Appendix 10 Mass and Energy Balances for Filtered Technologies 72
Appendix 11 Air Pollution Control in Municipal Solid Waste Combustion/ Incineration 73
Appendix 12 The Classification of Municipal Solid Wastes Managed by Public Authority .77
Appendix 13 The Energy Potential of Waste Matrix Data.....77

List of Figures

Figure 1 Different Phases of The Project (see Appendix 1 for exhaustive task) ... 9
Figure 2 Waste Management Hierarchy ... 10
Figure 3 General Waste Classifications in France based on Its Production Sector (adapted from ADEME) ... 11
Figure 4 The Production of Wastes in France (2012 data) ... 12
Figure 5 The Trades of Wastes between France and the Other Countries ... 12
Figure 6 The Trading of Wastes in France, according to Waste Types ... 13
Figure 7 RDF, SRF, and CSR Comparisons ... 15
Figure 8 Resource Potential, adapted from ADEMEand EIFER reports ... 16
Figure 9 Estimated Number of Valorization Units in France (Year 2030) ... 17
Figure 10 Valorization Techniques for Different Fuels or Combustibles ... 17
Figure 11 Energy valorization pathways from wastes ... 18
Figure 12 Wastes inputs and its final energy/ material forms ... 20
Figure 13 Waste Conversion Routes through Different Technologies and Its Maturity ... 21
Figure 14 Illustration of Possible Byproducts Valorization from Waste to Energy Plant ... 24
Figure 15 Research Methodology of Energy Valorizations from Waste ... 25
Figure 16 Process Flow Diagrams for Several Schemes (Metropolitan Case Study) ... 29
Figure 17 Treatment Cost Comparison for All Schemes and Parametric Schemes (Residual wastes valorization) ... 31
Figure 18 Comparison of Material Valorization Between Schemes (Residual wastes valorization) ... 32
Figure 19 Metal and inert flows in the schemes (Scheme 2 upper, Scheme 5 lower) ... 33
Figure 20 Process Flow Diagrams for Several Schemes (SEI Case Study) ... 34
Figure 21 Treatment Cost Comparison for All Schemes with Different Population Size (SEI) ... 35
Figure 22 Greenhouse Gas Emission of Different Schemes, Displacing Electricity from Fossil Fuel ... 36
Figure 23 Greenhouse Gas Emission of Different Schemes, Displacing Electricity from Solar Energy 37
Figure 24 Gantt Chart of the Internship ... 45
Figure 25 A French example of classification of a waste derived fuel sample according to FEDEREC nomenclature ... 46
Figure 26 Production of CSR/ SRF from Municipal Solid Wastes (MSW) ... 46
Figure 27 TRL Levels and its Definition ... 47
Figure 28 Thermochemical conversion of combustibles ... 49
Figure 29 General stages of process at TM facilities ... 50
Figure 30 General stages of processes at TM facilities ... 51
Figure 31 Production of biogas through methanization process ... 51
Figure 32 Sequences of reaction (thermochemical conversion) ... 52
Figure 33 Schematic comparisons between combustion (C), staged combustion (SC), and gasification (G) ... 53
Figure 34 Pyrolysis products with the function of heating rate and operating temperature ... 53
Figure 35 HTU principles, operating condition, and product ... 54
Figure 36 State of the art of waste to energy valorization pathways ... 55
Figure 37 Range of sizes for incinerators and circular economy oriented unit in France ... 55
Figure 38 Physical-chemistry phenomenon for combustion process ... 61
Figure 39 Physical-chemistry phenomenon for gasification process ... 61
Figure 40 Comparison of Outotec's furnaces portfolio ... 62
Figure 41 Comparison between C (combustion), C w/ OFA (combustion with overfire air), SC (staged combustion), and G (gasification) ... 62
Figure 42 Illustration of CSR demand vs. Cement industry (left) and TRL chasm (right) ... 64
Figure 43 Comparison of old grate furnace (longer grate) and new grate furnace (shorter) ... 64
Figure 44 Process of filtering technologies for SEI case studies ... 65
Figure 45 Technology selection based on four criteria by Foster Wheeler ... 66
Figure 46 Finding the Selected Schemes for Further Assessments (Residual wastes valorization in Metropole) ... 68
Figure 47 Finding the Selected Schemes for Further Assessments (SEI) ... 71

Figure 48 Main inputs and outputs of MSW incinerators 73
Figure 49 Generic structure of (a)- polychlorinated dibenzo-p-dioxin (PCDD), (b)-polychlorinated dibenzofurans (PCDF). 76
Figure 50 Classification of municipal solid wastes 77

List of Tables

Table 1 Different Classes of SRF (EN 15359:2011) 14
Table 2 List of Common Pollutants in Waste to Energy Plants and Its Hazards 22
Table 3 Selection criteria to determine suitable technologies 25
Table 4 Assessment criteria to evaluate selected technology 26
Table 5 Parameters Used for Technical Aspects 26
Table 6 List of Equipment with its CAPEX Estimation Method 27
Table 7 List of Consumables in the Processes and Its Costs 28
Table 8 Developed Schemes for Residual wastes valorization Case Study 30
Table 9 Overall Results of Techno-economic Assessments (Residual wastes valorization) 30
Table 10 Developed Schemes for SEI Case Study 34
Table 11 Cost of Avoided CO_2 (€/ tonne of CO_2) for Different Schemes 38
Table 12 Comparison of SRF (EU regulation) and CSR (French regulation) Criteria 45
Table 13 Solid recovered fuel classification system proposed by FEDEREC 45
Table 14 Comparison of CSR properties from different sources 47
Table 15 Composition of MSW/ HH Wastes in France and DOM 48
Table 16 Installed CSR preparation units (TM and TMB) in France, up to 2015 50
Table 17 State of the art for the untreated wastes treatment in France (I) 56
Table 18 State of the art for the untreated wastes treatment in France (II) 57
Table 19 State of the art for the treated wastes treatment in France (I) 58
Table 20 State of the art for the treated wastes treatment in France (II) 59
Table 21 State of the art for the treated wastes treatment in France (III) 60
Table 22 Technology screening and selection for residual wastes energy valorization 66
Table 23 Technology screening and selection for SEI case studies 69
Table 24 Techno-economic Assessments of AD Process (100 and 10 000 inhabitants size) 71
Table 25 Exhaustive Treatment Cost Data for All Cases with Different Schemes 72
Table 26 Required efficiency to remove pollutants from MSW incineration 74
Table 27 Gas cleaning processes and typical range of emission reduction by combination of unit operations 74
Table 28 List of Wastes with Its Energy Potential in 2050 77

Glossary

BFB : Bubbling fluidized bed

CFB : Circulating fluidized bed

CAPEX : Capital expenditure

CSR : *Combustibles solides de Récupération*

DOM : *France d'outre-mer*

GHG : Greenhouse gas

HTC : Hydrothermal carbonization

HTL : Hydrothermal liquefaction

LCA : Lifecycle analysis

RDF : Refuse-derived fuel

SRF : Solid recovered fuel

DPIT : *Division Production Ingénierie Thermique*

OPEX : Operational expenditure

PAC : Pollution air control

SEI : *Systèmes Énergétiques Insulaires*

WtE : Waste to Energy

TRL : Technology readiness level

MSW : Municipal solid waste

TM : *Traitement mécanique* (or sorting center)

TMB : *Traitement mécano-biologique* (or treatment center/ mechanical-biological treatment)

NCV : Net calorific value

1 Introduction

"Waste to Energy" ever since its implementation remains one of the popular trends in the mission towards fossil (heat, electricity, and fuels). In conjunction with the recent circular economy approach encouragement in territorial scope, EDF as one of the key players in this industry possesses multiple interests in determining the suitable scenarios (technical, economic, environmental, and other associated factors) depending on the needs and availability of the resources.

The first section of the report covers the context and objective of the study. Some specific parts from EDF's perspectives will also be shown as company's stakes.

1.1 Context

In overall, there are three interconnected reasons which favor the study of waste to energy utilization in France. The corresponding reasons are:

1) Energy Transition Law from the Government
   Following the introduction of French energy transition law or « *La loi relative à la transition énergétique pour la croissance verte » (LTECV)* in 2015, France has been directing the country itself towards sustainability and green-economy based orientation. As one of the imposed targets, it basically accelerates the penetration of renewable energy in the current portion of energy utilization (from the level of 14% in 2014 to 32% in 2030) [1]. Inside this notion, waste to energy utilization contributes certain amount of portion to supply the country with carbon-friendly energy.
2) Appearance of Various Technologies and Players
   Due to the fact that the implementation has created a supporting environment for the actors to participate and collaborate, simultaneously it also instigates the emergences of technology developers which manufacture various processes and means to convert wastes into energy.
3) EDF as the Energy and Waste Actor has its Specific Targets to Fulfill
   Lastly, EDF operates with the preferences towards highly deployable technologies considering the time constraint it has. Thus, looking for commercialized and mature processes hold a higher priority if the company/ subsidiaries show interests in either investing or retrofitting its current facilities which would be designed for waste valorization. Some of the stakes in its entities are:
   - Mother company entity, DPIT – Transition towards greener business model (switching fuels either by adding/ shifting technology).
   - Mother company entity, SEI – Seizing the opportunity of energy production from waste on site, instead of exporting (to meet 2030 fuel autonomy).
   - Tiru – Key stakes are to try finding alternative solution to conventional combustion that has better social acceptance.

1.2 Objective

Considering the contexts of this study, hence the objectives that are expected out of the project can be divided into four major parts.

1) Clear mapping of waste resource potential (non-hazardous waste with energy content) in France. Having an exhaustive information about wastes availability in France would provide some vivid insights on what to focus and anticipate if there are changes due to regulation amendments.
2) Building robust information about the waste to energy technologies in terms of technical data, technology developers, number of industrial units, and maturity level.

3) Obtaining techno-economic and environmental evaluation of the selected WtE case studies.
4) Giving perspectives towards EDF stakes related to waste-to-energy sector.

2 Methodology

Following the context and objectives of this study, thus, it leads to dividing the tasks into four separate sections in which each one comes after another as the inputs. Figure 1 exhibits the process of conducting the study with brief description for each major block.

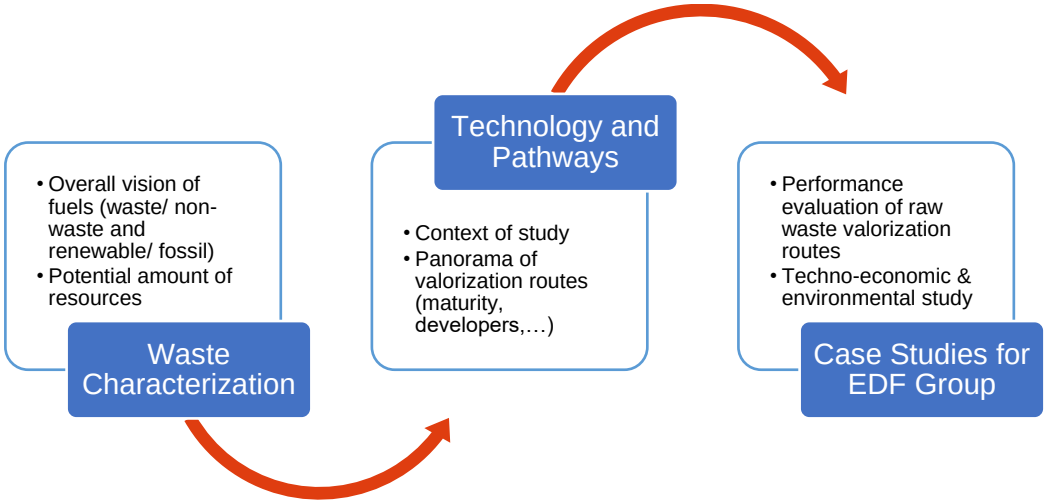

Figure 1 Different Phases of The Project (see Appendix 1 for exhaustive task)

The initial part of the study begins with waste characterization in France, which puts a heavy focus on “non-dangerous” energy recoverable waste. It implies that only the wastes which are dedicated for energy valorization (if material valorization has been prioritized) would become the main source of feedstock in the next phase. Volumes, producers, and waste of flows are going to be justified as well to examine clearly the resources potential in France (thus, a form of table and/ matrix might help to elucidate this intention).

Afterwards, a rigorous technology assessment of various technology options is performed as the basis for further analysis. Notably, the developers, maturity (TRL), industrial units/ references and capacity of input have to purpose to give complementary information for the comparison with other possible technologies. By building important technical parameters in conjunction with waste regulatory explanations in France (CSR-related), it is expected to comprehensively define the criteria for techno-economic and environmental analysis.

Since the study aims to compare equally energy valorization technologies with set of criteria, thus at the beginning of this phase those multi criteria are defined by taking into account some inputs from EDF’s partners/ entities. After completing the multi criteria approach, the goal of last step is to draw perspectives altogether with the corresponding entities.

Elements associated in this section:

- *Appendix 1 Working Schedule with Checkpoints (Internship Calendar)*

3 Waste Characterization

This chapter elaborates the definition of wastes, starting from the necessity to hierarchically promote waste management in the context of EU and the specificities of wastes statistics in France. Grasping these elements can provide some essential information to have a vision of waste valorization (energy, non-recyclable) in the next decades.

3.1 Waste Management

In retrospect, the Waste Framework Directive (WFD) has set the basic concepts and definitions related to waste management since the 1st of April 1993. Among them are definitions of waste, recycling, and waste recovery. It gives some distinctions that when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products. The revised WFD (Directive 2008/98/EC) lays down some basic waste management principles: it requires that waste to be managed without endangering human health and harming the environment, and in particular without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odors, and without adversely affecting the countryside or places of special interest. Waste legislation and policy of the EU Member States shall apply as a priority order the following waste management hierarchy [2], as shown in Figure 2.

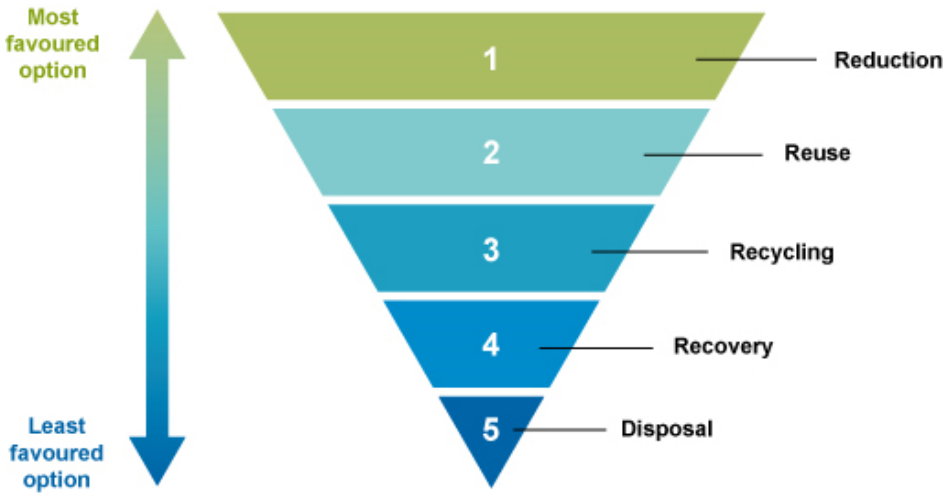

Figure 2 Waste Management Hierarchy [2]

As a more elaborative explanation from this hierarchy, it basically provides a priority order with the waste prevention/ reduction as the most preferred method and then followed by recycling, recovery, and waste disposal (landfilling) as the last option. In the middle of the inverted pyramid, material recovery/ valorization sits one level above energy recovery which eventually indicates that energy valorization can only be the solution for non-recyclable wastes (unaccepted wastes for material valorization). In addition, the Directive allows municipal waste incinerators to be classified as recovery operations provided they contribute to the generation of energy with high efficiency to promote the use of waste to produce energy in energy efficient municipal waste incinerators and encourage innovation in waste incineration [2].

3.2 Flow of Wastes in France

Overviewing the waste resources from different types of sources, ADEME in 2016 has classified them based on three main sectors which generate certain types of wastes [9]. The study which was conducted by ADEME in collaboration with ORDIF (The Paris region waste observatory) in general summarize the flow of wastes and end-treatment of wastes in the France's context nowadays. Although the study about flow of wastes by ORDIF only describes

the flow in Paris (Ile-de France as a greater extent), yet it has been considered to be one of the representatives to explain the classifications of waste in the country with its larger scope. Principally, the wastes itself are divided into three main types as shown in Figure 3.

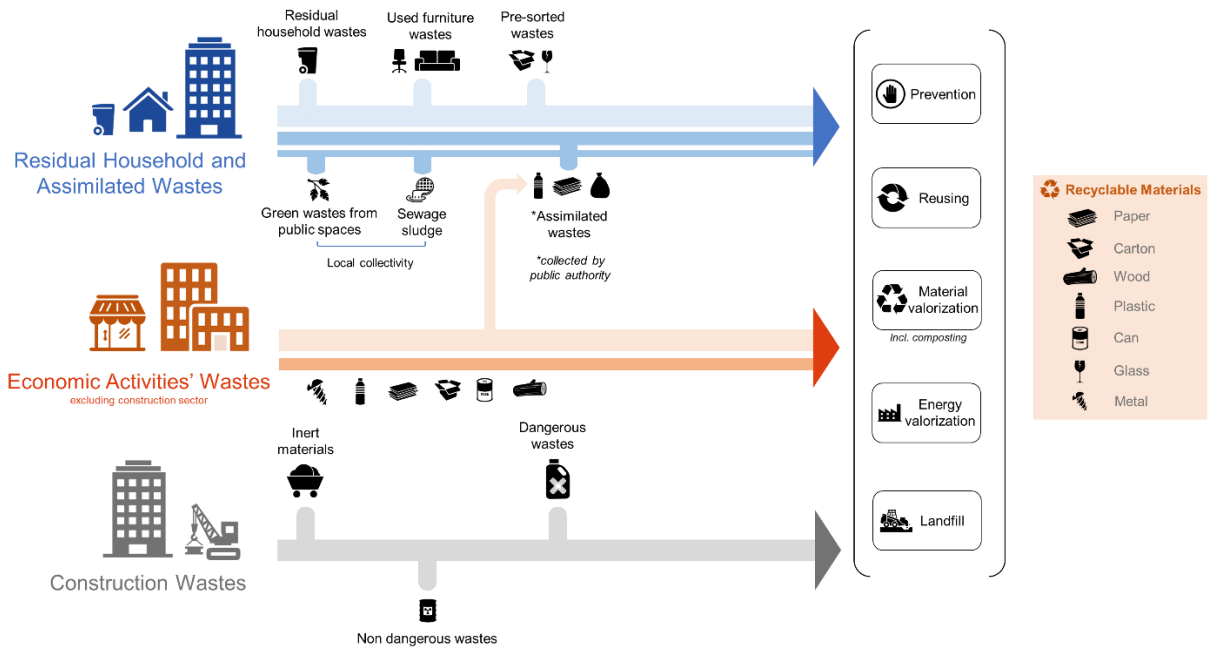

Figure 3 General Waste Classifications in France based on Its Production Sector (adapted from ADEME) [9]

It can be obviously observed that residual household and assimilated wastes group can have an overlap with the economic activities' wastes in terms of types and characteristics of the wastes itself. Therefore, some of the flows from economic activities' wastes (normally referred as assimilated wastes) should be included in the residual household wastes since it is collected by the public authority despite their production from the economic activities [3]. It follows the definition of municipal solid waste according to the European regulation, in which it covers household wastes and waste similar in nature and composition to household waste [5].

Annual data recording in 2012 by ADEME has elaborated that approximately 345 Million tons of wastes were generated annually in France (see Figure 4). Statistically, it can be divided into three major parts similar to the previous explanation in Figure 3, thus simplifying the categorization of these wastes. At least 70% of these wastes belonged to the construction wastes group due to its bulkier density than the others. Normally, inert materials such as rubbles, sand, and other residues from the construction are determined as this type of category. Since it contains nearly zero energy due to absence of combustible matters, nearly all the wastes from construction are either sent to landfill (34% out of total) or being recycled/ reused in another construction project [9].

On the flipside, economic activities' wastes and household wastes belong to the groups on the left-hand side of Figure 4 which comprise of energy valorizable matters. As of today's, case, nearly 14 Million ton of non-dangerous energy valorizable matters are being used to generate energy through classical incineration and anaerobic digestion [9]. Half of these wastes are generated by domestic households and includes fermentable matters such as kitchen wastes and other type of wastes namely paper, plastics, etc. The detailed contents of household wastes depend highly on the lifestyle, region, and many other factors associated with the habit of the people. Therefore, it can be said that the variability of wastes is very wide. For example,

two of the different household samples in France metropole [10] and France DOM [11] completely have different elements inside, following the condition in the corresponding region.

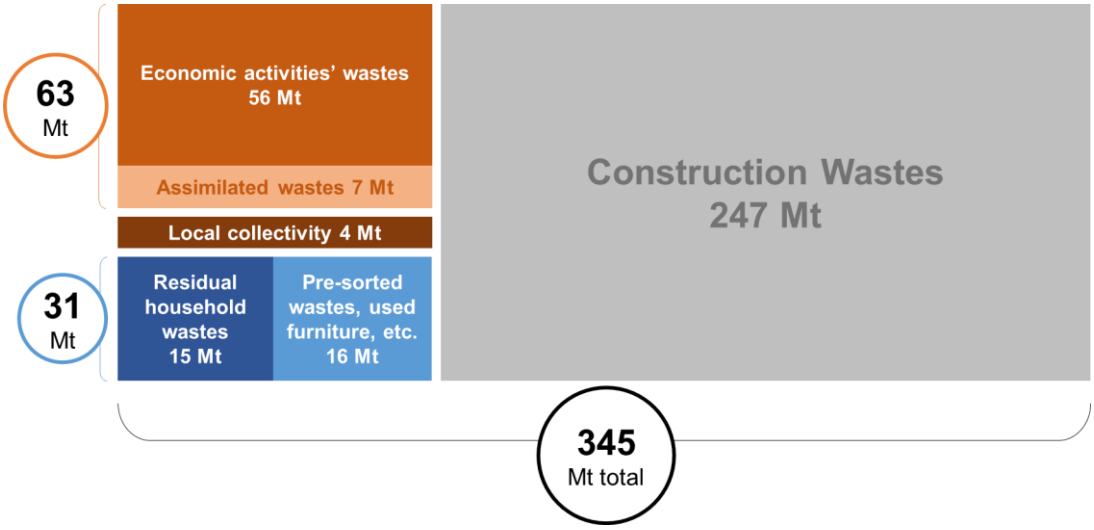

Figure 4 The Production of Wastes in France (2012 data) [10]

It should be noted that the amount of wastes flows in France also fluctuates depending on the trades with the other countries. According to the Ministry of Ecology and Sustainable Development [13], all the imported wastes going to France are coming mostly from European countries. The statistic is rather opposite for the export, since based on the recorded data in 2014, France also delivered its wastes to other non-European counties such as China and India. The portion of trades between France and the other countries are presented in Figure 5.

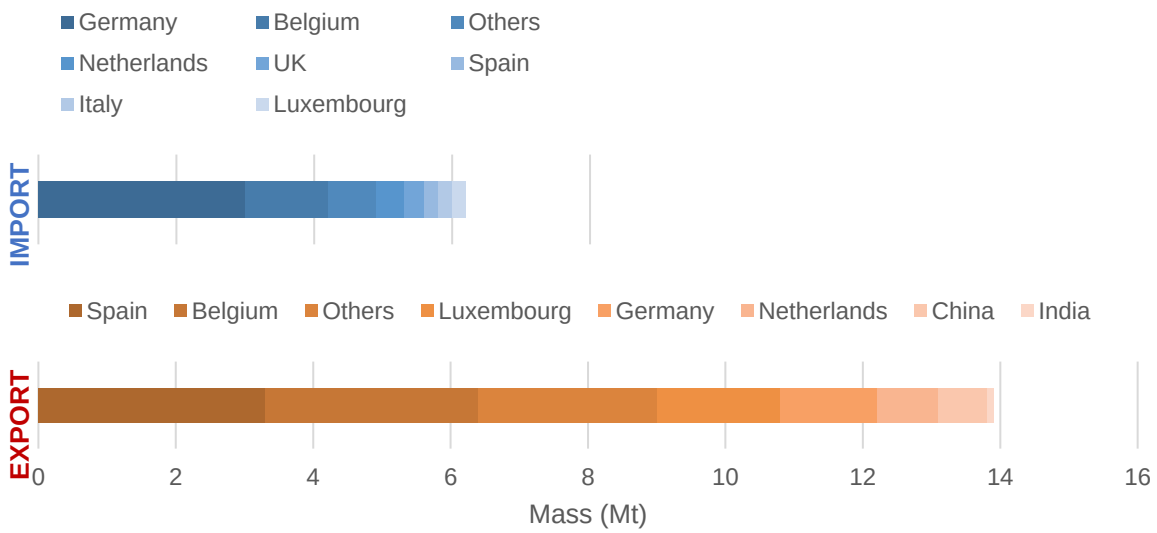

Figure 5 The Trades of Wastes between France and the Other Countries, Adapted from [13]

Another important fact that can be highlighted from the trend is that France has been exporting its recyclable materials ever since a decade ago (75% increment in 2014 compared to 1999) [13]. These materials consist of metals, wood/ wood-based materials, plastics, and minerals. Summing up all the trade flows in the year of 2014 gives the following results in Figure 6.

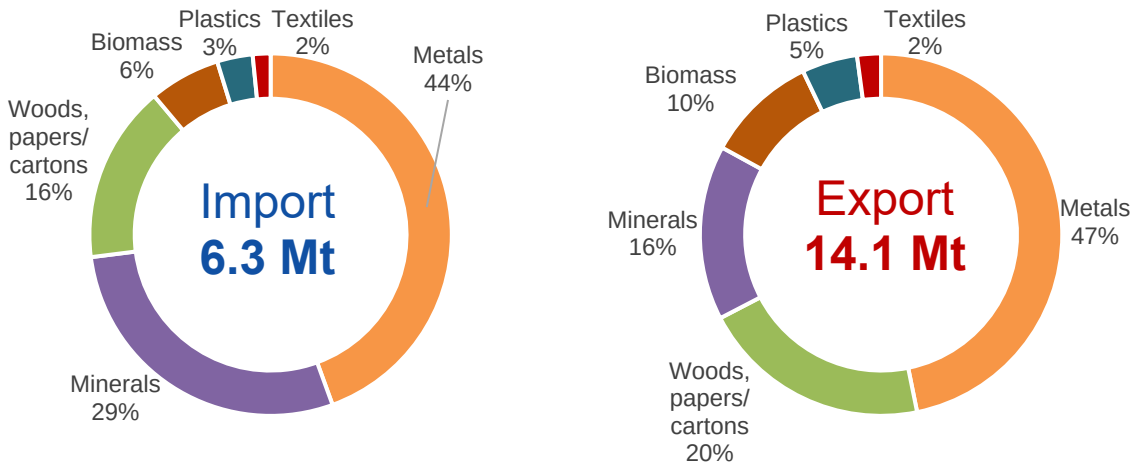

Figure 6 The Trading of Wastes in France, according to Waste Types [10]

Subtracting both values for calculating the net flows results in 7.8 Million ton of waste exported abroad each year, with the escalation trend in the future. However, if there is such a case where the country to adopt a 'circular-economy' approach with minimum amount of wastes generated, then it might imply an additional volume must be treated domestically. At the bottom line, recyclable materials in France's wastes such as paper, biomass, and plastics (in total, those are equal to approximately 3.4 Million ton of wastes combined) would become a surge of inputs for waste valorizations in the future. Thus, stressing these amounts with the notion of valorizing them can provide extra resources both for CSR production or direct utilization through specific technologies. More detailed elaborations about are to be explained in Chapter 4.

3.3 Classification of Waste Derived Fuels

In the mission to fulfill requirements imposed by Waste Framework Directive, hundreds of mechanical-biological treatment (TMB) facilities were built in Europe to treat residual municipal solid waste (MSW) in the last two decades. In France, there are currently around 25 TMBs and 5 TMBs, which are recognized as potential waste derived fuel producers [3]. These plants are capable to recover precious materials such as ferrous and non-ferrous metals (iron, aluminum) while at the same also produce bio-methane. As another important flow from these units, an alternative fuel is generated which comprises of high calorific value materials (such as plastics, fabrics, etc.).

3.3.1 Refuse-derived fuel (RDF) and Solid-recovered fuel (SRF)

Refuse-derived fuels (RDF) are defined as a heterogeneous group of non-hazardous/ dangerous wastes that can be used to generate energy. Many of calorific wastes are called refuse-derived fuel (RDF), in which are causing problems due to the fact that there is no official definition and no quality criteria for RDF. Usually, this fraction is obtained after simple processing of municipal or economic activities wastes, which is aimed at increasing of the calorific value treated, among others, by organic fraction removal. As there is no official standard for RDF, the content and quality of this may vary, therefore public acceptance and acceptance by competent authorities is commonly low [4]. As a consequence of this unclear regulatory aspect, a standardized way has been made possible by European standards of CEN/TC 343 that define 'solid recovered fuel' (SRF) and its classes [5]. Different classes of SRF can be examined in Table 1.

Table 1 Different Classes of SRF (EN 15359:2011)

Criteria	Unit	Classes of SRF				
		1	2	3	4	5
PCI	MJ/kg	25	20	15	10	3
Chlorine	% sec	0.2	0.6	1.0	1.5	3
Mercury	Mg/ MJ gross - median	0.02	0.03	0.08	0.15	0.50
	Mg/ MJ gross – 80th percentile	0.04	0.06	0.16	0.30	1.00

Note: orange shaded boxes are CSR-compliant properties

Elements associated in this section:

- *Appendix 2 CSR and Its Classification proposed by FEDEREC*

3.3.2 Combustibles solides de récupération (CSR)

Specifically, in France, the country has developed its own regulatory criteria to determine the characteristics of fuels which are produced from sorting centers/ treatment centers (TM/ TMBs), namely called as CSR. The CSR itself is actually the embodiment of the French decree No. 2016-630 of May 19th, 2016 [6]. The French CSR is defined as a solid non-hazardous waste consisting of waste that has been sorted to extract the recoverable fraction under the best technical and economic conditions and prepared for use as a fuel in a relevant facility, which meets the requirements of item 2971 of the nomenclature of classified installations for the protection of the environment.

According to French regulation (article 3 et annexe, arrêtés du 23 mai 2016), CSR has several important criteria to be fulfilled, which distinguished itself from other waste-derived fuels:

1. prepared from non-hazardous wastes
2. has an NCV equal or higher than 12 MJ/kg (as received)
3. does not exceed the following levels of contaminants:
    - Mercury (Hg): 3 mg/kg dry matter; (0.25 mg/ MJ for NCV 12 MJ/kg (ar))
    - Chlorine (Cl): 15 000 mg/kg dry matter; (1.5 %)
    - Bromine (Br): 15 000 mg/kg dry matter;
    - Total halogenates (bromine, chlorine, fluorine and iodine): 20 000 mg/kg dry matter (2%).

The item 2971 is defined as an installation for the production of heat or electricity from non-hazardous waste prepared in the form of recovered solid fuels in a facility for this purpose, whether or not combined with another fuel. These installations shall be designed to allow as complete a level of combustion as possible while limiting emissions into the environment by implementing the best available technologies [7]. The residues produced will be as minimal and harmless as possible and, where appropriate, recycled. Installations are designed to meet an identified and quantified local need for heat or thermal energy (steam, superheated water, hot water) for industrial use or to supply a heating network. Installations shall produce at least heat according to this local need and, where appropriate, electricity as a complement. To give a vivid comparison between SRF and CSR, a summary of criteria for both waste derived fuels is depicted in Figure 7.

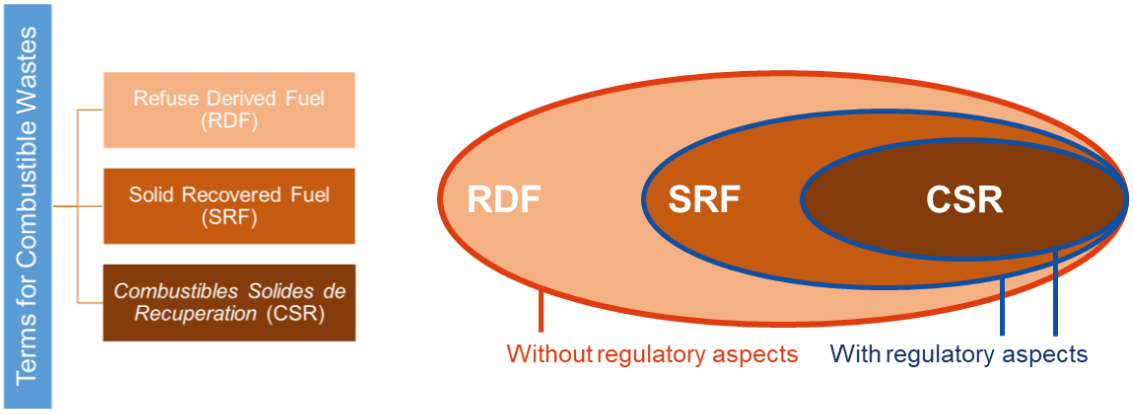

Figure 7 RDF, SRF, and CSR Comparisons

Based on this analysis, it can be inferred that CSR has a stricter requirement than SRF which leads to a higher waste-derived fuel quality in general (neglecting fuel with NCV<12 MJ/ kg and more contaminants restriction). On top of current definition, French CSR perimeter has been under investigation for improvement by FEDEREC (*la Fédération Professionnelle des Entreprises du Recyclage*) [8].

[WARNING: For the purpose of the naming and context, SRF definition throughout the report will be substituted by CSR. CSR is a French abbreviation but in order to make it aligned with the context of the study in which France is the main scope, thus this abbreviation remains as the substitution of SRF]

Elements associated in this section:

- *Appendix 2 CSR and Its Classification proposed by FEDEREC*
- *Appendix 3 Common CSR Characteristics in France*

3.3.3 Waste Matrix – Resources Potential

Knowing the amount of energy (in TWh) is essential since it gives an indication which flow of wastes that could provide additional energy resources (after its utilization for materials or other purposes), especially these potential data have been projected until 2050 (only until 2030 for CSR data [16] and [17]).

In the process constructing the matrix, one factor should be considered which is the regulatory distinction between waste and non-waste. By knowing this, energy containing materials which are not waste must be separated and considered to be treated differently unlike its counterparts.

Moreover, in the light of defining the wastes apart from non-waste materials, another factor has to be added which is called the degree of biogenic content in the form of renewable matters. This has the purpose to facilitate the GHG-related supports would be integrated in the project, such as carbon credits, green incentives, tax reductions due to renewables, and other similar supports. CSR has been given a unique indicator in Figure 8 as it can be mainly produced from different sources (household wastes or economic activities' wastes).

On the other hand, the addition of fossil fuel as the other spectrum gives a reminder that fossil fuel should be taken into account as one of the primary energy carriers (it implies there is no support for GHG-related aspects). However, the practice of co-processing fossil fuel materials (coal) with renewable materials (biomass, CSR, etc.) could potentially increase the flexibility and broadening the consumption of fuels in valorization units. For instance, this matrix can be

an initial method to perform an early selection when there is a dire need to co-incinerate fossil fuel at EDF DPIT fleet with other available biomass/ waste derived fuels based on its availability and flexibility in the existing valorization units. Lastly, this type of matrix can also be replicated to different context or study that has the objective to identify and to map the resource potential of specific territories. Apart from this, it can also give some indication about certain fuels that should be imported due to the limited amount in the evaluated regions (in this study, no indicator is shown in the graph).

Thus, combining both the aspects of waste/ non-waste material and renewable/ non-renewable origin of material produces matrix shown in Figure 8.

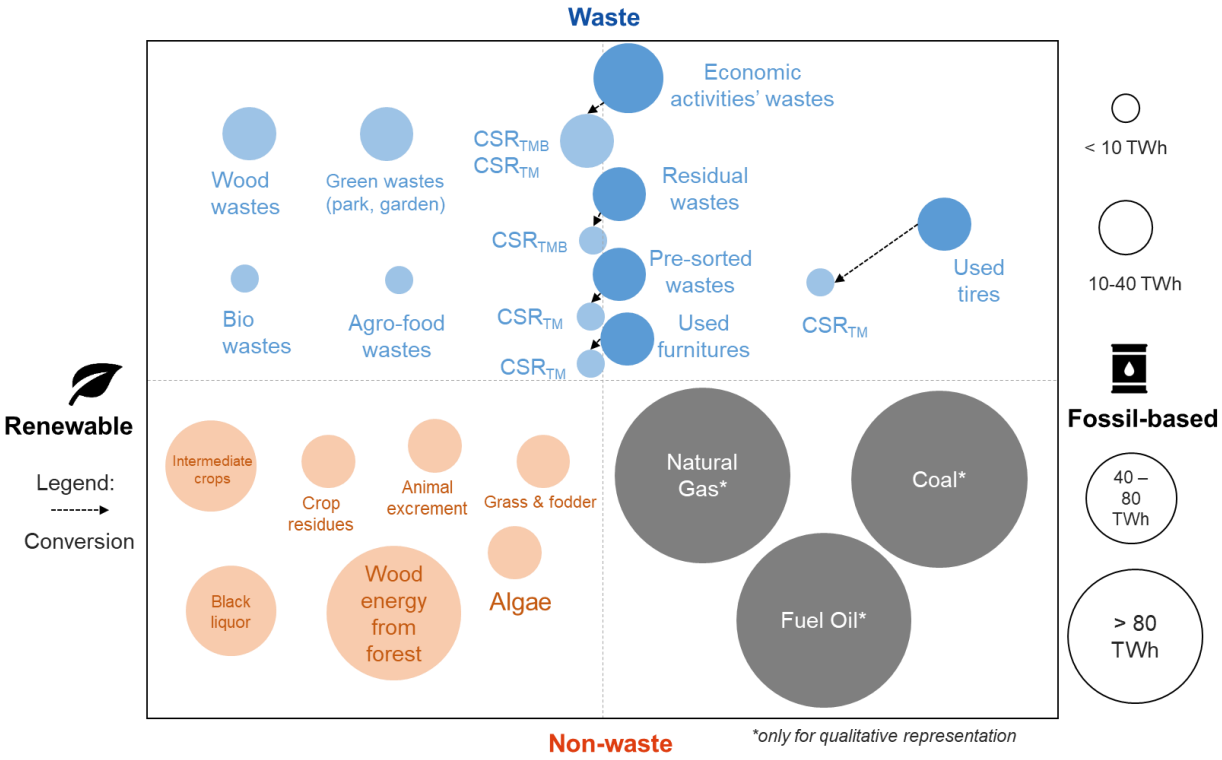

Figure 8 Resource Potential, adapted from ADEME [14] and EIFER [15] reports

Elements associated in this section:

- *Appendix 13 The Energy Potential of Waste Matrix Data*

3.4 Valorization of CSR in France

The utilization of CSR has gained enormous focus in France lately due to its effectiveness to solve both environmental waste management problems and energy issues. Therefore, ADEME in its study has explained that in the next decades until 2030, France would reorient itself as the CSR producing country with an additional CSR generation up to 2.5 million tonne annually (mainly dedicated for cement industries combustible fuels and estimated to be generated from economic activities' wastes) [17] [18]. On the other hand, EIFER internally has assessed the potential of CSR production as well from various resources in the country, which led to approximately 10 million tonne of CSR materials coming from household wastes, economic activities' wastes, and even waste/ used tires [16]. There are significant differences between two projections solely due to different hypotheses taken as the basis and conversion of raw input to CSR production. It can be projected that France should invest some of its budget

allocation to build valorization units which can accommodate these ranges (low to high scenario), as shown in Figure 9.

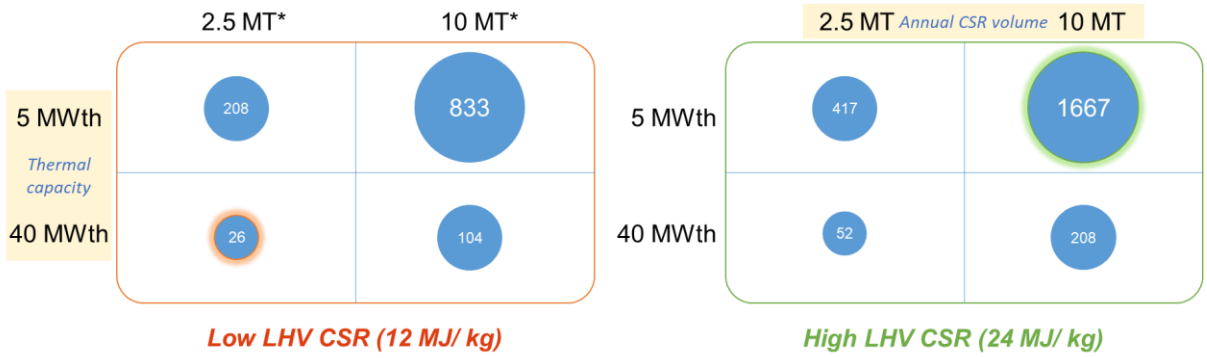

Figure 9 Estimated Number of Valorization Units in France (Year 2030)

ADEME based on its recommendation also puts a remark that the suitable size/ thermal capacity of a CSR valorization unit should fall in between 5 – 40 MWth, due the territorial optimum size. In recap, with different combinations of thermal capacity, annual volume, and classes of CSR (based on calorific value) might result in the new erections of valorization units from as low as 26 to as many as 1667 units with a small thermal capacity of 5 MWth. In order to grasp a better understanding about the type and characteristic of valorization unit, it is therefore essential to provide a broad panoramic view of possible pathways from diverse range of waste types.

Elements associated in this section:

- *Appendix 8 Sharing Session II and Exchange with Tiru*

4 Municipal Waste Management Pathways

There are diverse ranges of pathways to convert wastes into value-added materials or energy vectors. Majority of the waste's treatment process have the objective to reduce the volume of incoming wastes significantly, hence it can be disposed without hassles in the landfill sites. Among various conventional and alternative technologies which are prevalent within the context of France can be seen generally in Figure 10.

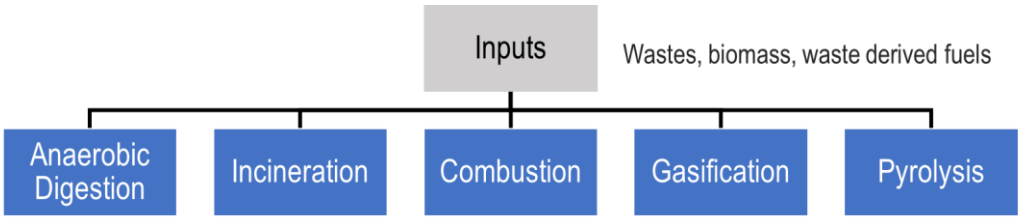

Figure 10 Valorization Techniques for Different Fuels or Combustibles

Among several techniques for valorization, some brief descriptions for each process is described:

- Anaerobic digestion : The conversion of biodegradable (organic materials) in a lack of oxygen condition into biogas
- Incineration : Practice of burning raw wastes with excess of oxygen or air
- Combustion : Practice of burning combustibles with a better controlled environment
- Gasification : Thermochemical conversion of fuels or combustibles in a partial oxidation state to produce synthetic gas (syngas or mixtures of H_2 and CO)

- Pyrolysis : Thermochemical conversion of biomass or waste derived fuels in an absence of oxygen to produce char, bio oil, and syngas

The selection of certain technologies also depends on the country's associated regulation and market condition. Unlike France which is mainly dominated by incineration and methanization at the moment, Germany has a more developed implementation CSR combustion technology. On the other hand, Japan's regulation makes it pertinent for gasification technology to be installed widely across the country.

In the past, landfilling method can be chosen as the primary treatment process before anything else due to its simplicity, despite its environmentally harmful and inefficient method. Nowadays, as mentioned earlier in Chapter 3, landfilling can only be selected as the end of waste management process if the waste materials itself could not be treated even further including material and energy recovery. Besides, the cost of landfilling wastes has increased significantly in the past years (mainly also due to tax increases in some countries such as UK, Austria, and Sweden [19]) with the recent data showed that between 80 – 95 €/ ton of waste is needed to bury wastes in France at a disposal site and even the landfill ban is imposed for untreated waste since 2002 [20]. Thus, the trend in Europe and other waste management is to shift from "old fashioned" ways of waste management to a cleaner and circular-economy oriented technology.

Elements associated in this section:

- *Appendix 6 Various Pathways for Waste to Energy Technologies*

4.1 Focus on Sorting and Treatment Options

Continuing the previous analysis, Figure 11 displays flows of different wastes which can be processed through certain units/ multiple units before undergoing further treatments at the downstream level. For example, residual (respective pre-sorted) household wastes and economic activities' wastes are sent to treatment centers or sorting center for its CSR manufacturing purpose, before being utilized by the valorization units. Meanwhile, some types of waste can be directly treated without having a lot of preparations since its properties match with the requirements of the valorization units.

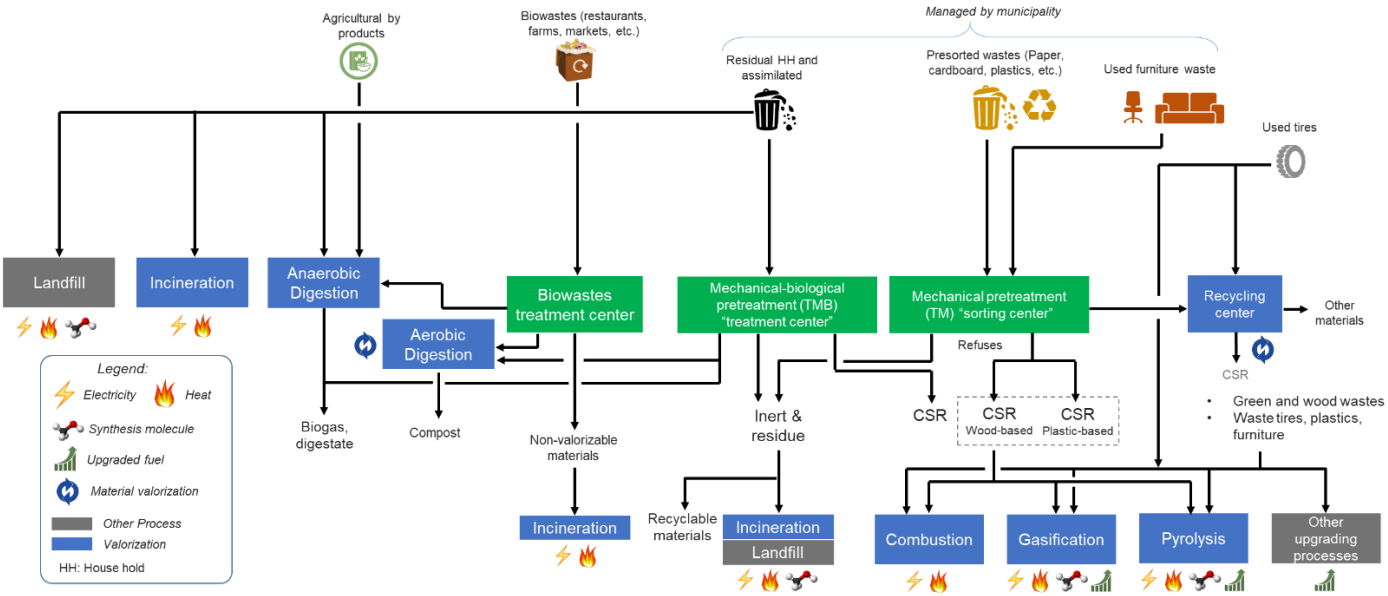

Figure 11 Energy valorization pathways from wastes

Based on this investigation, it can be noted that:

- There is an interesting notion in the process of preparing CSR as some suppliers are believed to be able to manufacture purely-made CSR (either wood-based or plastic-based) out of a sorting center. It would greatly affect the choice of downstream valorization equipment.
- Some of the additional flows for these CSR production in the future might come from used furniture waste sorting process as France will have an abundant source of these wastes from the *decheteries* in the future [17].
- There is an initiative to encourage the pre-sorting of biodegradable materials at source (home), hence minimizing the flow of input which goes to the TMB. Even though this is the case, but the pre-sorted wastes from household would still need post-sorting materials at TMB unit (still corresponding to the treatment cost which cannot be ignored), as it requires extensive effort to educate citizens for this scenario. On one side it can minimize the amount of flows going to the TMB unit, but it also implies the evolution of existing TMB to a different (new) TMB design to treat different composition of TMB with less biodegradable content. Additionally, this will instigate the necessity of biodegradables only collection from household wastes to a specific biowaste treatment that also needs some costs to be taken into account. On the other side, if there is no such initiative, TMB can always be modified to prioritize material valorization even at the treatment of its biodegradable unit through aerobic digestion process for compost production. Besides, having a larger unit of TMB can reduce the investment per tonne input (CAPEX) due to the economies of scale, which would not be the case if pre-sorting practice is imposed at source since the amount of waste flows would be divided into specific biowaste treatment unit and TMB unit. Finally, looking at this into perspective, there are diverse complex factors to be considered before concluding that pre-sorting at source would be the perfect and easy solution to implement as it involves many interactions among various flows.
- The treatment of CSR or other combustible materials in different technologies should always favour the process which enables the material valorization of the output. For example, if CSR is to be gasified with a certain technology, then the selected technology must be able to convert the CSR as well as valorize the materials output for further material valorization (such as recovery of bottom ash for other applications). Thus, it can be similarly said that both material and energy valorization will always appear together in any schemes, with material valorization is given higher priority.

Focus on energy valorization options Figure 12 elaborates how the pathways can be grouped into three major classifications in which the end products in the forms of electricity, heat, or synthetic molecules are obtained. In general, regardless of the technologies, it has to pass through a specific power cycle/ conversion unit that matches with the output of corresponding valorization pathways. For example, gasification chamber can produce syngas, that can be utilized as fuel for combustion, catalytic conversion, or even upgraded fuel itself

Some interpretations can be made from this illustration:

- Multiple flows from one product to various valorization options and eventually different products may imply a complex outcome to draw a practical assessment or to compare between different routes.
- In particular for CSR, the decision of valorizing it (or even landfilling) highly depends on the local context where there would be an interaction between CSR quality and demand. For instance, in France majority of the CSR is used as the fuel for cement industries, but only limited to a good quality CSR. Often times, when the CSR does not match the quality requirement for cement industries (mainly concerning pollutants), it

could be landfilled as the last disposal method, especially if there is minimum or no heating demand in the surrounding areas to produce energy through CSR valorization.

- Nonetheless, there is an alternative way to increase the valorization rate of medium or low-quality CSR via gasification-syngas production. Following this scenario, some burdens related to the pollutants inside CSR can be avoided by supplying clean syngas to cement kilns.

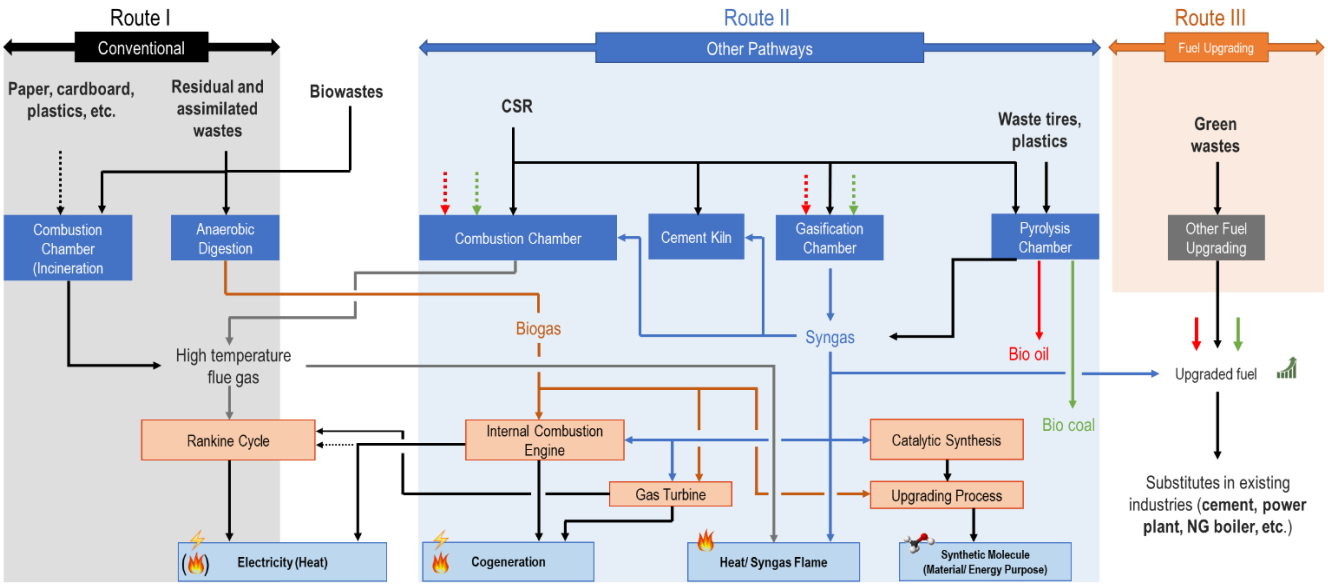

Figure 12 Wastes inputs and its final energy/ material forms

4.2 Thermochemical Conversion Routes for Wastes Valorization

A rigorous research has been conducted to evaluate the pathways of converting various types of wastes through different technologies, as exhibited in Figure 13. This chart entails the technologies overview from a more holistic perspective in terms of reactor/ technologies' types. For instance, combustion can be classified according to:

- Its combustion mode (classical or advanced/staged)
- its furnace types
- its quantity of air/ oxidant injection

In addition, this chart also summarizes the collection of technical data from various suppliers into a practical technology view. The assessed data includes:

- Capacity or the power range of the valorization units, thus allowing an easy screening should there be any selection necessity based on thermal power input.
- Products (energy, materials, or upgraded fuels)
- Technology readiness level (TRL) and number of industrial units, that can represent the degree of maturity for such technologies

A more exhaustive result for each technology (along with the details for its suppliers, capacity, etc.) can be examined in the Appendix. Note that TRL definition can be clearly observed in the following Appendix as well.

Elements associated in this section:

- *Appendix 4 Definition of "Technology Readiness Level" or TRL*
- *Appendix 6 Various Pathways for Waste to Energy Technologies*

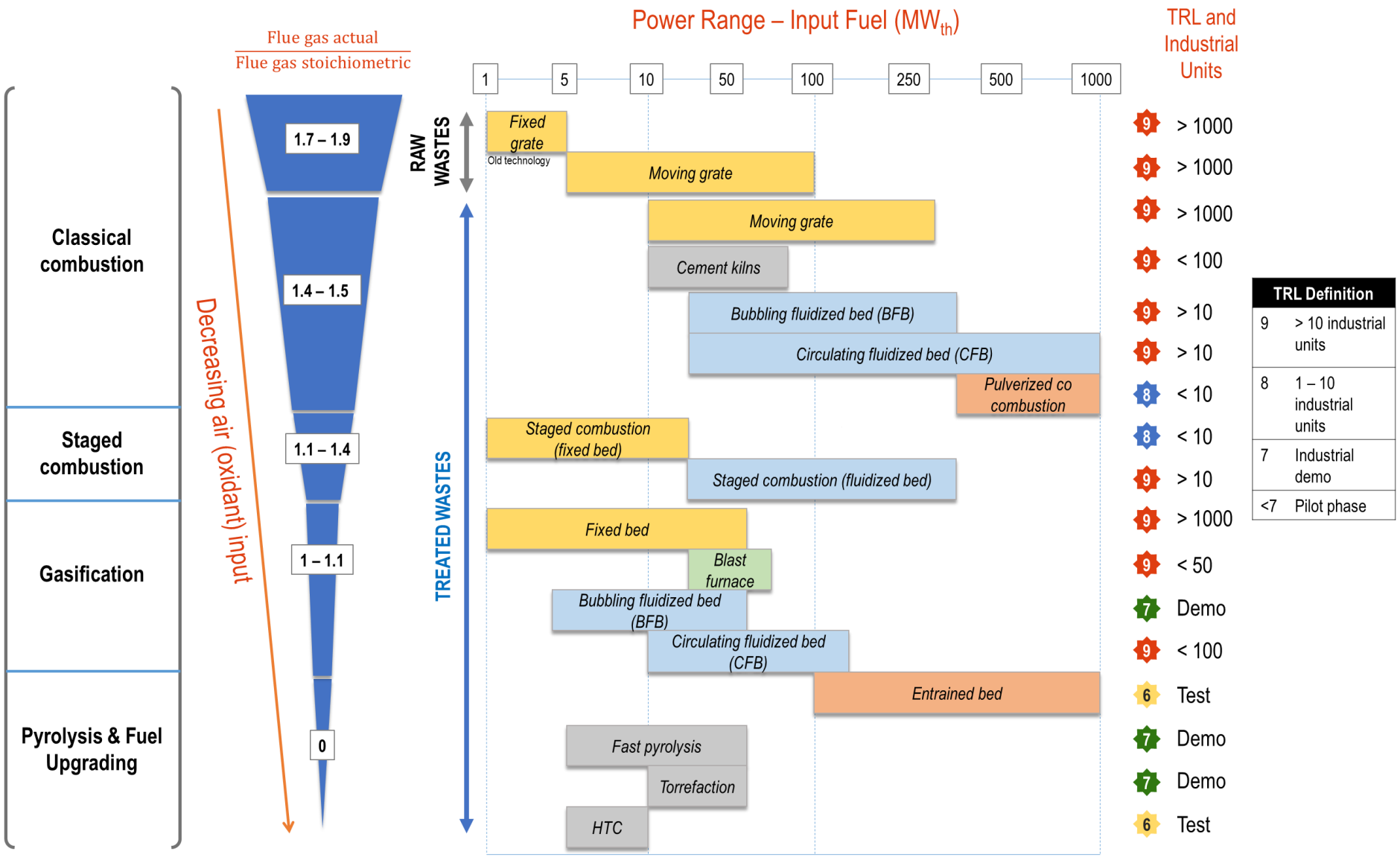

Figure 13 Waste Conversion Routes through Different Technologies and Its Maturity

5 Environmental Aspects Related to Waste-to-Energy Plants

This section is created to discuss about two major elements in accordance with waste to energy plants, namely the pollutants (including risks/ hazards) and the possible side products which are generated from the process. The latter aspect is a continuation of waste hierarchy implementation, as several output streams have its own end-purpose depending on the technologies/ schemes. Both aspects would complement the energy valorization as it broadens the perspectives of valorizing wastes in general.

5.1 Key Pollutants and Impacts

The appearance of pollutants which are emitted from waste to energy valorization unit is inevitable, since the wastes itself contain mixtures of elements that can cause harmful compounds to be released [20]. Besides this fact, even fossil fuel thermochemical conversion technologies require specific gaseous, liquid, or solid treatment techniques in order to prevent the leakage of pollutants to the environment as well as to comply with the corresponding regulations where the facility is operated. Table 2 shows the possible pollutants that might be produced from such operation.

Table 2 List of Common Pollutants in Waste to Energy Plants and Its Hazards

Pollutants	Formation Mechanisms	Hazards
Particulate matter (Dust)	Some parts of ash and unburned carbon	Health problems (lungs and hearts) Environmental damage to soil, water, air, etc. (depending on the composition) [21]
Carbon monoxide (CO)	Product of incomplete combustion	Exposure leads to nausea, dizziness, or headache. Severe level might cause brain and heart damage [22]
Sulphur dioxide (SO_2)	Reaction products of S-compounds in the waste/ combustibles	Health problems (lungs, eyes, others) Acid depositions to vegetation, water sources, and buildings (corrosion) [20]
Acid gases (HCl, HF, etc.)	- Main sources of chlorine (Cl) are polyvinyl chloride (PVC), salty food wastes, and other inorganic chlorides - Fluorine can come from fluorinated textiles and others	Health problems: Irritation and corrosive to humans Acidifications for soils and surface waters. The emitted acid gases will come down by rainfall [23]
Nitrous oxide (NO_x)	Based on three mechanisms: - From air: Thermal NO_x - From fuel: Fuel NO_x - Radical reactions with organic compounds: Prompt NO_x (less in MSW) Generally, all occurs significantly at	- Health hazards: poisonous to humans and can cause irritation to eyes, tightness of chest, nausea, headache. Prolonged exposure might engender violent coughing, breathing difficulty, etc. - Diminishing the layer of ozone in the atmosphere - Acid rain problems - The formation of smog by having the reaction with fog (smoke + fog) [24]

	temperature above 1300°C [20]	
Heavy metals	The residues that are contained in electronics, batteries, paints, metal-supported plastics, etc.	Carcinogenic emission and may provoke respiratory damages [20]
Dioxins and furans	- Precursor compounds are already present in the wastes - Synthesized from smaller and innocuous molecules in the low temperature range Maximum formation rate is in the range of 300 – 400°C	- Provoking significant risks to human health The effect of dioxin on humans is associated with increased risk of chloracne and hyperpigmentation (skin disorder), changed liver function, changes in activities of various liver enzymes, depression of the immune system, and endocrine & nervous-system abnormalities [20] - Carcinogenic to humans
Bottom ash	The remaining part of combustibles/ MSW after being converted	Contamination to soil, surface, and underground waters

Since the emission of these pollutants might pose threat and adversity to the surrounding environments (health/ environmental related), thus the presence of air pollution control before the stack is crucial to limit the concentration. These techniques according to meta study Quina et al. [25] have shown that in the modern waste to energy facility, it is obliged to install a proper conditioning and cleaning system before emitting harmful pollutants. Henceforth, there is no relevant health/ environmental problems in the modern facility, as long as it complies with the maximum concentration limit. However, the process of separating these pollutants would directly impact the overall cost of operation such systems, including the emission input from different thermochemical conversion units.

Elements associated in this section:

- *Appendix 11 Air Pollution Control in Municipal Solid Waste Combustion/ Incineration*

5.2 Byproducts from Waste-to-Energy Plants

The classical waste hierarchy principle can be referred as a guideline to manage wastes properly while optimizing the benefits for different levels. In the context of waste to energy plants, there are numbers of flows as the exiting streams from the main processes which should be treated carefully before being disposed as the end of its lifecycle. For instance, during the processing of wastes thermochemical conversion, there are some portions of streams which are generated as the products such as bottom ash/ slag, fly ash, residue and other chemicals that contains minerals and metals. This is in fact becomes more evident if the separation of metals and inert are prepared at the upstream process via a mechanical-biological treatment (TMB) technology or via collection of valorizable materials during/ after thermochemical conversion, as depicted in Figure 14.

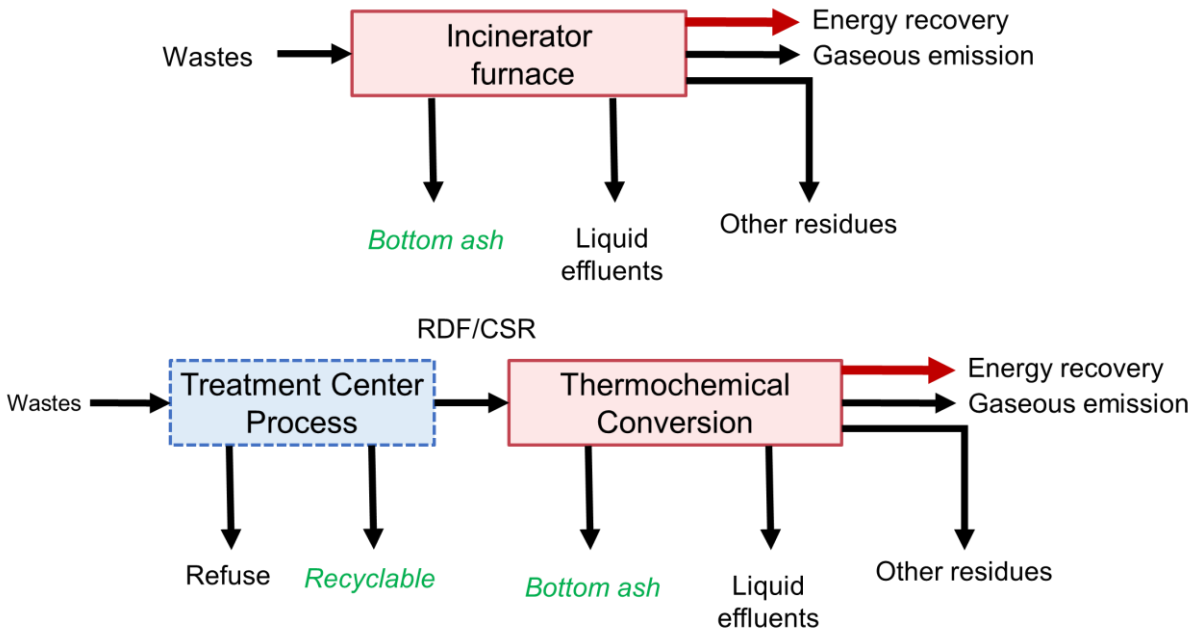

Figure 14 Illustration of Possible Byproducts Valorization from Waste to Energy Plant

Note: green colored products = valorizable materials

It is essential to note that the presence of treatment center process before the thermochemical conversion unit allows the extraction of recyclables and inert (plastics, metals, glasses etc.) in a relatively better quality for recycling rather than recovering it as the bottom ash product. Thus, this practice generally favors the material valorization above energy valorization which is strongly encouraged based on the hierarchy. Meanwhile, refuse and other residues if it cannot be utilized further are most of the cases sent to landfill. In France, there are two common practices of valorizing the byproducts [26]:

1. Recycle materials (minerals, metals, etc.) directly that have good quality. The materials itself can be obtained with a better condition for recycling purpose.
2. Recover some materials from the bottom ash stream for further treatment. With this method, landfilling (gate fee cost = 80€/ tonne) of bottom ash product can be reduced while increasing the value of the wastes itself for multiple application. The most commonly known usage of bottom ash in France is its purpose as mixtures/ aggregates in the road construction. Yet, it is foreseeable that other ways of valorization would open different valorization options for bottom ash as a more useful byproduct in other areas (Example: Wet extraction of waste to energy bottom ash at 'Green Deal' project in the Netherlands [26]).

6 Case Studies

This chapter discusses two main case studies which are developed in the frame of energy valorization from wastes. Each of the case study includes the comparison between schemes, as well as some pertinent results in accordance with multi-criteria assessments. Before the case studies, there is an initial section that describes the relevant parameters which are considered in order to implement such assessment.

6.1 Assessment Methodology

The overall methodology of this study is presented in Figure 15. More complete information about the elements in each block are described in the subsequent subsection.

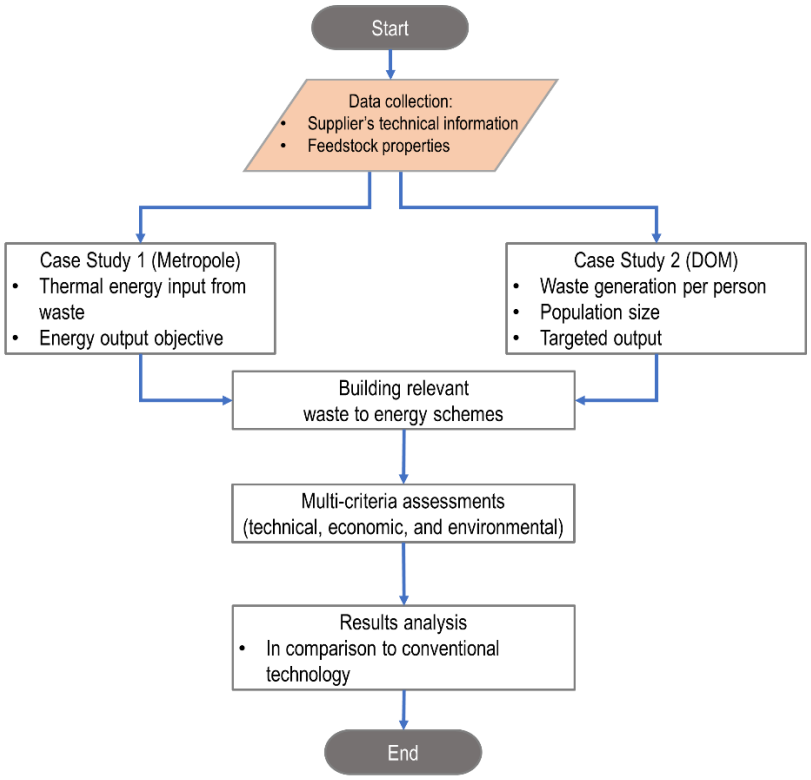

Figure 15 Research Methodology of Energy Valorizations from Waste

6.1.1 Technology Filtering by Different Criteria

The objective of this part is to screen and select relevant technologies which are appropriate within the constraints of the case study. Data collection is focused mainly for wide array of technologies, yet there are only certain suppliers to be retained following the complete technical-economic data that can be gathered. Parameters for two case studies are given in Table 3.

Table 3 Selection criteria to determine suitable technologies

Parameters	Details
Residual Wastes Valorization in Metropole - Case Study 1	
Feedstock	- Municipal solid wastes, properties based on [11] [27] - CSR, properties based on [9]
Output	- Cogeneration (heat & electricity) - Biomethane production (only for parametric analysis)
Size of the unit *(nb: local valorization)*	- 100 MWth input (maximum) - 50 MWth input (average), average circular economy size - 10 MWth input (small)
Maturity level (TRL)	Focus on TRL 9 + TRL 8 (max. time to market = 5 years)
SEI - Case Study 2	
Feedstock	Household wastes, properties based on ADEME [27]
Output	- Electricity - Gas for cooking
Size of the unit (nb: local valorization)	For household wastes: Population context: 20 / 100 / 1 000 / 10 000 inhabitants - Waste ratio (waste production / inhabitant) - Check capacity (target should be less than 1MWe)
Maturity level (TRL)	Focus on TRL 9 + TRL 8 (max. time to market = 5 years)
Simplicity	Levels of temperature, pressure, and process integration
Storability of upgraded fuel (if any)	For solids / liquid: stability For gas : complexity to store (tank, pressurized, etc.)…

The results from this part that will be fed directly to the proceeding part are the technologies from specific suppliers along with its possible schemes for further assessments.

6.1.2 Assessments based on Different Parameters

As explained in the methodology process, the aspects which are going to be assessed can be seen in Table 4.

Table 4 Assessment criteria to evaluate selected technology

Aspects	Description
Technical	- Energy yield (energy per tonne of waste input) - Overall efficiency
Economics	- Treatment cost of waste - Capital expenditure (CAPEX) and Operational expenditure (OPEX) - Cost of avoided CO_2
Environmental	In comparison to reference cases (today's practices): - GHG emission - Production of recyclable products/ valorizable materials (recyclability index)

6.2 Technical Aspects

The mass and energy balance in the principal process flow diagrams should be calculated in order to have reliable results for the assessments. Important technical values which are used in the evaluation can be observed in Table 5.

Table 5 Parameters Used for Technical Aspects

Parameters	Value
Residual wastes valorization in Metropole – Case Study 1	
Calorific value (LHV), MSW	10 MJ/ kg (40% moisture, 54%biogenic) [27]
Calorific value (LHV), CSR	18 MJ/ kg (22% moisture) [9]
Mechanical-biological treatment (TMB) [3]	
CSR output	35% of total input
Metals, inert output	18% of total input
Biogas output	5% of total input
Thermochemical conversion [29]	
Boiler efficiency	90%
Gasifier efficiency	85% cold gas efficiency
Rankine cycle efficiency	30 – 35%
Internal combustion engine efficiency	40%
Anaerobic digestion [30]	
Biogas yield	175 m^3 biogas/ tonne of organics
SEI – Case Study 2	
Calorific value (LHV), Household wastes	12 MJ/ kg (46% moisture, 47% biogenic) [28]
Anaerobic digestion [31]	
Biogas yield	90 m^3 biogas/ tonne of input
Biogas engine efficiency	40%
Thermochemical conversion [32] [33]	
Open burning carbon conversion	40-50%
Organic rankine cycle (ORC) efficiency	22%
Gasifier efficiency	80% cold gas efficiency

6.3 Economic Aspects (Hypothesis)

This section entails the estimation of economic aspects, mainly in terms of capital expenditure, operational expenditures, and additional parameters for completing the economic assessment.

6.3.1 Capital Expenditure (CAPEX) Inventory

The estimation of CAPEX is determined by correlating the size of the designed equipment with the size of previously installed facility. Thereafter, the cost can have a relation by extrapolating the size using a scaling factor, as shown in this equation:

$$C_2 = C_1 \left(\frac{q_2}{q_1}\right)^n$$

Where C2 (cost of new designed equipment) is equivalent to the cost of previously installed equipment (C1) multiplied by the ratio of both sizes with the power factor of n. A value of 2.3 [9] is chosen as the multiplier to convert this cost of equipment to CAPEX which includes installation, erection, and other complementary aspects before it can be operated properly.

Table 6 List of Equipment with its CAPEX Estimation Method

Main Equipment/ Processes	Size as the basis	Cost (€)	Source	Extrapolation law (scaling)
SEI Case				
Belt conveyor + trommel	Per foot	425	Bastian Solutions [20]	-
Milling equipment	18 kWe	17k	CSBE [21]	n = 0.7
Fuel storage	336 ton of fuel stock	940k	Internal EDF	n = 0.7
Incinerator/ Combustor	65 kg/ h (throughput)	36k	Supplier's sites [22] [23]	n = 0.7
Gasifier (fixed-bed)	Per kWe	4150	Supplier's site, IRENA [24]	n = 0.7
Filter	100 MW	2M	Internal EDF	n = 0.7
Crusher/ grinder	52 kW	38k	CSBE [21]	n = 0.7
Bio digester	10 – 100 kWe	Different suppliers' data (3500 – 6000€/ kWe)	Different suppliers' data, IRENA [24]	n = 0.7
Rankine cycle (organic)	5 – 1000 kWe	Various supplier's data (2000 - 8000€/ kWe)	U. Liége Survey Study [39]	n = 0.7
Internal combustion engine (syngas)	Coupled with the gasifier	Included within the gasifier	-	-
Internal combustion engine (biogas)	Coupled with the digester	Included within the bio digester	-	-
Metropole case (Residual wastes valorization)				
Mechanical-biological treatment (TMB) unit	Tonne/ year MSW input	60 Million €	EDF ZAK TMB and [40] IEA Bioenergy Arcadis consultancy [41]	0.7
Anaerobic Digestion process	5 – 10 MWth	3500 – 6000€/ kWe	Various data from IRENA [24]	0.7
Biogas cleaning and conditioning	2000 m^3/ hour of biogas	4.6 Million €	Reaseheath Enterprise [42]	0.7
Moving grate furnace	5 – 35 t/ hour	600 – 900€/ ton/ annum	WSP consultancy [43]	0.7
Boiler and rankine cycle equipment	Coupled with the combustion unit	Included within the combustion unit	-	
Air pollution control (APC)	Coupled with the combustion unit	Included within the combustion unit	-	-
Gasifier (fluidized bed)	P_{CSR} (thermal input)	CAPEX= 0.3261 * $P_{CSR}^{1.3597}$	Leroux Lotz project and Eqtec economic data [44]	-
Syngas cleaning and conditioning	Coupled with the gasifier	Included within the gasifier	-	-
Internal combustion gas engine	Coupled with the gasifier	Included within the gasifier	-	-

6.3.2 Operational Expenditure (OPEX) Inventory

In addition to the CAPEX, the list of consumables and produced output in each proposed scheme. The costs are gathered mainly from internal EDF documents (past studies) as well as other external resources. The summary of OPEX inventory is shown in Table 7.

Table 7 List of Consumables in the Processes and Its Costs

Consumables	Price	Details
Wastes (household wastes)	-	Input for SEI case study
Wastes (wastes from black bin)	-	Input for metropole case study
CSR	-	Self-production
Cooling water	0.3€/ m^3	Including treatment of water
Demineralized water	2€/ m^3	Utilized for steam cycle Scrubber medium to remove pollutants
Olivine	200€/ tonne	Tar removal process (3.2 kg/ MWh)
$CaCO_3$	50€/ tonne	Acid gases treatments (3.2 kg/ MWh)
Active carbon	180€/ tonne	To adsorb dioxins and furans (0.5 kg/ tonne of input)
Bottom ash	18€/ tonne (sent to a third party)	Containing minerals, metals, and other mixtures
Fly ash	80€/ tonne (landfilling)	Hazardous wastes from APC system
Maintenance	2% CAPEX/ year [38]	
Administration, insurance, and others	3% CAPEX/ year [38]	
Salary	60k€/ year (source: typical value)	Number of employees: vary according to schemes
Production	**Price**	**Details**
Electricity	• 35€/ MWh • 25€/ MWh	Selling of energy production from the plant [19]
Bio methane	70€/ MWh [39]	Injection to the grid
Metals from thermochemical conversion	50€/ tonne of ferrous metals [26]	Valorized metals from thermochemical unit

Apart from these costs, other economic parameters which are included as the basis, namely:

- Lifetime of equipment: 20 years for case study 1 (metropole) and 8 years for case study 2 (SEI) with an interest rate of 8% for future projection
- Availability: 8000 hours/ year for case study 1 (metropole) and 4200 hours/ year (SEI)

6.4 Environmental Aspects

Eventually, environmental aspect is a relevant supplement to the other two previous aspects as it puts into relieve the emissions that can be potentially released during the operation of each scheme in both case studies. The selected methods to assess each case study are described:

1. Lifecycle analysis (LCA) for GHG emission
   This method calculates the total amount of emission from CO_2 that is emitted to the atmosphere, mainly as the boundary scope of this project. Moreover, biogenic content in the waste is assumed to give zero impact to the GHG emission. Apart from that, displacement of electricity from fossil fuel would result in negative value as it always reduces the amount of utilized fuel at the upstream part.
2. Material/ byproducts management (in conjunction with the material flow analysis)
   Referring to the waste hierarchy, this method determines the amount of recyclable materials and landfilled flows on top of valorized materials for energy recovery. Additionally, it also gives some information related to materials valorization in the evaluated schemes.

6.5 Residual Wastes Valorization in the Metropolitan

Residual household wastes or in France generally collected into a black colored bin, are one of the major waste sources besides economic activities' wastes. These wastes can either be treated through an incineration unit or be processed in a treatment center before further managements. The main idea behind this case study is that most of the cases, benchmark of technologies among raw residual household wastes and CSR valorization has different and unclear boundary limit to be perceived comparable in terms of performance and costs. Therefore, some schemes are constructed to accommodate the comparison between conventional residual household wastes valorization process and the other alternatives as displayed in Figure 16.

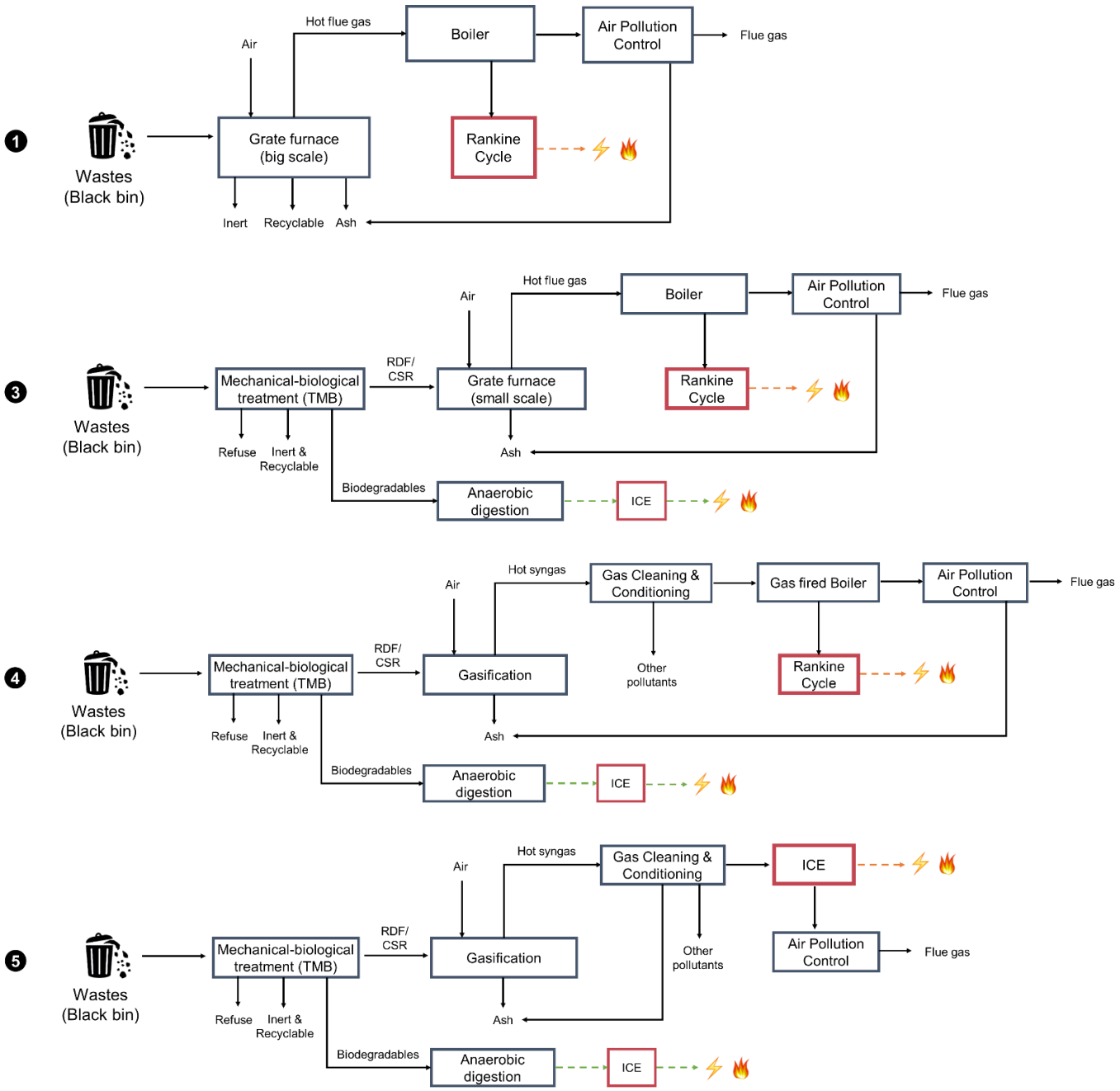

Figure 16 Process Flow Diagrams for Several Schemes (Metropolitan Case Study)

**note: Scheme 2 has exactly the same technology as scheme 1, but with a smaller thermal power input*

There are mainly five developed schemes based on available data and information gathered to have fair assessments. The critical distinction appears between the first group of schemes (1 & 2) and the latter ones (3,4,5) as there is a TMB unit to produce CSR in the last three. Other than that, more detailed specificities are exhibited in Table 8.

Table 8 Developed Schemes for Residual wastes valorization Case Study

Scheme	50 MWth (medium size)		
	Heat	Cogeneration	Electricity
1: Large scale combustion, RC	100 MWth input, only for Scheme 1		
2: Small scale combustion, RC	✓	✓	
3: TMB + combustion, RC	✓	✓	
4: TMB + gasification, RC	✓	✓	
5: TMB + gasification, ICE	✓	✓	

**note: RC = Rankine cycle; ICE: Internal combustion engine*
It is not allowed to produce only electricity when the thermal energy input of wastes/ CSR > 20 MWth according to the French regulation, Arreté 23 Mai 2018, Article 4 [46]

➢ Techno-economic and Environmental Assessment

The summary of assessments is provided the Table 9, which recaps the main techno-economic results and in parallel with the material flows percentage to measure the degree of material valorization in different schemes.

Table 9 Overall Results of Techno-economic Assessments (Residual wastes valorization)

Scheme	Energy Valorization		Overall efficiency%	CAPEX (Million €)	OPEX (Million €/ year)
	Electricity (MWh) * 10^3	Heat (MWh) * 10^3			
1	205	257	0,57	190	12,3
2	96	128	0,56	104	7,8
3	94	106	0,49	125	8,1
4	90	122	0,53	131	8,7
5	86	116	0,50	121	8

**note: overall efficiency is defined as the total energy output (heat and electricity) divided by the total energy input (thermal) from the raw residual household wastes*

Based on these results, some of the notable elements can be analyzed:

- Scheme 1 (large scale incineration, 100 MWth input) has the largest energy production and efficiency due to its biggest volume throughput at the conversion unit. This allows some parameters in the scheme to yield better performance such as the steam cycle, moving grate furnace, etc. Besides this fact, reducing the size of several units can eliminate the benefit from economies of scale, as shown by scheme 1 and scheme 2 incineration units (halving the thermal input does not mean necessarily to have 50% of the cost)
- The presences of TMB and anaerobic digestion process could increase the CAPEX and OPEX up to 20% compared to the raw residual household wastes incineration (scheme 2). Yet, this is compensated by a higher calorific value for combustibles in the form of CSR (18 MJ/ kg) than raw residual household wastes (10 MJ/ kg) and the generated energy from biogas valorization.

In addition to the five main schemes, parametric analysis is additionally conducted in certain schemes to study the impact of changing some parameters for the treatment cost evaluation. It would later provide some results of comparison, namely:

1. Smaller size of direct raw wastes incineration (10 MWth input): taking scheme 1 as the basis of calculation
2. Bio methane injection to the grid as the valorization technique for biogas from TMB: taking scheme 4 as the basis for the other technologies, except the AD
3. Byproducts (metals) valorization from thermochemical conversion unit: taking scheme 4 as the basis for other technologies, except that there are some ferrous metals valorization from gasifier bottom ash

The overall treatment cost results for all five main schemes and three additional parametric scenarios are presented in Figure 17.

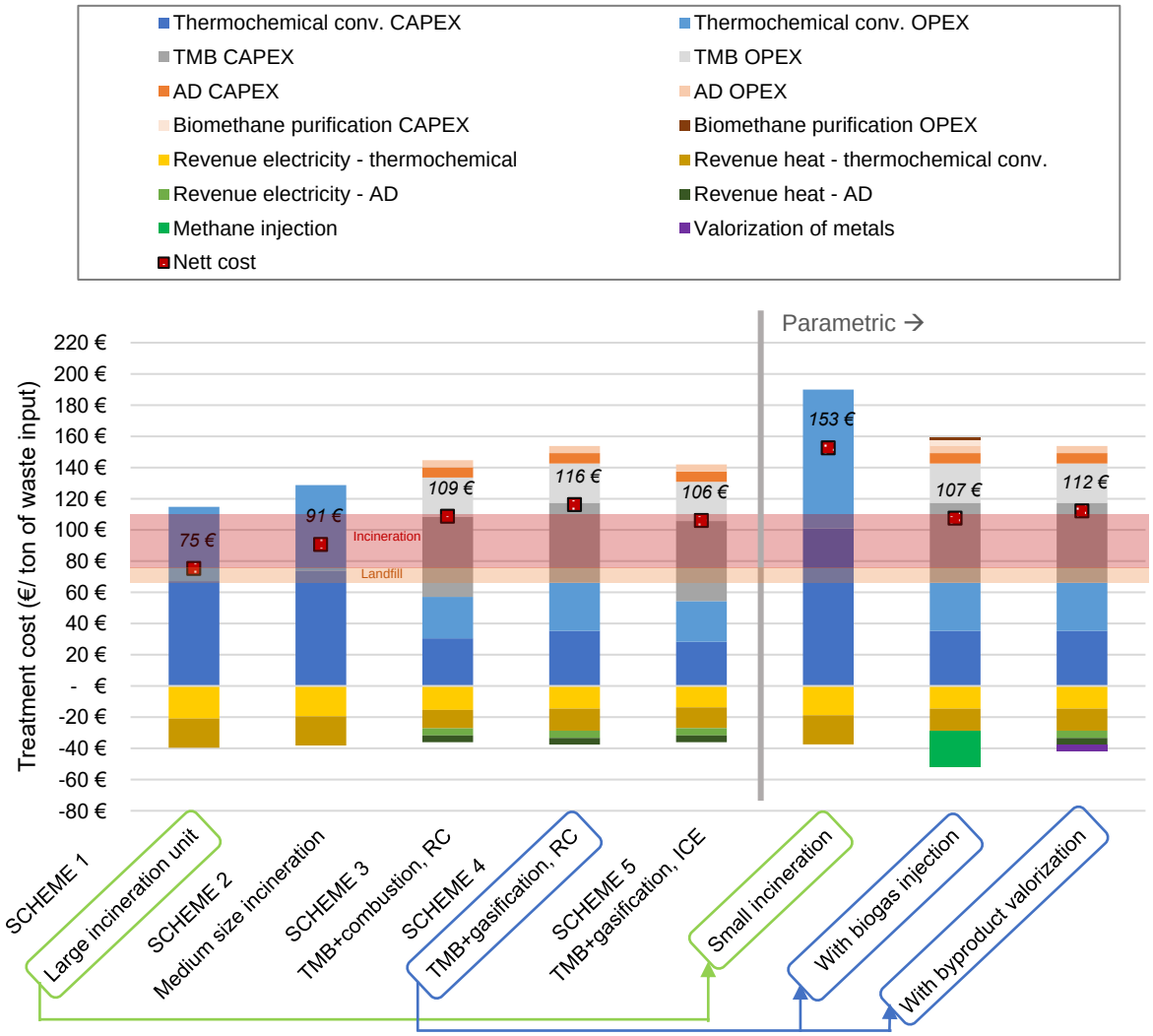

Figure 17 Treatment Cost Comparison for All Schemes and Parametric Schemes (Residual wastes valorization)

Several points that can be observed from Figure 17 are:

- Alternative processes are mostly near the high ceiling-value of incineration's treatment cost (75-110€/ tonne of waste [20]), except that for certain schemes which are higher such as the small incineration (10 MWth) and scheme 4. For the case of incineration units, the small moving grate furnace in this assessment could not gain further benefit

from economies of scale, thus the CAPEX increases significantly per amount of waste treated.

- Meanwhile, scheme 4 has comparably higher treatment cost due to a more expensive gasifier system in combination with rankine cycle. Apart from this, the scheme produces approximately the same amount of energy output which eventually gives its revenue at the same level as scheme 3 and scheme 5.
- Furthermore, TMB system as a treatment process before valorization units has considerable impact to the treatment costs (addition of 76€/ tonne of waste input). Nevertheless, this can be adequately offset by producing more thermal energy from CSR input, thus despite its lower mass flow entering the valorization units (calculated to be 35%-w of total residual household wastes), these schemes can deliver comparable electricity and heating for the consumers.

Eventually, the last section is dedicated to discussing about material valorization analysis for the five main schemes. There are three types of streams which are given some emphasis in this analysis, namely:

1. Metals: recyclable with good condition and oxidized metals post-thermochemical conversion (appeared together with bottom ash)
2. Inert: recyclable with good condition and altered/ transformed shape post-thermochemical conversion (together with bottom ash)
3. Materials to landfill (combination of residue flows from air pollution control system and non-valorizable bottom ash)

Based on this classification, Figure 18 is built to compare the flow percentage of each material.

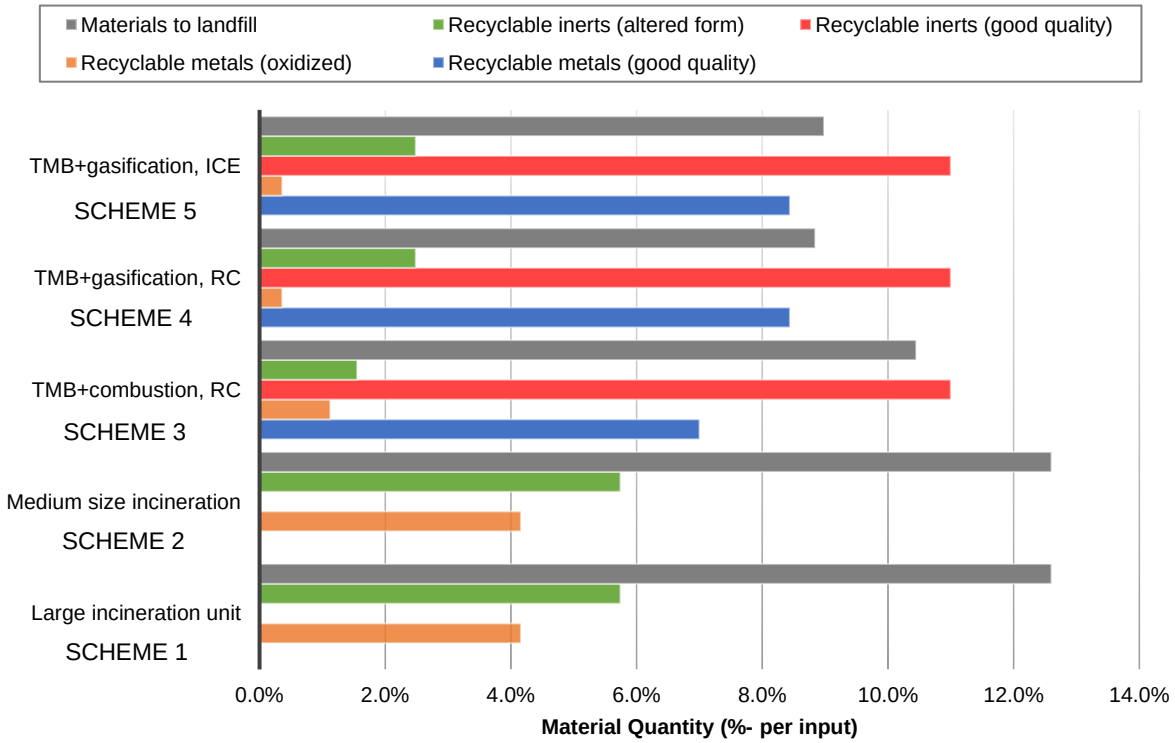

Figure 18 Comparison of Material Valorization Between Schemes (Residual wastes valorization)

Note: LCA of greenhouse gas is not particularly conducted for the 1st case study as each of the scheme has the same type of input with roughly the same boundary through thermochemical conversion units.

It can be interpreted that both large scale and small scale incineration unit lack of material valorization strategy as neither has recyclable inert and metals that can be recycled directly in good quality. Along with this, both mainly generate bottom ash from the furnace that are difficult to valorize, hence majority of the materials will be disposed in the landfill (as indicated by 12.6% quantity as opposed to less than ≤10% in other schemes). A better visual illustration for selected schemes (in the following examples, scheme 2 and scheme 5) are shown in the Figure 19.

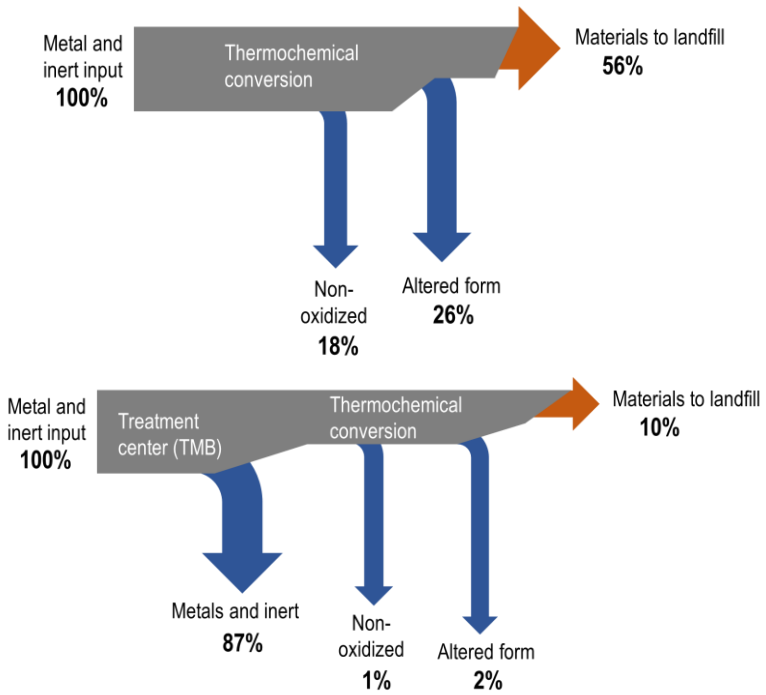

Figure 19 Metal and inert flows in the schemes (Scheme 2 upper, Scheme 5 lower)

On the other hand, schemes which are equipped with TMB (3, 4, and 5) have a better recyclability due to the sorting of metals and inert materials at the upstream before the valorization units, particularly for the inert quantity (11%). This strategy would considerably distinguish the schemes with and without TMB, as the separation process of metals/ inert are mainly involving mechanical equipment without exposing the materials to oxygen and changing the chemistry like thermochemical conversion process. Specifically, for gasification, some portion of metals can be retrieved in its non-oxidized form due to the lack of oxygen in the furnace, hence can be recovered at a slightly more quantity (8.4%) than the moving grate furnace (7%). Following this assessment, it can be clearly seen that TMB process has advantages over direct energy valorization, in addition to being aligned with the recommended waste hierarchy principle.

6.6 Household Wastes Valorization in French Overseas Territories

Viewing the case from different perspective, this case study focuses more on the implementation of waste treatment techniques in the French overseas territories with limited access to proper management system. As a context for the case study, the current practice of disposing wastes from household is simply by burning it in an open space, which can indeed cause detrimental environmental problems and resources depletion. As EDF and its subsidiary have the intention to promote appropriate waste management solution in these regions, hence this case study aims to compare the reference case (open burning) with the other possible alternative ways of treating household wastes. Based on the collected and processed information from the clients, Figure 20 represents the developed schemes that are assessed in this case study.

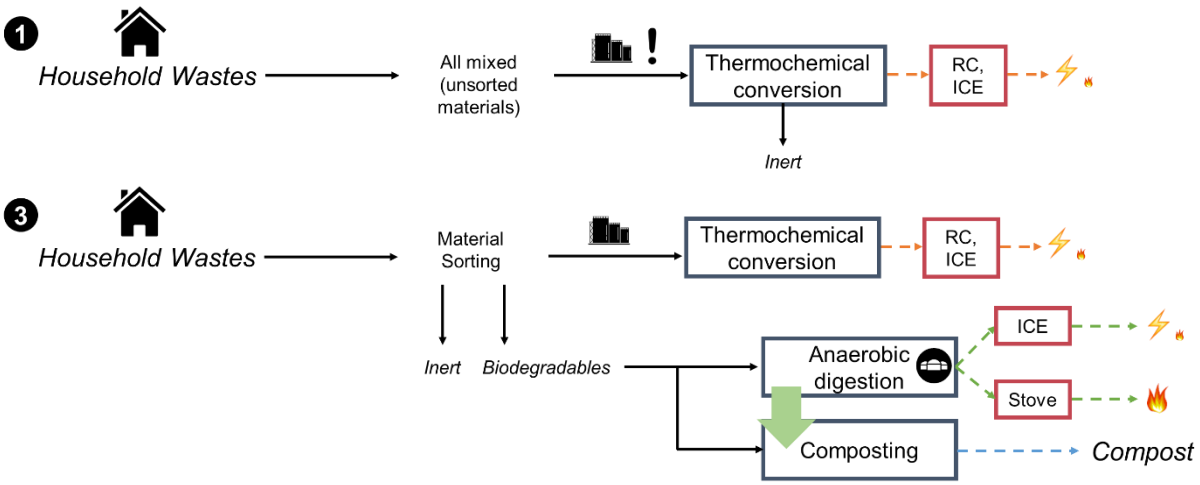

Figure 20 Process Flow Diagrams for Several Schemes (SEI Case Study)

**note: Reference scheme resembles the open burning (no technology associated)*
Scheme 2 is not retained in the figure because there is no relevant supplier that can follow such process. However, the complete information about the construction of schemes could be checked further in the Appendix 9 The Process of Filtering Technologies (pre-selection part of the studies)

Complementary explanations for these schemes are elaborated:

For Scheme 1

- The exclamation mark in the 1st scheme means that the waste should be stored and handled properly as it contains fermentable materials (it may become toxic)
- All type of wastes regardless of its condition are to be converted thermochemically through this scheme (non-combustible stream such as inert is produced along with the ash)

For Scheme 3

- As more materials are being removed from the raw household wastes, scheme 3 has theoretically the highest waste quality for thermochemical conversion. In addition, biodegradable materials can be valorized further either via anaerobic digestion (for biogas production) or compost product
- The choice of anaerobic digestion or composting depends on the local needs for energy (electricity/ heating for cooking purpose). If there is a little demand for electricity/ gas for stove, thus compost can become a good alternative as it encourages material valorization

In total, there are four different schemes with four population size in the assessments, each with different combination of technologies from the suppliers, as tabulated in Table 10.

Table 10 Developed Schemes for SEI Case Study

Technologies	Case Studies				Scheme
	20	100	1 000	10 000	
	Thermal Input (kWth)				
	4	22	217	2 167	
Open burning	Conventional (no technology)				Reference scheme
Combustion	-	Inciner8			Scheme 1
Combustion	-	Inciner8			Scheme 1* (no valorization)
Gasification	-	-	Ankur		Scheme 3 and mass allocation • 10%-w inert, • 30%-w biodegradables, • 60%-w mixtures of combustibles for gasification
Anaerobic digestion/ Methanization	Homebiogas, Puxin	Biogas SA, Novatech Gmbh	Bio4gas	Biofermnergy	

**note: green colored words are the selected technology for the assessments. Notice that for anaerobic digestion technologies, only two processes are selected - this is due to the suitable size range for bio digester as there is a separation process for the entering wastes before thermochemical conversion unit, refer to scheme 3.*

Following the initial assessment of waste generation per inhabitant in these regions, it has been found that in average, 0.27 ton of household wastes is produced annually, which is lower than French metropole ratio that was equivalent to 0.57 tonne of residual household and assimilated wastes [47]. This value will influence the amount of thermal input being processed in specific case studies, as inferred in Table 10.

Supposedly there are 16 scenarios to be assessed in overall, yet in some cases there is no supporting technology from the suppliers that can facilitate the treatment of household wastes for such scheme. Thus, based on the available suppliers' data and schemes, 12 scenarios are evaluated thoroughly.

➢ Techno-economic and Environmental Assessment

The assessments for SEI case study are more focused on finding the affordable waste management options with low environmental impacts to the surroundings. Consequently, treatment costs for different schemes and GHG emission have been computed to determine the alternative schemes against current practice.

The first result that gives an elaborative proportion of treatment cost is shown in Figure 21.

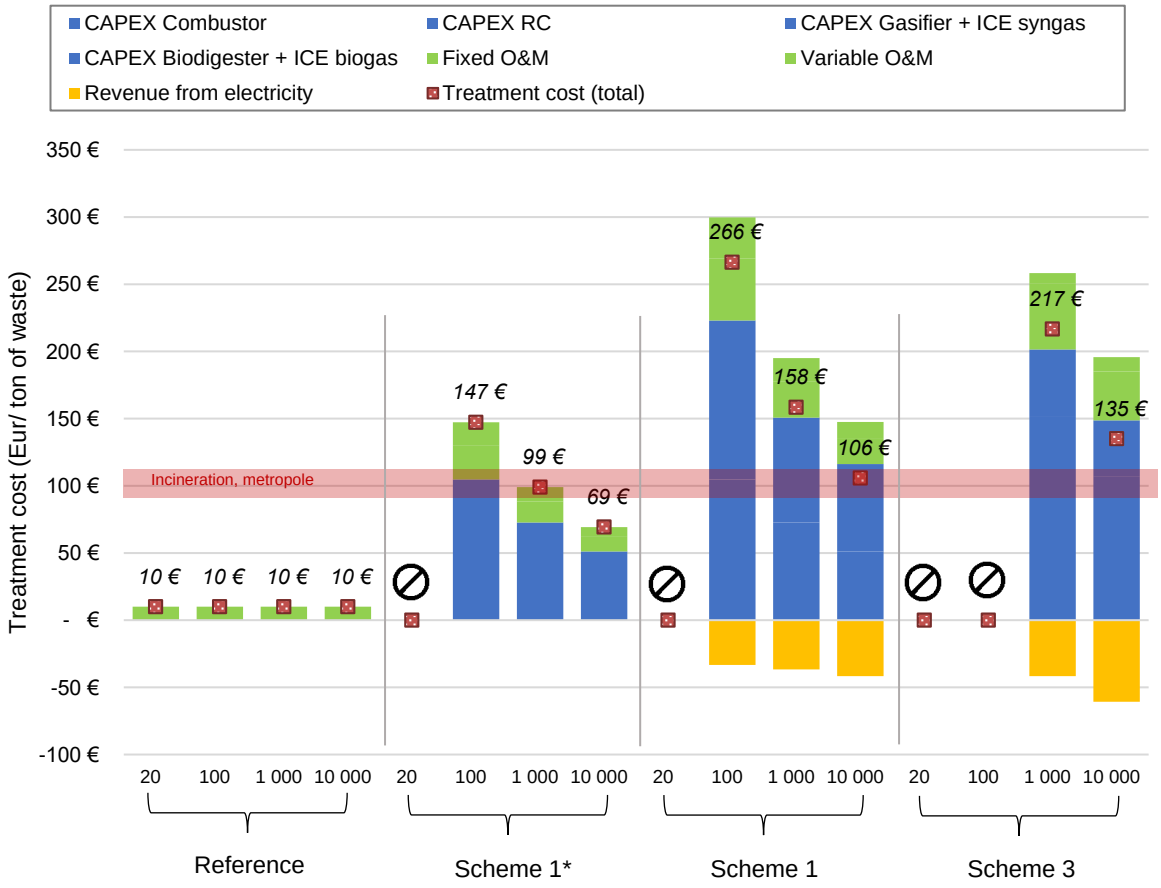

Figure 21 Treatment Cost Comparison for All Schemes with Different Population Size (SEI)

Some important essences can be taken from this result:

- The increment of population size affects the selection of technology to be more cost-competitive, as it opens the access to a larger equipment with cheaper cost per unit (economies of scale effect). Except for reference scheme which relies on human labour for collection cost, the other schemes show the same downward trend.
- Scheme 1 and scheme 3 have higher treatment cost compared to scheme 1* because both include the investment of valorization equipment (organic rankine cycle and internal combustion engine). On top of that, scheme 3 has exclusively a bio digester coupled with internal combustion engine which makes it costlier than scheme 1.
- Within the same scheme with different population size (ex: scheme 3), the performance of anaerobic digester can also impact the overall treatment cost and therefore, gives the advantages for larger size. In this case, 10 000 case study has a better anaerobic digester technology (slightly more production of biogas) with additionally better internal combustion engine efficiency (5% electrical efficiency above the 1 000 case study). However, scheme 3 does not incorporate the utilization of gas combustion engine (single unit) for both syngas and biogas simultaneously.
- If all of the treatment costs are compared with the French metropole incineration cost, then only scheme 1* (except for 10 000 inhabitants case study) and scheme 1 which fall within this range at the upper limit. Some schemes can be attractive in a smaller population size but on the other hand, the more complex the system, the bigger population size it requires for making it competitive.

Another meaningful assessment to be discussed is the GHG emission for different schemes as depicted in Figure 22.

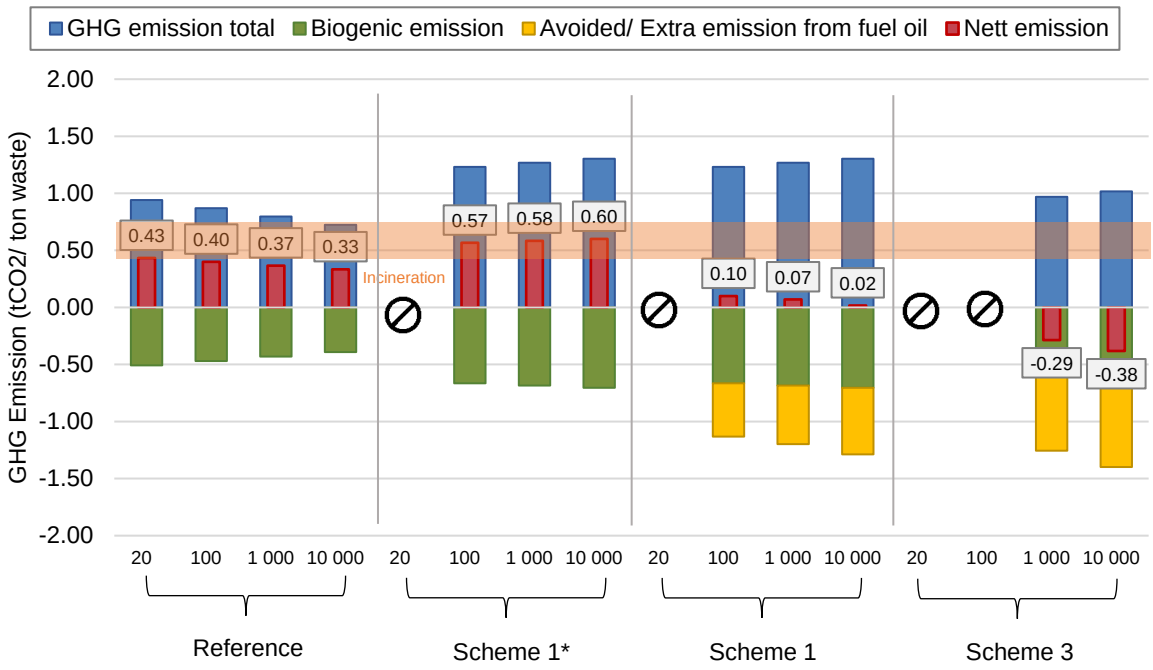

Figure 22 Greenhouse Gas Emission of Different Schemes, Displacing Electricity from Fossil Fuel

**note: incineration= assuming emission factor of 0.7-1.2 kg GHG emission per kg of MSW with 40% biogenic content. Accordingly, the fossil fuel (fuel oil) is assumed to be generating electricity from fuel oil combustion with 0.77 kg CO_2/ kWhe emission factor* [48].

This result mainly emphasizes the LCA analysis in three main elements: CO_2 emission due to the combustion of fuels, offset of CO_2 emission due to biogenic content, and offset of CO_2 emission due to the fossil fuel electricity displacement in the territory. Some notable output can be recapped:

- Reference scheme has distinctively declining trend as the population size reduces since it has more unburned carbon for 10 000 case study than 20 case study. It is rather difficult to control the combustion process in this scheme and therefore giving much more leftover at the combustion product, which somehow maintains the carbon content intact without converting it to CO_2 [32].
- Scheme 1 and scheme 3 appear to be interesting as opposed to the reference/ scheme 1* since the former ones emit less GHG per tonne of processed household wastes. Both schemes gain the benefits due to the electricity production (a form of selected energy valorization) for the community, in which decrease the consumption of the same amount of electricity from fuel oil. Scheme 3 has more electricity displacement since it accumulates the energy production from two valorization units (Gas engine for syngas and gas engine for biogas).
- Should there be any side by side comparison with the conventional municipal solid wastes incineration's GHG emission, hence the reference scheme and scheme 1* yield approximately the same value since both are principally incinerator unit with modular size. Energy valorization option in this exercise puts some schemes in a better environmental aspect for its fossil fuel substitution.

Nonetheless, some evolutions might occur in the future particularly through energy transition from fossil-based economy into a more renewable powered community. It is important also to consider the position of the current result with the possible renewable energy alternative (solar power, for instance) instead of fossil fuels, thus allowing the comparison between the current waste management practice in the future scenario, as shown in Figure 23.

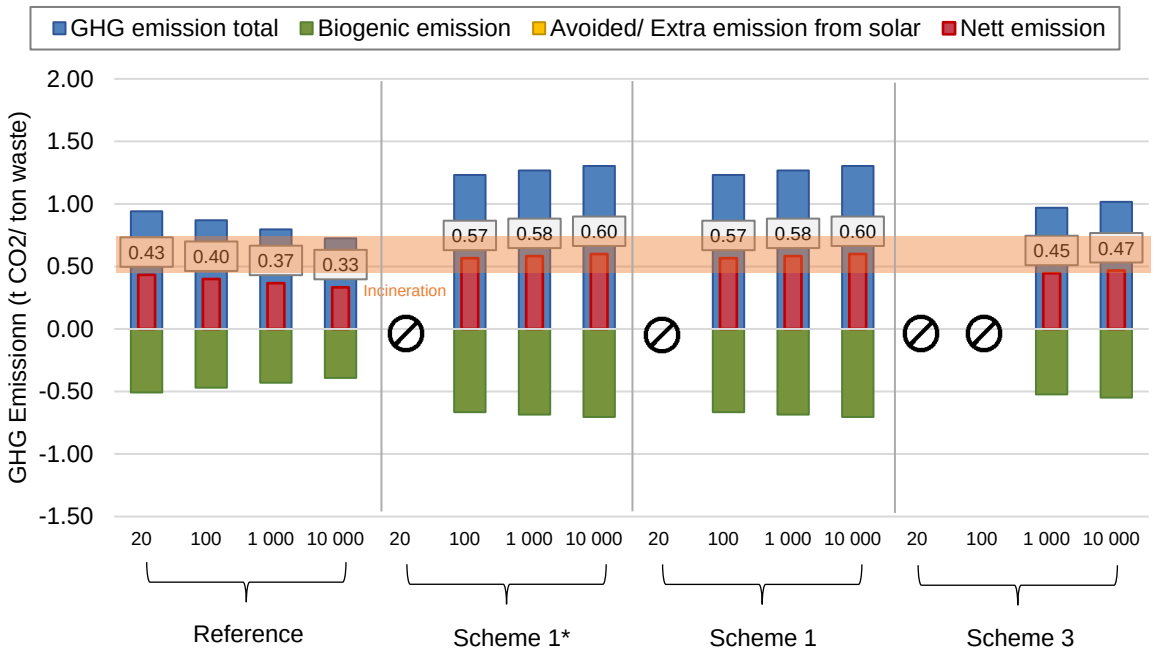

Figure 23 Greenhouse Gas Emission of Different Schemes, Displacing Electricity from Solar Energy

**note: incineration= assuming emission factor of 0.7-1.2 kg GHG emission per kg of MSW with 40% biogenic content. As a simplification, no emission is emitted during the usage of solar electricity production.*

Directly putting the results in Figure 23 and Figure 22 together can obviously indicate that without electricity displacement production from fossil fuel, all the schemes including the alternative lose its GHG emission benefits significantly. Even, reference scheme in a comparably same population size can have lower GHG impact than its counterparts (yet with much more unburned carbon left as waste residues for reference scheme). These results in a way give some leads that there should be more holistic environmental aspects analysis on top of LCA for GHG emissions.

In order to have an integrated result in all aspects (techno-economic and environmental), an evaluation on cost related to the avoid CO_2 is also conducted in the frame of the study. Combining the treatment cost and GHG emission from the previous results can give a connected value which can be interpreted as the amount of expense to be spent to emit certain quantity of CO_2 in comparison to today's practice (reference scheme in this case).

$$Cost\ of\ avoided\ CO_2 = \frac{Difference\ of\ treatment\ cost\ with\ reference}{Difference\ of\ GHG\ emission\ with\ reference}$$

The summary of results can be examined in Table 11.

.

Table 11 Cost of Avoided CO_2 (€/ tonne of CO_2) for Different Schemes

Case	WITHOUT VALORIZATION	WITH ENERGY VALORIZATION			
	Present	Before 2030 (Replacing Fossil fuel)		After 2030 (Replacing Renewable energy)	
	Combustion	Combustion	Gasification and Anaerobic digestion	Combustion	Gasification and Anaerobic digestion
	Scheme 1*	Scheme 1	Scheme 3	Scheme 1	Scheme 3
20	-	-	-	-	-
100	-824	854	-	-1539	-
10 00	-411	500	317	-685	-2598
10 000	-222	302	175	-359	-929

**note: in terms of GHG emission; Dark green = best case; Dark red = worst case*

As it can be quickly noticed, there are only five schemes that can be compared to the reference scheme. Several critical information that can be inspected are:

- Schemes with red background are to be neglected since they represent some cases where those associated technologies emit more CO_2 than the reference scheme.
- In general, all the costs of avoided CO_2 are large since it is being evaluated in comparison with the reference scheme which involves zero to minimum treatment costs. As an information, in the last decade, the price of CO_2 in the carbon market has been fluctuating from 5 - 35€/ tonne [49] which is drastically lower than even the smallest value in all schemes.
- Looking in details for schemes with energy valorization before 2030 scenario (fossil fuel electricity), it can be deduced again with the same pattern that having a larger population would increase the competitiveness in terms of avoided CO_2 cost. On top of the positive values in all case studies, switching from scheme 1 to scheme 3 that

generates more electricity can further decrease the cost nearly half of the value. Besides that, scheme 3 splits the waste flows into different streams that avoid the burning of biodegradables that can also contribute to the production of more CO_2 if combusted directly in a furnace.

Elements associated in this section:

- Appendix 9 The Process of Filtering Technologies (pre-selection part of the studies)
- Appendix 10 Mass and Energy Balances for Filtered Technologies

7 Conclusion and Perspectives

From three main parts of the study, there are separate sections for conclusions and perspectives which will be explained correspondingly.

1) Waste Characterization

This part comprises of understanding the flows of wastes in France including its management techniques and classification of waste derived fuels.

Conclusion :

- Waste management techniques should always refer to the more favorable process when selecting multiple choices of technologies (reusing > recycling > energy recovery), unless there is no other benefit at the higher level of hierarchy before moving to the lower level
- In terms of energy valorization, France is relying mostly on incineration and methanization for its non-hazardous energy containing wastes
- The emergence of fuels production from waste (or referred as CSR in France) has broadened the interest to valorize such kind of combustibles through different technologies

Perspectives :

- Since France has also published its circular economy roadmap in the May 2018, it is interesting to make a connection and analysis between the outcome of this study with the larger contextual framework
- Concerning a specific topic of discussion, it would be enlightening to find a clear explanation behind the additional production of CSR from ADEME (2.5 MT/ year that will be mainly derived from economic activities' wastes)

2) Municipal Waste Management

This part has major takeaways in the form of waste hierarchy practices in France and various treatment methods, complemented with choices of valorization from different technologies.

Conclusion :

- In the present situation, residual wastes and economic activities' wastes are processed in TM and TMB to separate its material valorizable materials before further handling
- In terms of energy valorization, France nowadays relies on incineration and methanization

Perspectives :

- To further complement the valorization study, having an in-depth research about byproducts valorization from different thermochemical conversion is an essential part to better comprehend material valorization in general

3) Case Studies

A) Case study 1: Residual wastes valorization in French metropole

The unclear boundary limits in the comparison between residual wastes incineration and CSR valorization are investigated through some schemes in this study.

Conclusion :

- The appearance of TMB (sorting center) to produce CSR increases the total treatment cost by a decent amount (40% contribution of CAPEX and OPEX from TMB unit)
- On the positive side, TMB is able to practically separate non-combustible materials before valorization unit (recyclables) and some portion of biodegradable materials for other purposes. The former part is principally dedicated for material valorization, either through reusing or recycling, depending on the quality

Perspectives :

- Assessing additional scheme where the installation of larger TMB units have the objective to serve multiple valorization units can be an alternative scenario to observe the economies of scale effect for TMB
- Performing case study with fluctuating waste characteristics is another appealing analysis to be conducted (ex: more moisture or more inert content, less biodegradables)
- Apart from the current residual wastes' valorization, creating new schemes in which pre-sorted wastes (yellow bin) as extra schemes would be a reliable case to evaluate. Besides, ADEME and EIFER have concluded that most of the CSR production in the future will be converted from economic activities' wastes
- Investigating the trade-off between the scaling up of valorization unit (more than circular economy size) against the losses when distributing electricity to some distant areas

B) Case study 2: French overseas territories: SEI

Some substitutes to the open burning strategy as the reference scheme are proposed in this part of the study.

Conclusion :

- Three alternative schemes with available data can be the relevant waste management solution in the territories, mainly relying on combustion, gasification, and anaerobic digestion following the suitable cases
- Larger population can provide the corresponding scope of areas with some new technologies with better performance, since it has lower treatment cost and higher energy output from valorization
- GHG assessment (only CO_2) seems to be insufficient to analyse the environmental impacts between schemes, as it neglects the other environmental related aspects

Perspectives :

- Collective collaboration to centralize waste within reasonable distances should be assessed, so that bigger population allows for less costly investment (less treatment cost). Yet, the cost for distributing energy should also be considered to spread the electricity in different places
- For scheme 3, composting technique is chosen as the product instead of electricity generation, if the population favors compost for their land (in other words, higher waste hierarchy as well)
- Optional strategy to reduce the cost is by installing an engine that can burn simultaneously syngas and biogas
- Other environmental impacts such as soil, water, and other pollutions should be included

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Appendix

Appendix 1 Working Schedule with Checkpoints (Internship Calendar)

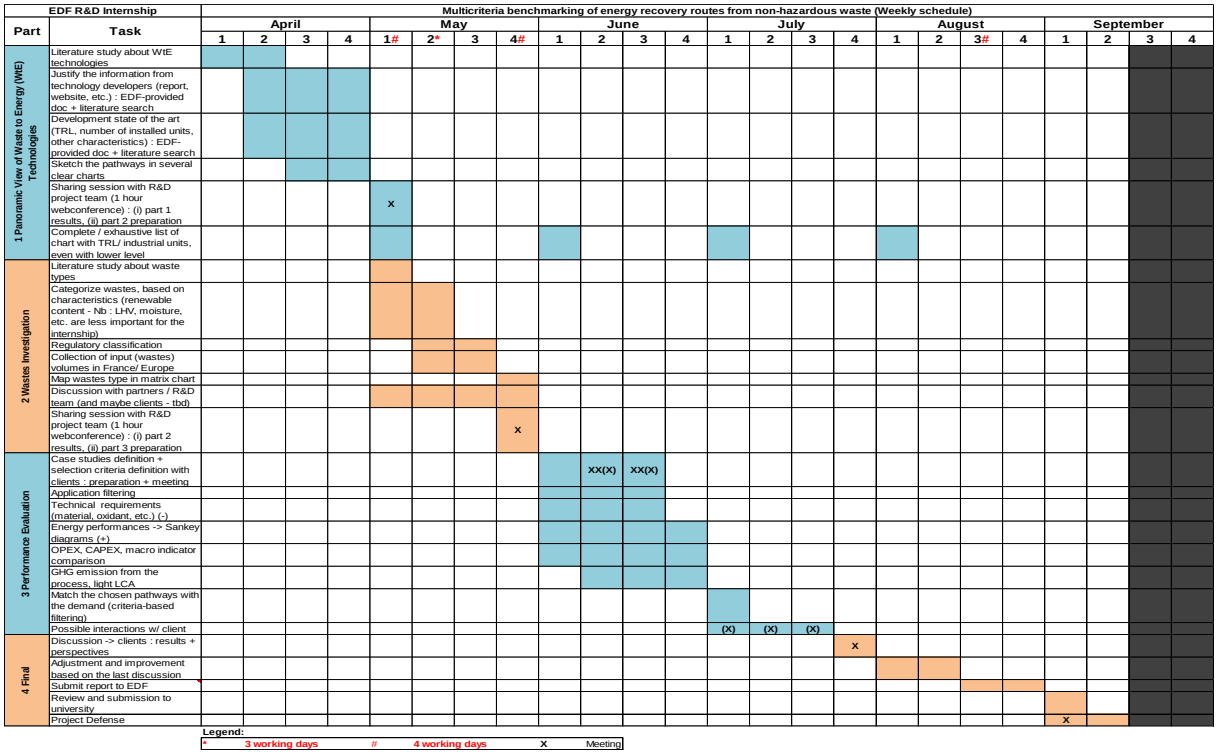


Figure 24 Gantt Chart of the Internship

Appendix 2 CSR and Its Classification proposed by FEDEREC [8]

Table 12 Comparison of SRF (EU regulation) and CSR (French regulation) Criteria

Criteria	SRF	CSR
Origin	Non-hazardous wastes	
Production method	Sorting centers (TM and TMB)	
Heating value	3 – 25 MJ/ kg (5 classes)	> 12 MJ/ kg
Contaminants Limit	Cl, Hg	Cl, Hg, Br, Halogens
Compliance rule (sampling)	12 months basis with 1500-ton lot size/ sample	Capacity <50 ton/day: 4 sampling/ year Capacity >50 ton/day: 8 sampling/ year

Table 13 Solid recovered fuel classification system proposed by FEDEREC

Criteria	Unit	Category A/1	Category B/2	Category C/3	Category D/4
NCV	MJ/ kg (ar.)	> 20	16-20	12-16	<12
Total halogens	% dry	< 0.5	0.5-1	1-2	>2
Sulfur	% dry	<0.25	0.25-0.5	0.5-1	>1
Nitrogen	% dry	<0.5	0.5-1.5	1.5-3	>3
Ash	% dry	<15	15-25	25-35	>35
Bulk density	Kg/ m^3	>500	350-500	100-350	<100
Granulometry	mm	<30	30-60	60-100	>100

Critère	ECH002
PCI brut (MJ/kg)	24,6
Chlore + fluor + brome (% MS)	0,49
Soufre (% MS)	0,24
Azote (% MS)	0,49
Cendres (% MS)	16,5
Masse volumique (kg/Nm³)	88,4
Granulométrie (mm)	> 100

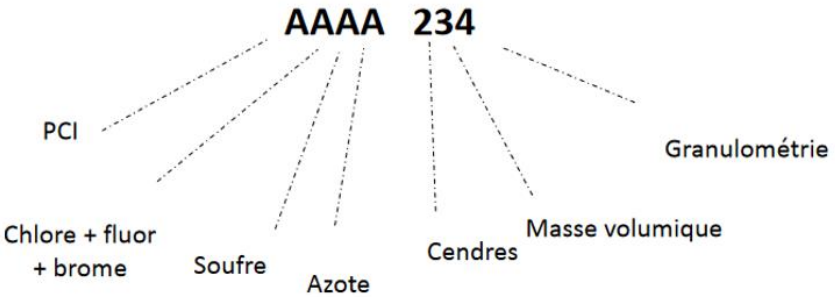
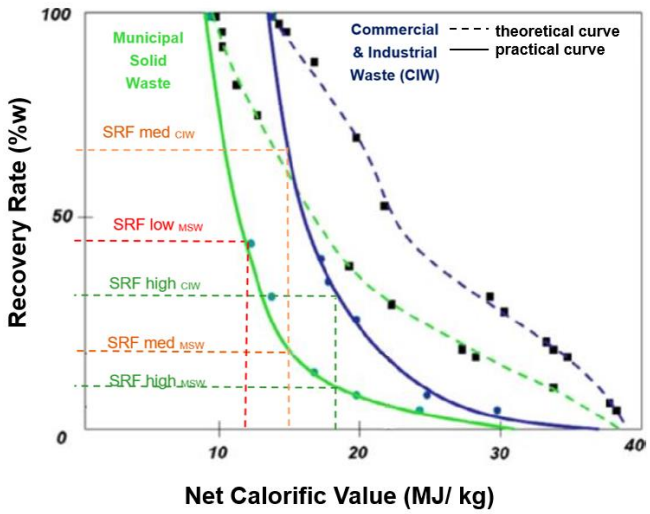


Figure 25 A French example of classification of a waste derived fuel sample according to FEDEREC nomenclature

Knowing that CSR can be manufactured from different types of wastes, it is necessary to know the degree of recovery (so called recovery rate) from municipal solid wastes (MSW) and economic activities' which are generally available. In this context, recovery rate refers to the amount of collectible waste derived fuels (combustible and non-valorizable further) after being performed with sorting and recovery process, either through mechanical or mechanical-biological treatment. The main findings of theoretical and practical yield are shown in Figure 26. For the purpose of approaching real case scenario, practical curve is being used to create a table in this figure without being overly optimistic with the recovery rate.



Recovery rate (%) for each class

CSR type	MSW	CIW
CSR Low (12 MJ/ kg)	46%	-
CSR Medium (15 MJ/ kg)	17%	65%
CSR High (18 MJ/ kg)	10%	35%

Figure 26 Production of CSR/ SRF from Municipal Solid Wastes (MSW) [8]

Based on Figure 26, the higher CSR that is manufactured from a certain unit, the more difficult it is to recover since it shows a declining trend towards both types of wastes. The sharp drops occur after medium class CSR (simply referred with 15 MJ/ kg calorific value) as the amount

of recoverable can be as little as 10% for municipal solid waste. Thus, for this type of waste, it is more appropriate to obtain low quality CSR with higher recovery rate rather than high quality CSR with significantly less production. This phenomenon also implies that the production of high-quality CSR requires more costs than relatively lower ones, especially if the inputs contain a lot of fermentable matters such as in municipal solid waste.

Appendix 3 Common CSR Characteristics in France [9]

Table 14 Comparison of CSR properties from different sources

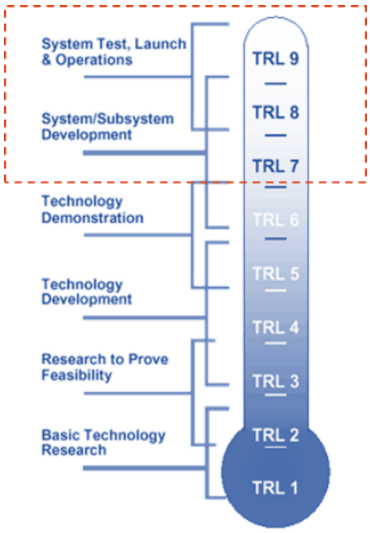
	PCI	Humidité	Carbone fixe	Volatiles	Cendres	C	H	N	Cl	S	O
CSR « moyen »	MJ/kg	% humide	% sec								
	19,2	12,2	9,6	75,2	15,2	46,7	6,4	1	0,8	0,3	29,6

	PCI	Humidité	Carbone fixe	Volatiles	Cendres	C	H	N	Cl	S	O
CSR d'OMR	MJ/kg	% humide	% sec								
	14,1	22,1	10,2	66,3	23,5	42,1	5,8	1,3	1,1	0,5	25,7

	PCI	Humidité	Carbone fixe	Volatiles	Cendres	C	H	N	Cl	S	O
CSR de DNDAE	MJ/kg	% humide	% sec								
	23	5,6	88,5		11,5	53,9	7,7	0,5	0,3	0,1	26

Appendix 4 Definition of "Technology Readiness Level" or TRL

It comprehensively examines program concepts, technology requirements, and demonstrated technology capabilities. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology.



9	8	7	< 7
> 10 Commercial units	1-10 Commercial units	Industrial demo (0 commercial unit)	Pilot phase (0 commercial unit)

Figure 27 TRL Levels and its Definition

Appendix 5 Waste Composition in France Metropole and DOM [10] and [11]

Table 15 Composition of MSW/ HH Wastes in France and DOM

<table>
<tr><th>Covered Region</th><th>Detailed Composition</th></tr>
<tr><td>France Metropole</td><td>
<table>
<tr><td>Fractions fermentescibles (DA et DV)</td><td>18.7%</td></tr>
<tr><td>Fines (< 20 mm)</td><td>34.9%</td></tr>
<tr><td>Papiers (papiers de bureau, magazines, journaux)</td><td>21,1%</td></tr>
<tr><td>Cartons (dont emballages)</td><td>15.5%</td></tr>
<tr><td>Textiles (coton, ...)</td><td>0.5%</td></tr>
<tr><td>Textiles sanitaires</td><td>3.0%</td></tr>
<tr><td>Combustibles non classés CNC</td><td>0.8%</td></tr>
<tr><td>Composites (Tetrabricks, emballages multicouches, ...)</td><td>5.1%
0.5%</td></tr>
</table>
</td></tr>
<tr><td>France DOM</td><td>
<table>
<tr><th rowspan="2">Catégories</th><th colspan="2">Déchets des ménages</th><th colspan="2">Déchets issus des activités économiques</th><th colspan="2">Total OMR</th></tr>
<tr><th>kg/hab.</th><th>%</th><th>kg/hab.</th><th>%</th><th>kg/hab.</th><th>%</th></tr>
<tr><td>Déchets putrescibles</td><td>83,8</td><td>23,5%</td><td>26,1</td><td>7,3%</td><td>109,8</td><td>30,9%</td></tr>
<tr><td>Papiers</td><td>25,4</td><td>7,1%</td><td>10,0</td><td>2,8%</td><td>35,4</td><td>9,9%</td></tr>
<tr><td>Cartons</td><td>19,6</td><td>5,5%</td><td>18,5</td><td>5,2%</td><td>38,2</td><td>10,7%</td></tr>
<tr><td>Complexes/Composites</td><td>8,0</td><td>2,3%</td><td>3,2</td><td>0,9%</td><td>11,2</td><td>3,2%</td></tr>
<tr><td>Textiles</td><td>5,5</td><td>1,5%</td><td>1,1</td><td>0,3%</td><td>6,6</td><td>1,8%</td></tr>
<tr><td>Textiles sanitaires</td><td>19,3</td><td>5,4%</td><td>8,8</td><td>2,5%</td><td>28,1</td><td>7,9%</td></tr>
<tr><td>Plastiques</td><td>26,8</td><td>7,5%</td><td>17,7</td><td>5,0%</td><td>44,5</td><td>12,5%</td></tr>
<tr><td>Combustibles non classés</td><td>5,8</td><td>1,6%</td><td>4,6</td><td>1,3%</td><td>10,4</td><td>2,9%</td></tr>
<tr><td>Verre</td><td>20,3</td><td>5,7%</td><td>10,0</td><td>2,8%</td><td>30,2</td><td>8,5%</td></tr>
<tr><td>Métaux</td><td>13,0</td><td>3,6%</td><td>6,4</td><td>1,8%</td><td>19,4</td><td>5,5%</td></tr>
<tr><td>Incombustibles non classés</td><td>5,0</td><td>1,4%</td><td>1,7</td><td>0,5%</td><td>6,7</td><td>1,9%</td></tr>
<tr><td>Déchets dangereux</td><td>2,0</td><td>0,6%</td><td>0,8</td><td>0,2%</td><td>2,8</td><td>0,8%</td></tr>
<tr><td>Eléments fins (<8mm)</td><td>9,4</td><td>2,7%</td><td>3,0</td><td>0,8%</td><td>12,4</td><td>3,5%</td></tr>
<tr><td>Total</td><td>243,9</td><td>68,6%</td><td>111,9</td><td>31,5%</td><td>355,7</td><td>100,0%</td></tr>
</table>
</td></tr>
</table>

Appendix 6 Various Pathways for Waste to Energy Technologies

The initial part of this section covers some of the details following the panoramic view of waste flows in France described in Chapter 4.

1. Household wastes (indicated by a black bin)
   This type can generally be treated in various ways since it contains multiple kinds of waste materials in it (ranging from fermentable matters such as food wastes to dry wastes such as used paper/ carton).
2. Economic activities' wastes (indicated by a yellow bin)
   It includes waste produced both by private and public institutions of all sizes. Mostly it is collected by private means, yet partially by public utilities in some cases as the characteristics are overlapping with the household wastes [10].
3. Agro-food industrial wastes (indicated by green circle logo) and bio wastes
   Both of these types are generally rich in fermentable matters since they are generated from farms, restaurants, kitchens, or other by product of agricultural/ food manufacturing activities.

As for the agro-industrial wastes, most of it will be fed to a methanization unit on site (80 units are recorded in France) before alternatively being composted for the next cultivation around the area [19]. Thus, presently these industries favor to manage their wastes onsite rather than partnering with 3rd party private waste management company to accelerate a *'circuit court'* or short loop approach.

4. Used furniture wastes, used tires wastes, and plastics (or other specific/ pure flow of wastes)
   In certain cases, some industries are also encouraged to collect specific flow of wastes from economic/ industrial sites which have a specific characteristic of wastes such as used tires and plastics. Meanwhile, used furniture wastes are normally being delivered to a *'decheterie'* and/ or 'sorting center' for its recycling purpose (in addition to the CSR production from the same unit as the side product).
5. Wood-based green wastes
   Some notable examples are the residues from construction industries or collectible green wastes from park/ streets. It is important to distinguish between the wood-based wastes against bio wastes since they have completely different structures (the former being lignin rich than the latter). Therefore, if it remains in the pure concentrated flow, a fuel upgrading technology can be selected to improve the quality of these green wastes for better combustion/ conversion performance.

In addition, this section also shows the details of TRL, number of installed units, and choice of developers for different type of WtE technologies. It is grouped into three main pathways: 1) Conventional treatments of untreated wastes; 2) Upgrading of untreated wastes; and 3) Alternative technologies for WtE pathways. In addition to that, the following figure by Peter, et al (2015) about "Status of Alternative Techniques for Thermal Waste Treatment" [17] broadly summarizes group 3 based on temperature level, injection of oxidants, and any other determining factors which distinguish itself from other technologies.

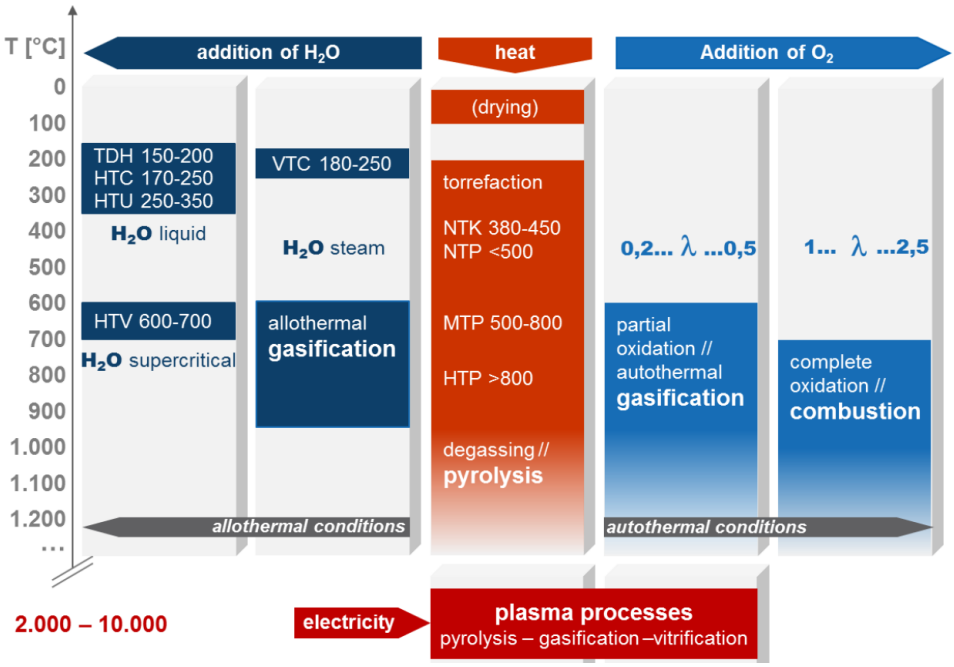


Figure 28 Thermochemical conversion of combustibles [22]

Abbreviations:

HTC	HYDROTHERMAL CARBONIZATION
HTP	HIGH-TEMPERATURE PYROLYSIS

HTU	HYDROTHERMALE LIQUEFACTION („HYDROTHERMAL UPGRADING“)
HTV	HYDROTHERMAL GASIFICATION
MTP	MIDDLE-TEMPERATURE-PYROLYSIS
NTK	LOW-TEMPERATURE CONVERSION (GERMAN: NIEDERTEMPERATURKONVERTIERUNG)
NTP	LOW-TEMPERATURE PYROLYSIS (GERMAN: NIEDERTEMPERATUR-PYROLYSE)
TDH	THERMO-DRUCK-HYDROLYSE
VTC	VAPOTHERMAL CARBONIZATION

1) TM and TMB Details

There are two types of CSR production facilities being used worldwide, namely mechanical treatment (in French abbreviated as ‘TM’) and mechanical-biological treatment (‘TMB’) [20]. In 2015, at least there are about 29 of CSR preparation units in France, in which 24 units are mechanical treatment accepting economic activities’ wastes, used furniture, and refused sorting materials while the rest are TMBs specifically dedicated for household wastes from black bins. Summing up all the units give an approximation of 300 – 370 thousand tonne CSR/ year being generated, whose around 150 thousand tonne/ year are used in cement industries. Yet, it neglects the number of units preparing CSR at the upstream process of incineration/ co-incineration units [16]. The breakdown of each values is shown in Table 16.

Table 16 Installed CSR preparation units (TM and TMB) in France, up to 2015 [16]

Type of CSR preparation	Existing operational units	Units in construction (project)	CSR production estimation (t/ year)
TM	24	2	33 200
TMB	5	6	341 600
Total	29	8	374 800

The differences between both are:

- TM mainly sorts and treats through consecutive mechanical process to obtain recyclable materials, residues, and waste derived fuel (CSR in France). There could be some modification in this process depending on the quality of incoming wastes. In that case, an additional installation of drying machine can be added at the upstream or extra sets of sorting/ screening to obtain desired outflow from TM facility [16].

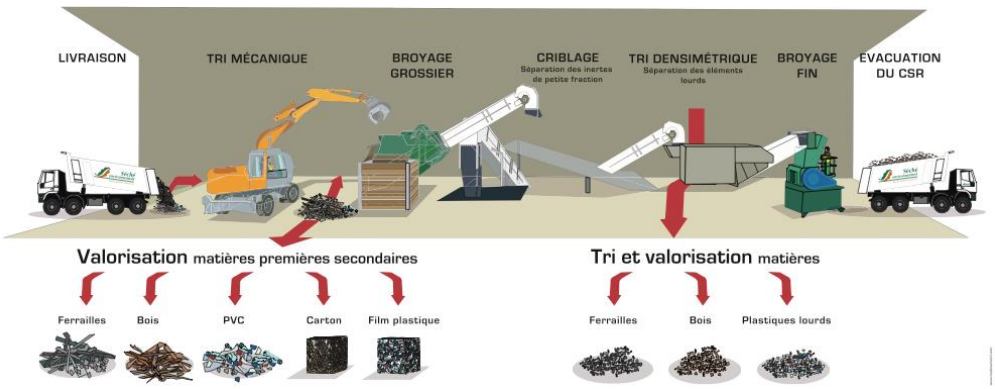


Figure 29 General stages of process at TM facilities [20]

- TMB facilities aim at treating mixed municipal wastes (generally coming from household/ economic activities’ wastes in black bin). To separate high organic content (bio wastes) from the mixtures, it is necessary to perform a biological recovery process (production of compost, biogas, or stabilized residues). On the other side, recyclable/ CSR fractions would be subjected to a form of resource recovery while the residual fractions end up in landfill. The common manufacturing process of TMB facilities is depicted in Figure 30.

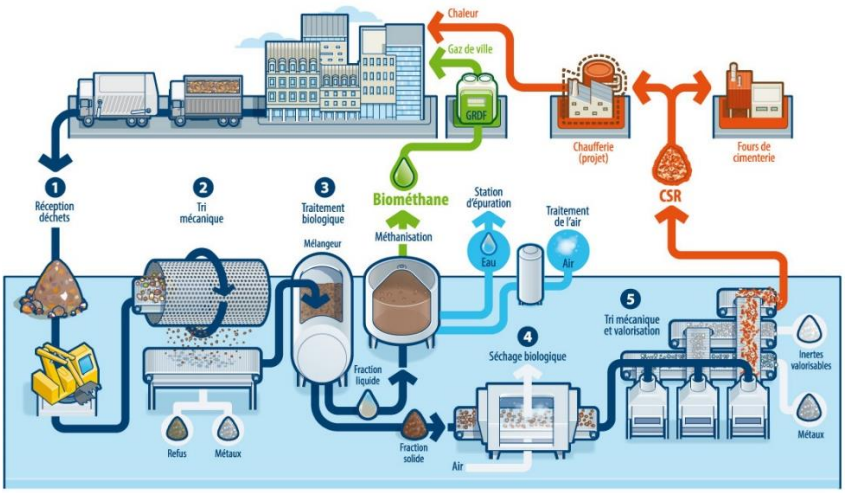


Figure 30 General stages of processes at TM facilities [21]

2) Anaerobic Digestion (AD)

Anaerobic digestion (AD) or similarly recognized as methanization is a process in which the organic materials are digested in a closed environment (so called 'bio digester') under constant temperature of 30 – 57ºC and absence of oxygen [23]. At this state, the microorganisms are biochemically converting organic materials into methane and carbon dioxide. In order to maintain the temperature of the bio digester, usually an internal heat consumption of 10 – 15% is necessary that can be obtained from onsite biogas production [24].

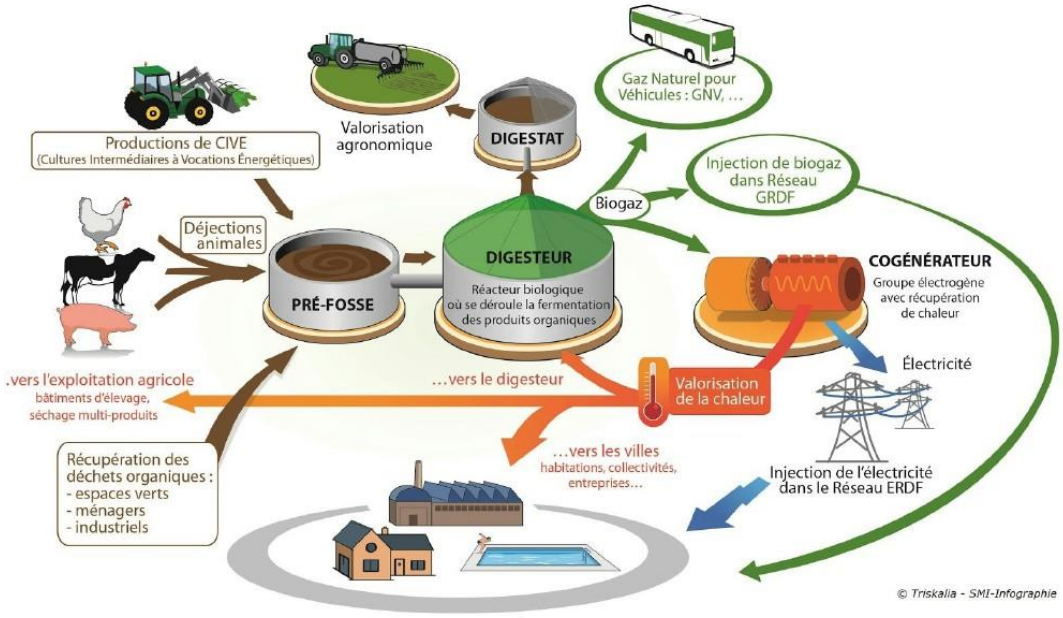


Figure 31 Production of biogas through methanization process [23]

On the other hand, as the byproduct, a slurry form of material called digestate is also generated as the effluent from a bio digester system. Often time this material can be valorized after passing through a mechanical separation phase to finally develop into a fertilizer (especially it is rich in nitrogen, ammonia, and potassium elements) [24]. Thus, the anaerobic digestion at the end opens the possibility to recover organic wastes in terms of energy aspects (heat, electricity) and material aspects (compost/ digestate).

From the bio digester itself, the generated gas consisting of methane and carbon dioxide can be either burned in an internal combustion engine or be injected to the gas network after fulfilling certain requirements. The former way of valorization, particularly through a co-generation is the most common in France as it allows the production of power or even sales of electricity to the electricity network [24]. The general scheme of anaerobic digestion is presented in Figure 31.

3) Thermochemical Conversion

The main concept of this conversion lies under the concept of supplying heat, oxygen/ limited oxygen, medium (water, bed material), and other related factors towards the combustible materials, hence it can be broken down thermochemically through certain reactions. Three of the general conversions are discussed briefly.

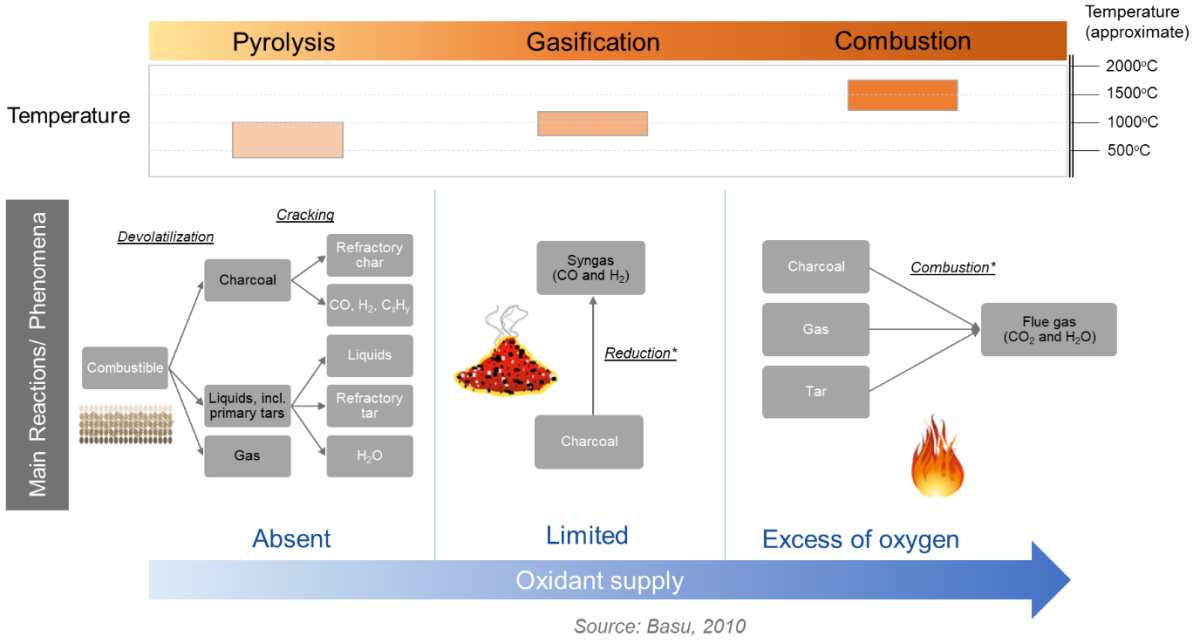


Figure 32 Sequences of reaction (thermochemical conversion) [28]

A. Combustion

Combustion is a chemical process in which a substance reacts rapidly with oxygen and gives off heat. Usually, the amount of oxygen (as the oxidizer) would be excessively supplied to the reaction in order to ensure the full conversion of combustibles (carbon) during the process. Within the frame of this study, it has been found that there are generally two types of combustion processes which some suppliers provide in the market, namely:

1) Classical combustion
2) Staged combustion (advanced)

The main differences between both are influenced by the separation phases of gasification and combustion processes inside the furnace. Staged combustion has a controlled way of injecting oxygen thus allowing the process of converting the combustibles to a syngas before being burned in the later stage. In contrast, classical combustion bluntly introduces significant amount of oxygen from various places for assuring complete combustion at the end [23]. In addition, an illustrative chart in Figure 33 can also reveal the main distinction between both.

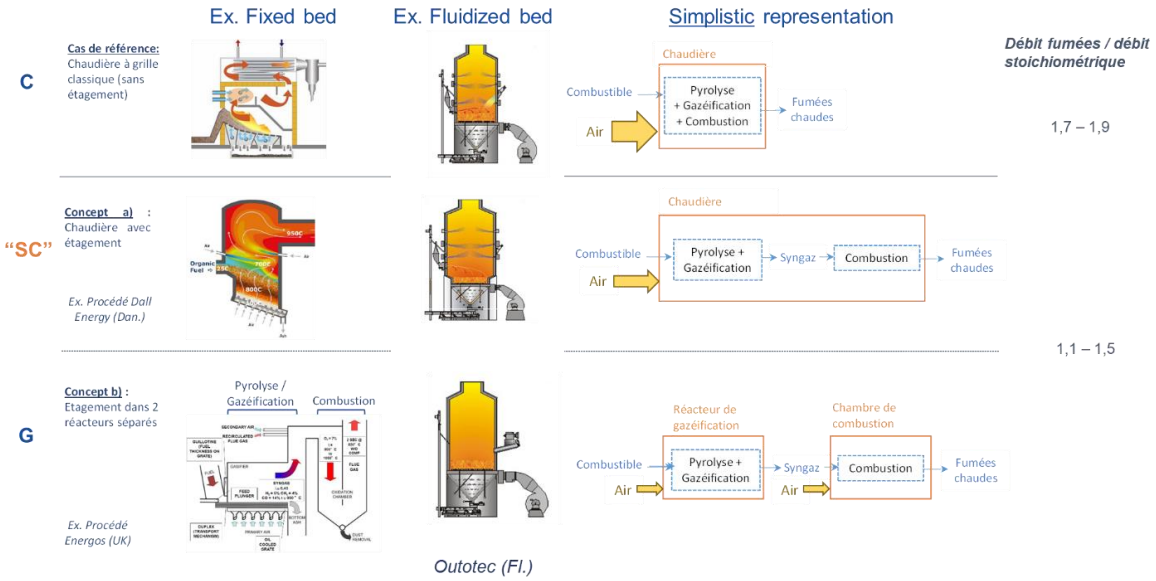


Figure 33 Schematic comparisons between combustion (C), staged combustion (SC), and gasification (G)

B. Gasification

On the contrary with combustion, gasification is defined as auto thermal when the gasification agent causes partial oxidation of the fuel. This partial oxidation is attained by limiting the amount of injected oxygen to the system, thus allowing the pyrolysis and devolatilization to occur in the beginning. Generally, the overall reactions of the gasification process can be referred as an endothermic reaction as it requires external/ internally produced heat (limited combustion of the fuel) to perform the sequence of processes. The limitation of oxygen supply is crucial for gasification in order to prevent energy loss or complete oxidation of feedstock.

C. Pyrolysis

Pyrolysis involves heating of combustibles in the absence of air or oxygen at a specified rate to a maximum temperature, known as the pyrolysis temperature, and maintaining it for a specified time. The nature of its product depends on several factors, including pyrolysis temperature and heating rate as shown in Figure 34.

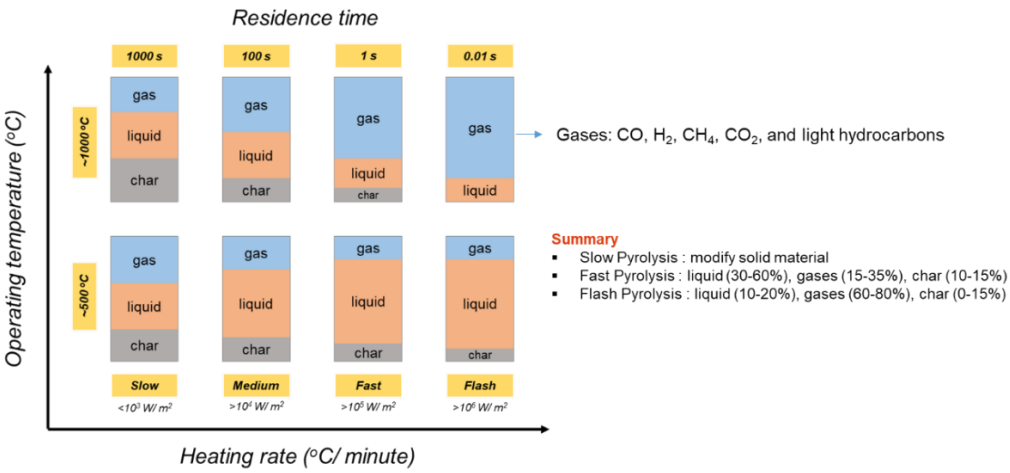


Figure 34 Pyrolysis products with the function of heating rate and operating temperature [29]

D. Fuel Upgrading Technologies

In this section, some fundamental concepts of fuel upgrading technologies to convert raw wastes into different forms/ upgraded characteristics of fuels are presented. These details (including definition, players in the market, etc.) are generally summarized and referenced from EDF fuel densification study [30], EIFER state of the art for unconventional fuel oil [31], and RECORD wastes valorization techniques through thermochemical processes [32].

1) Hydrothermal carbonization (HTC)

Hydrothermal conversion (carbonization, liquefaction or gasification) copies the natural formation of fossil fuels from biogenic materials but shortens the artificial coalification process from millions of years to seconds, minutes or hours. It proceeds at elevated temperatures and pressures for a suspension of biomass and water. Basically, HTC converts all kind of biomass into a solid fuel, suitable for combustion, co-firing or gasification. Because it takes place in aqueous conditions, it is highly suitable for densification of wet biomass samples (pumpable samples with >50% moisture content), e.g. municipal organic wastes, sewage sludge, digestates or industrial wastes from food industry like pomaces.

2) Steam Explosion

Steam explosion process involves degradation of the main components of woody biomass (lignin, cellulose and hemicelluloses) by both chemical degradation and mechanical deformation. The process involves adiabatic expansion of water inside the pore of wood tissue and auto hydrolysis of cell components.

3) Torrefaction

Torrefaction is a thermal pretreatment performed in the absence of oxygen at temperatures between 200 and 300°C. The absence of oxygen is necessary to prevent the ignition of the most volatile compounds and to control the temperature and the degree of devolatilization.

4) Hydrothermal Liquefaction (HTL)

There are various types of HTL with different operating conditions to control the reactions. One of them is HTU which was developed by Biofuel BV, as displayed in Figure 35.

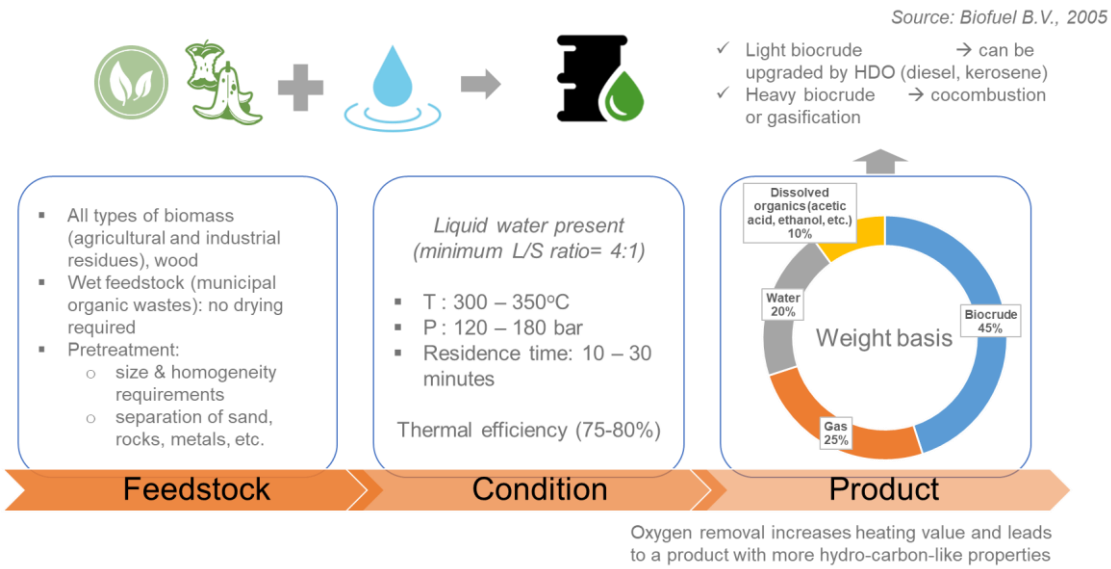


Figure 35 HTU principles, operating condition, and product

5) Depolymerization

Depolymerization is basically one type of HTL processes, in which the polymer/ rubber like materials such as used tires are dissolved in a solvent at elevated temperature and then be converted into fuel oil for combustion purpose. Several identified players are IFP (France),

Agilix (USA), and KDV Alphakat (Germany), yet none of them is continuing the development due to some technical issues and problems.

The overall schemes which have been discussed in the main report can be presented in Figure 36. On the other hand, the typical size of incinerators in France and the recommended size for a valorization unit (territorial) are shown together in Figure 37.

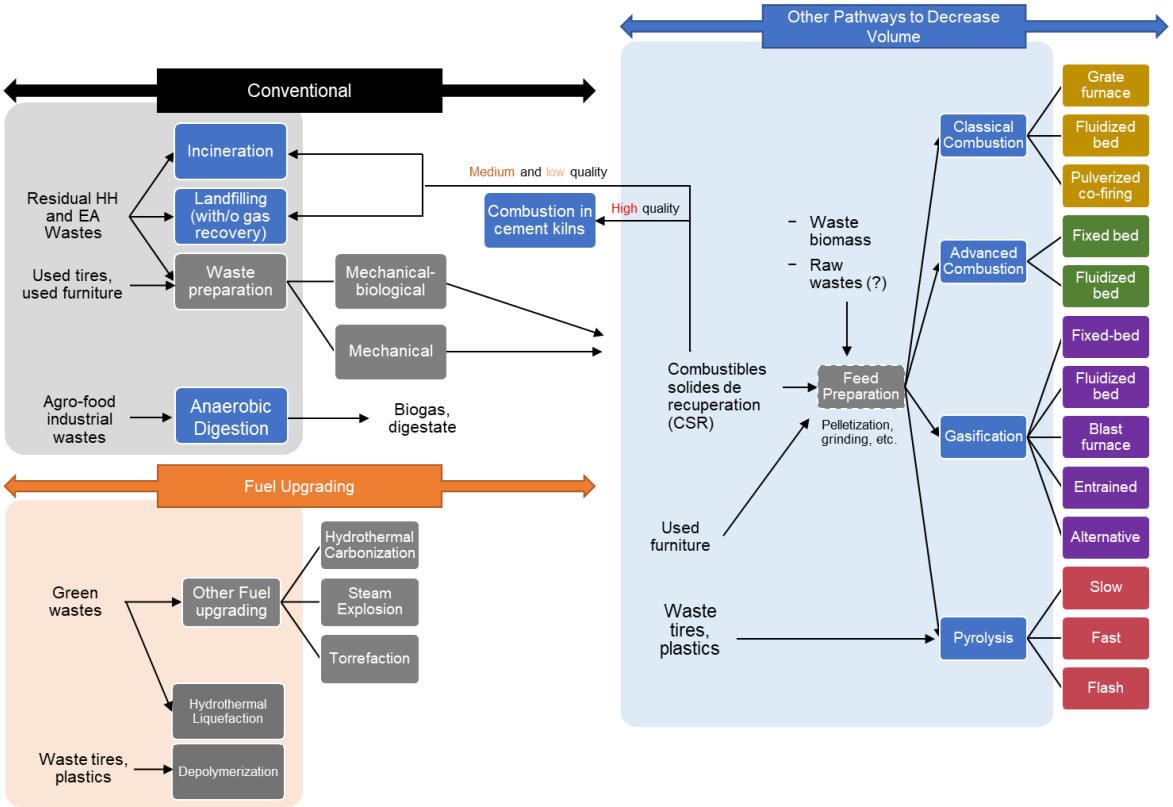
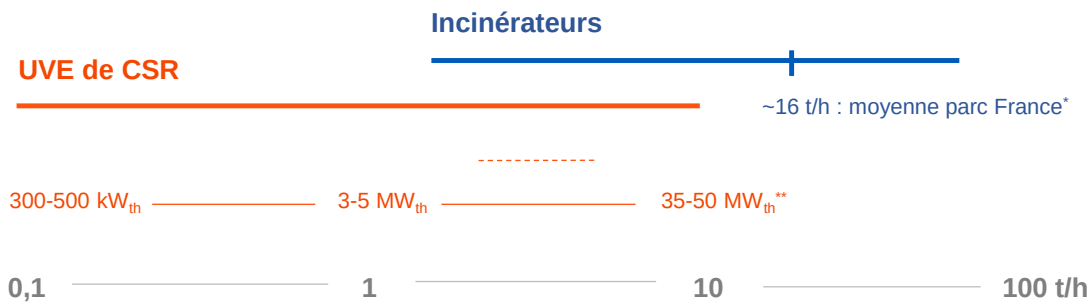


Figure 36 State of the art of waste to energy valorization pathways



----- Vision Ademe : 10 à 20 MW_{PCI}

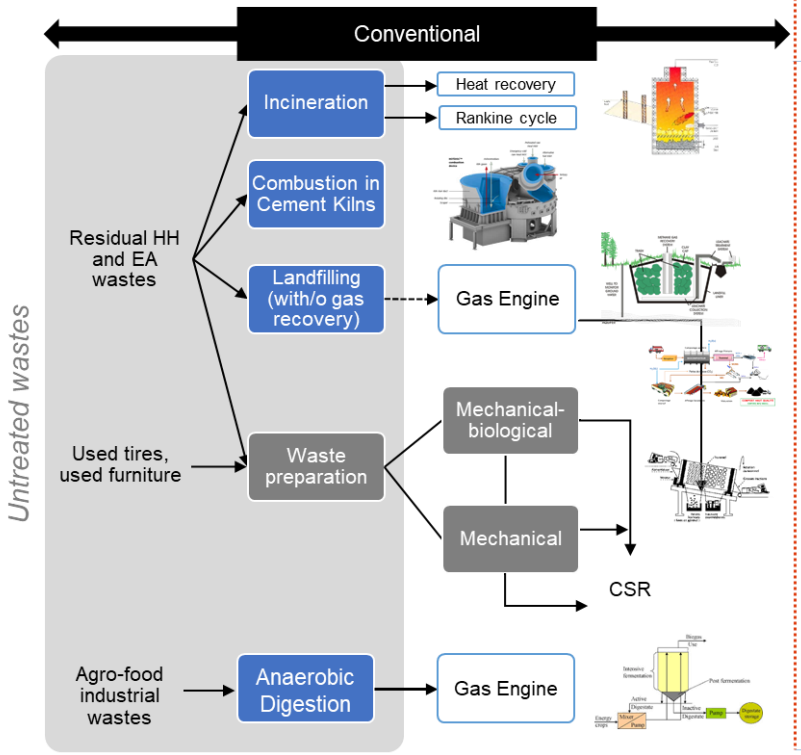
UVE Unité de valorisation énergétique

** Donnes Amorce 2011,*

*** Gamme de PCI considérée : 12-18 MJ/kg_{CSR}*

Figure 37 Range of sizes for incinerators and circular economy oriented unit in France

Table 17 State of the art for the untreated wastes treatment in France (I)



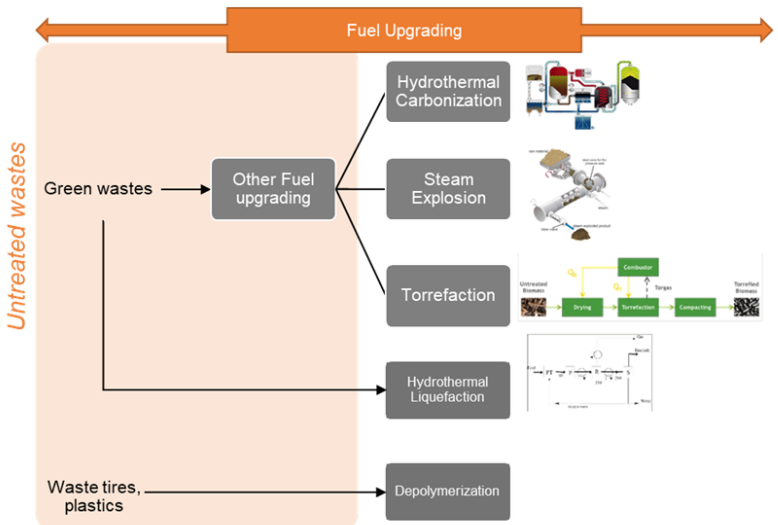
Site Capacity (Type) Input[1,*]	Site Capacity Output[1]	Energy Product(s)	TRL	Installed Units	Developers
(W) 1-100 MW_{th}	1-30 MW_e; 20-60 MW_{th}	Heat, Electricity	9	>1000	HZ Inova AG (CH), Danstoker (DK), SCS (US), Misubishi (JP)
(C) 10-80 MW_{th}	6-50 MW_{th}	Heat	9	>100	FLSmidth (DK), ZKG (DE), Feeco (US)
(W) >1 Mt/ yr	>2 M Nm^3/ yr; >1.2 MW_e	Heat, Electricity, (Synthetic molecule)	9 (8)	>1000	Venture Eng. (US), LFG Tech (US), GTI (US) Upgrading E.M.S. (DE), DMT (NL)
(W) 1-80 t/h	0.5-30 Nm^3/h_{biogas}; 1-35 t/h_{CSR}	Heat, Electricity	9 (8)	>1000	Vinci (FR), Bekon (DE), Kompogas (FR), Valorga (FR), Dranco (BE), ZAK (DE)
(W) 5-10 t/h	0.5-5 t/h_{CSR}	-	9	>500	MetalTechSystems (US), Hantsch (FR), Vinci (FR)
(B & W) 1-10 t/h	0.15-2 Nm^3/h_{biogas}	Heat, Electricity	9	>500	Kompogas (FR), Valorga (FR), Dranco (BE), Laran (AT), ZAK (DE)

Legend: Heat; Electricity; Synthetic molecule; B Biomass; W Raw wastes; C CSR

[*]fuel LHV = 8 MJ/ kg (Waste), 14 MJ/ kg (biomass), and 18 MJ/ kg (CSR)

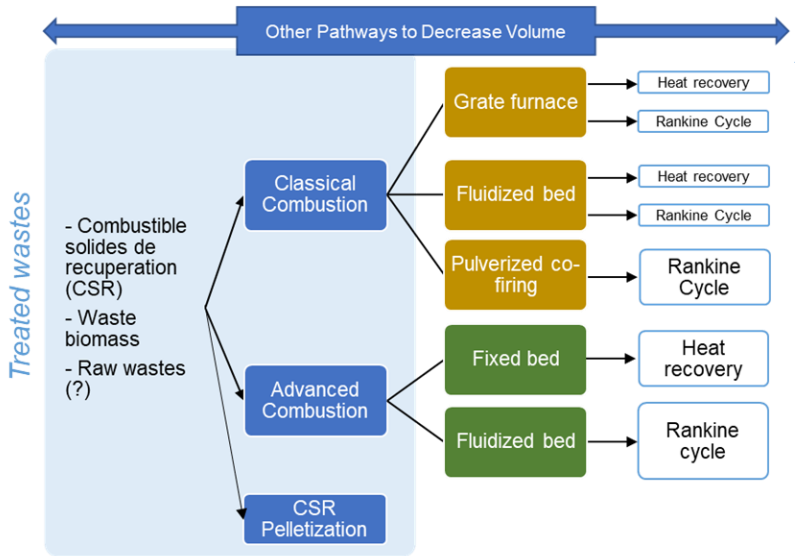
[1]References: see literature

Table 18 State of the art for the untreated wastes treatment in France (II)



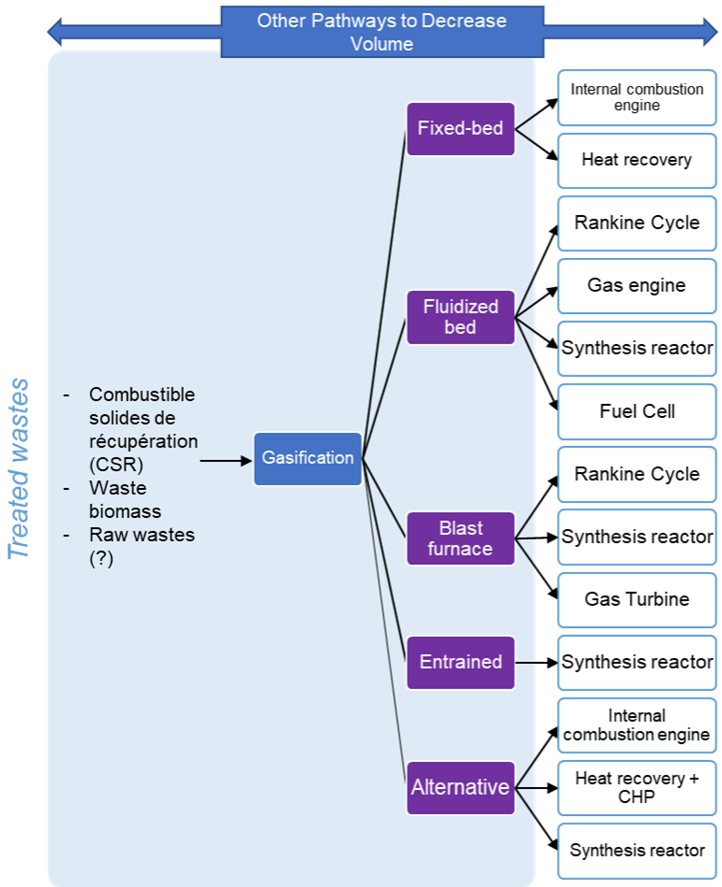
Site Capacity (Type) Input[1,*]	Output[1]	Energy Product(s)	TRL	Installed Units	Developers
(B) 1-5 t/h	0.7-3.5 t/h		8	<10	Terranova (DE), Suncoal (DE), AvaCO2 (DE), HTCycle (DE)
(B) 35 t/h	30 t/h		8	<10	Zilkha (US), Arbaflame (NO)
(B) 0.5-12 t/h	0.45-10 t/h		8	<10	Blackwood (NL), TORBED (UK), Cener-LIST (ES), Torr-Coal (NL)
(B) 3 t/h	Not available		7	Demo plant	Shell (NL) consortium, Renew ELP (UK)
(B & W) 2-10 MW_{th}	1-12 kLt/ h		6	Pilot plant	CDP IFP (FR), Agilix (US), KDV Alphakat (DE)

Table 19 State of the art for the treated wastes treatment in France (I)



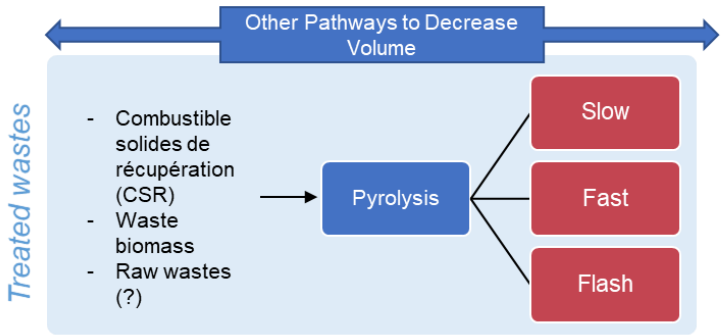
Site Capacity (Type) Input[1,*]	Site Capacity Output[1]	Energy Product(s)	TRL	Installed Units	Developers
(**B**, **W** & **C**) 10-250 MW_{th}	2-60 MW_e; 40-100 MW_{th}		9	>1000	Wellons Group (CA), HZ Inova AG (CH), Misubishi (JP), LLT (FR)
(**B**, **W** & **C**) 50-1000 MW_{th}	5-100 MW_e; 20-300 MW_{th}		9	>200	Valmet (FI), Leroux Lotz (FR), Outotec (FI)
(**B** & **C**) >500 MW_{th}	>200 Mw_e; >200 MW_{th}		9	>200	Siemens (DE), GE (US), Foster Wheeler (UK)
(**B**) 1-30 MW_{th}	5-10 MW_e; 10-20 MW_{th}		8	<50	Dall Energy (DK)
(**B** & **C**) 50-500 MW_{th}	10-100 MW_e; 20-250 MW_{th}		9	>250	Outotec (FI)
(**C**) 1.5 – 30 t/h	1.5 – 30 t/h		9	>50	Ladurner (IT), BMH Tech (FI), WasteKnot (UK), NPT (UK)

Table 20 State of the art for the treated wastes treatment in France (II)



Site Capacity (Type) Input[1,*]	Site Capacity Output[1]	Energy Product(s)	TRL	Installed Units	Developers
(B & C) 1-50 MW_{th}	2-10 MW_e; 10-35 MW_{th}		9	>700	Teri (IN), Ankur (IN), Cogebio (FR), B&W Volund (DK)
(B & C) 0.1 -50 MW_{th}	2-10 MW_e; 0.1-30 MW_{th}		9	>700	Teri (IN), Ankur (IN), Berkes (UR)
(B & C) 10-150 MW_{th}	5-100 MW_{th}		9	<100	Ebara (JP), Amec FW (UK)
(B & C) 10-150 MW_{th}	5-50 MW_{th}		8	~10	Andritz (AT), Eqteq (ES), Leroux Lotz (FR)
(B & C) 10-150 MW_{th}	5-100 MW_{th}		7 8	~10	Enerkem (CA), Ebara (JP), TRI (US)
(B & C) 10-150 MW_{th}	5-90 MW_{th}		?	Data not available	APP (UK)
(B, W, & C) 20-150MW_{th}	<20 MW_e; 10-60 MW_{th}		9	50	JFE (JP), Nippon Steel (JP), Sierra Energy (US)
(W, & C) 20-60 MW_{th}	8-30 MW_{th}		8	~10	Alter NRG (CA)
(W, & C) 20-150 MW_{th}	<15 MW_e; 20-60 MW_{th}		8	~8	IWT (US)
(B, W, & C) <1200 MW_{th}	<300 MW_{th}		6 8	<10	Thyssen Krup (DE), Chemrec (SE)
(B, W, & C) 3-50 MW_{th}	1-25 MW_{th}		9	~15	Inentec (US), Concord Blue (US), GreenE (ES)
(W & C) 5-15 MW_{th}	13-16 MW_{th}		9	~10	Energos (NO)
(B & W) 2-10 MW_{th}	3 MW_{th}		8	~2	Concord Blue (US)

Table 21 State of the art for the treated wastes treatment in France (III)



Site Capacity (Type) Input[1,*]	Output[1]	Energy Product(s)	TRL	Installed Units	Developers
(B) 1-2 MW_{th}	200 kWe (side product)		7	Demo plant	Pacific Pyrolysis (AU), Biochar SI (US, Pyreg (DE)
(B & W) 5-20 MW_{th}	1-2 ton/ h (bio oil) others not available		6 9	>10	Alucha (NL), Pyrum (DE), Ensyn (CA), Handerek (PL), BioCRACK (AU), Green Fuel Nordic (FI)
(B) 25 MW_{th}	2 ton/ h (bio oil) 6 MW_{th}		8	~3	Empyro - BTG (NL), Fortum (FI)

Appendix 7 Sharing Session I and Exchange with Internal R&D Team

Topic : Advanced Combustion/ Staged combustion vs. Classical combustion

The purpose of this sharing session is mainly to determine the main specificities between the new technology by Outotec/ Dall Energy (equipment suppliers of thermochemical conversion unit) against the other conventional gasification and classical combustion technology. Therefore, it is necessary to refer back to the basics of both processes through some diagram of explanations below.

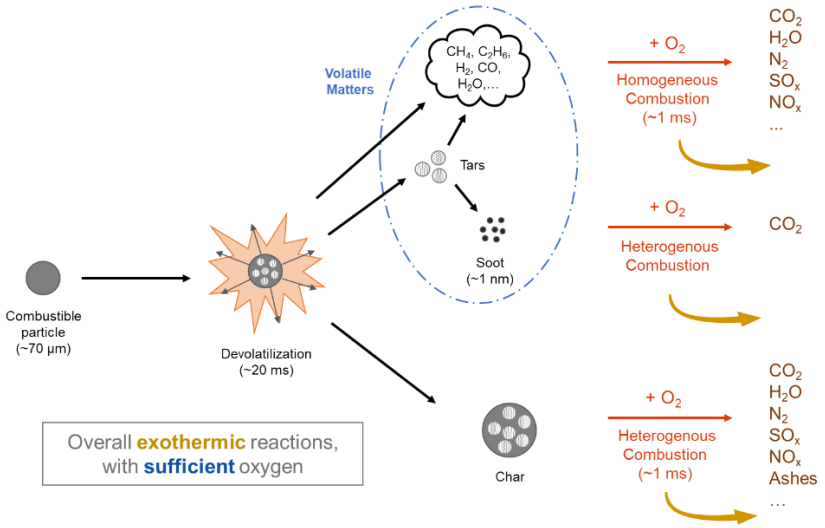


Figure 38 Physical-chemistry phenomenon for combustion process

Main characteristics:

- Excess of oxygen to support complete combustion and produce considerable amount of heat from the fuels (due to exothermic reactions)

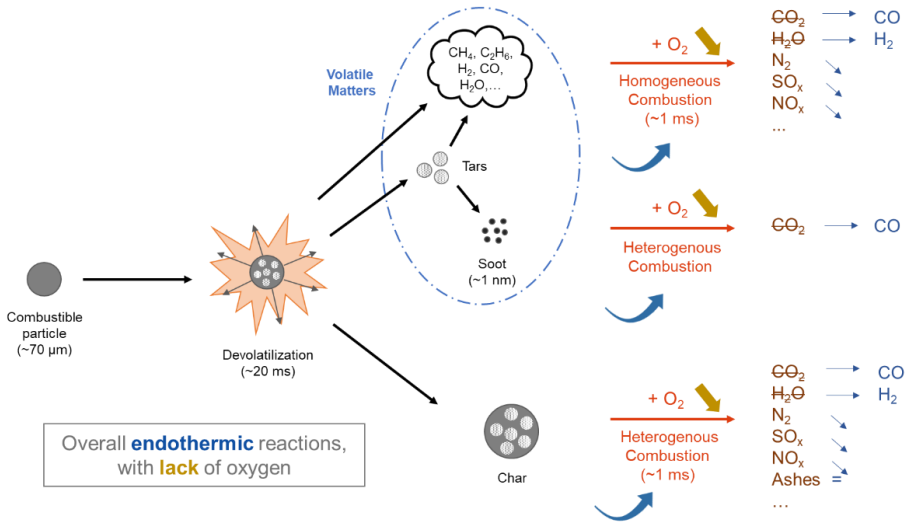


Figure 39 Physical-chemistry phenomenon for gasification process

Main characteristics:

- Excess of oxygen to support complete combustion and require certain amount of heat from the initial reactions to perform set of reactions (due to endothermic reactions)
- Synthetic gas (syngas) consisting dominantly of CO and H_2 is the intended product

The notion of advanced/ staged combustion becomes an actual implementation when one of the suppliers manufactures such technology in their portfolio (see below).

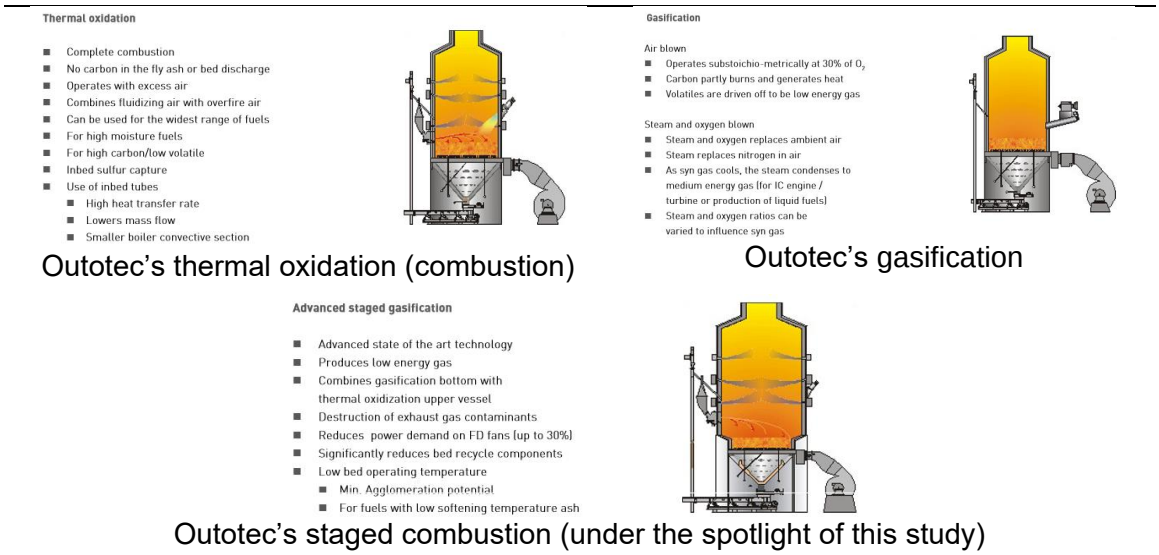


Figure 40 Comparison of Outotec's furnaces portfolio [34]

Unraveling to a wider extent, thus the thermochemical reactions can be simply classified into four different types as displayed (complemented with its block diagram that emphasizes the differences) in Figure 41.

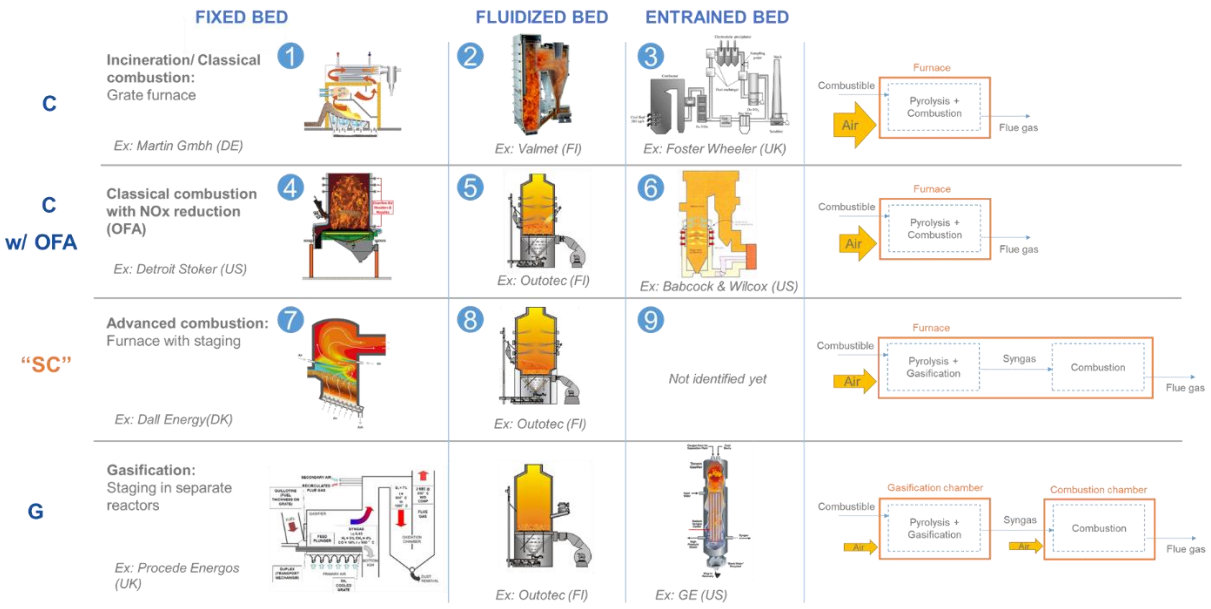


Figure 41 Comparison between C (combustion), C w/ OFA (combustion with overfire air), SC (staged combustion), and G (gasification)

The essences of discussion are summarized in the following points.

Participants : Sébastien, Raka, Chloé, Lynda, Myriam

Important topics:

- Are the concepts from Dall Energy and Outotec to be considered different from classical combustion (with OFA)? ✓

Responses:

Yes, indeed. Dall and Outotec have clear separations of thermochemical reactions spatially inside a reactor, with only limited amount of oxygen at the bottom (gasification) and sufficient oxygen at the top (to ensure complete combustion). While on the contrary, classical combustion (w. and without OFA) inject a lot of excess air throughout the furnace which drives the heterogeneous combustion to occur. As a consequence, there is no gasification at all due to quick reaction mechanisms after devolatilization (combustion is occurring around the particles)

Refer to Slide 3 and Slide 8 *of Air Staging v2 Discussion*

- As an illustration, how much air should be injected to classical combustion (w./ without OFA) and Dall/ Outotec furnaces? ✓

Responses:

- **Classical combustion, no OFA** : Excess air for burning all the solid fuels (complete combustion)
- **Classical combustion with OFA** : Excess air, but divided into more than one place with the aim to reduce Nox (lower temperature, preventing NOx production from air/ fuel)

  Disadvantages: higher combustion temperature (fouling, NOx) and fly ashes being carried to the flue gas by the air flow.

  Too much excess air has some disadvantages: 1) lowering the flue gas temperature due to more gases flow (higher heat capacity) 2) higher fan power to transport flue gas and 3) heat losses due to the presence of induced air which does not react (instead absorbing heat from combustion) Source: Link texbook

  Example: grate furnace which can have multiple positions of air injection
- **New concepts (Dall and Outotec):** Potentially less air, initial injection of air to drive gasification process while the 2nd etc. to have a gas combustion

  Advantages: less diluted flue gas at the output flow (decreasing the nitrogen mostly), thus allowing more energy dense flue gas to be recovered energetically in the downstream

  Refer to Slide 8 of Air Staging v2 Discussion

Appendix 8 Sharing Session II and Exchange with Tiru

Topic : Information Exchange with Barthélémy FOURMENT (Head of International Development at TIRU La Défense) about CSR knowledge in general
People involved : Sébastien, Barthélémy, Raka
Place/ Time : Tiru La Défense at 10 AM

- UK has a staggering number of RDF export to Europe (3 million ton/ year since 2016) – more detailed figures in this source: https://www.letsrecycle.com/news/latest-news/rdf-exports-three-million-tonnes-2016/

However, most of these exports are dominated by low quality RDF in which do not meet the qualification for cement kiln industries. Cement kiln requires high quality RDF which is represented by its low level of contaminants and less inert contents in the RDF (no metals, rubbles, etc.).

According to the interlocutor, this is a way to gain margin from a low-quality RDF (less cost compared to landfilling)

- Landfill cost in the UK = 105 Eur/ ton

Rather than landfilling, which is expensive, it is better to export low quality RDF (right at the threshold of 75% RDF quality) with the cost of 40 Eur/ ton + around 40 Eur/ ton of shipping, equivalent to around 80 Eur/ ton – it offers ~20-25 Eur/ ton margin to the waste producers.

- What is the price of CSR for cement kilns? 20 Eur/ ton
- RDF from UK is exported in a plastic wrapped bale to other European countries. UK can easily save delivery cost since UK overall imports products from Europe hence these empty trucks/ shipments can transport RDF when they return back.
- France has lesser demand of cement for its construction purpose, due to tough competitiveness in the market. Besides, cement industry has one of the most fragile business models (always striving for the best way to cut expense).
- In addition to that, demand of cement follows a seasonal trend while RDF generation remains flat all along the year (as illustrated below) – both do not match, and it makes selling of CSR sometimes limited.

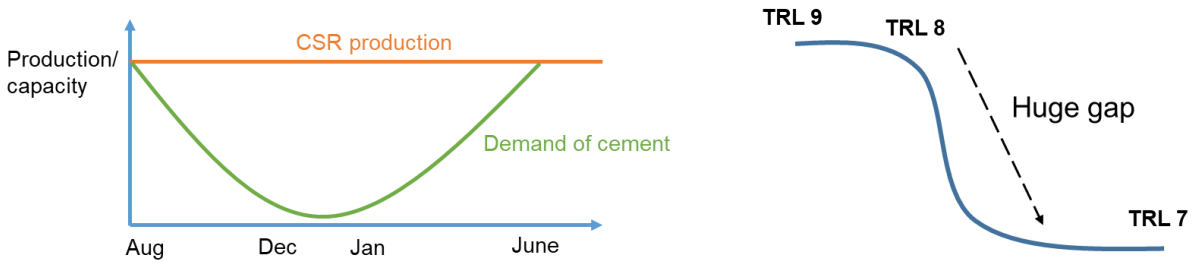


Figure 42 Illustration of CSR demand vs. Cement industry (left) and TRL chasm (right)

- TRL 7 according to Tiru's perspective is a risky business (unproven and lack of commercial operation). Even TRL 8-9 should be meticulously evaluated before being implemented by Tiru. 0 commercial unit is a big rejection for their business.
- High calorific value of RDF → there is a trend to shift towards advanced moving grates as opposed to fluidized bed furnace
- Why? Because there have been many issues with the fluidized bed technology in France (bad operation, issues, maintenance).
- The older grate furnace has longer slope than the recent generation as they were designed to treat low quality MSW (a lot of moisture with low LHV). Therefore, the grate has its own sequence to evaporate the moisture at the upper level before being burned at the lower part (hence the placement of heat recovery unit will change accordingly). In overall, it can reduce the cost of fabricating grate furnace (more compact) than the older ones.

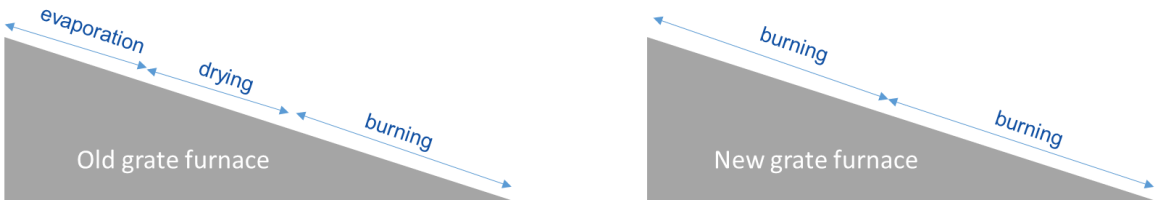


Figure 43 Comparison of old grate furnace (longer grate) and new grate furnace (shorter)

- In comparison to France's black bin, UK has higher calorific value (2400 – 2600 kcal/ kg or 10 – 11 MJ/ kg) vs France's (1600 – 1800 kcal/ kg or 6.7 – 7.5 M/ kg)

The reason: British people have a tendency to purchase 'cooked' food from the supermarket which contains plastics. It is reflected in their household wastes properties as it has more plastic than fermentable matters/ bio wastes.

- In France, it is allowed to transport wastes from one department/ region to another but depending on the rationality of transport cost → 50-60 km is considered as a relevant distance before it becomes too costly
- From Barthélémy's point of view, Japanese technologies for waste to energy valorization are among the most reliable compared to other suppliers. However, amidst its benefits and superiority there should be a clear justification to its weaknesses (for instance JFE gasifying and melting system):
  a) Higher CAPEX and OPEX
  b) Less energy production due to high operating temperature (up to 2000°C)

  Despite these drawbacks, they claim to have the cleanest flue gas emitted from the stack (positive point) since dioxin can be easily avoided when temperature reaches > 850°C in the furnace. Some researchers have reported that its formation degraded significantly at the temperature above 1000°C (Nagata, 1992) Link

  JFE has two main headquarters (one in Japan and another in Germany European market by forming partnership with local company named Baumgarte Gmbh) → Sébastien has taken a business card for its representative in Europe
- At the bottom line, some lessons are learned:

a) Household and economic activities wastes management are driven by regulation and laws (to obtain benefits, forbidden acts, rules, etc.)
b) Waste management requires mature technologies
c) For an advanced technologies to be deployed → incentives for green energy such as ROC (Renewable Obligation Certificates) and Cfd (Contract for difference) in the UK
d) Specific gate fees are interesting but in the UK there is no guarantee to waste availability in the long term

Refer to Slide TIRU La Defense

Appendix 9 The Process of Filtering Technologies (pre-selection part of the studies)

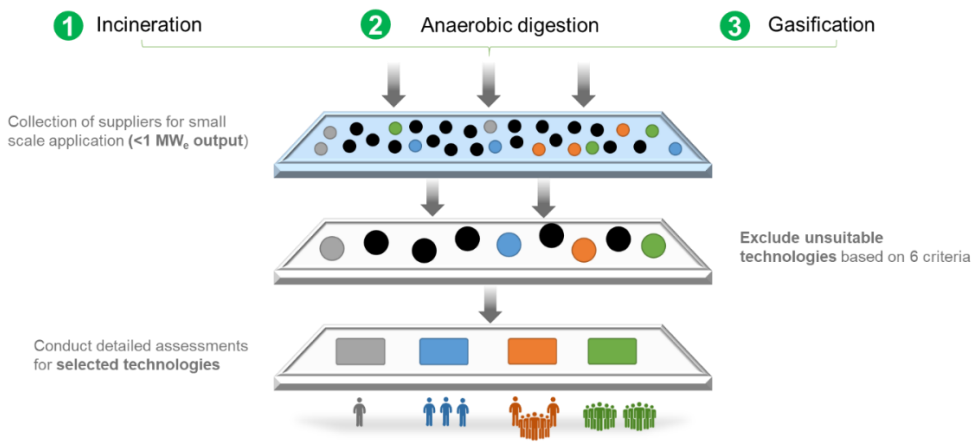


Figure 44 Process of filtering technologies for SEI case studies

Colour identifier (distinction of cases):

20 inh.	100 inh.	1000 inh.	100 000 inh.

- Medium scale technologies for MSW Residual wastes valorization (< 40 MWth)

AMEC FW as the supplier of various furnaces has developed a matrix for determining suitable technologies for thermochemical conversion, as shown in Figure 45.

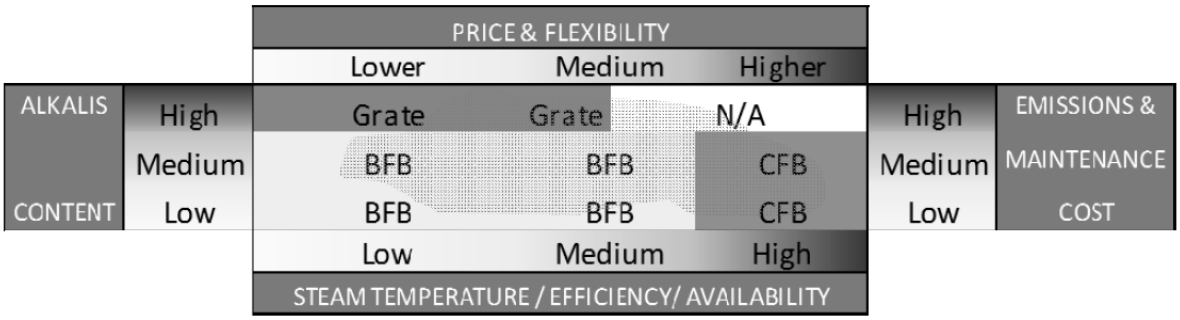


Figure 45 Technology selection based on four criteria by Foster Wheeler [35]

Color identifier (distinction of cases):

Black bin direct incineration	CSR combustion	CSR gasification

Table 22 Technology screening and selection for residual wastes energy valorization

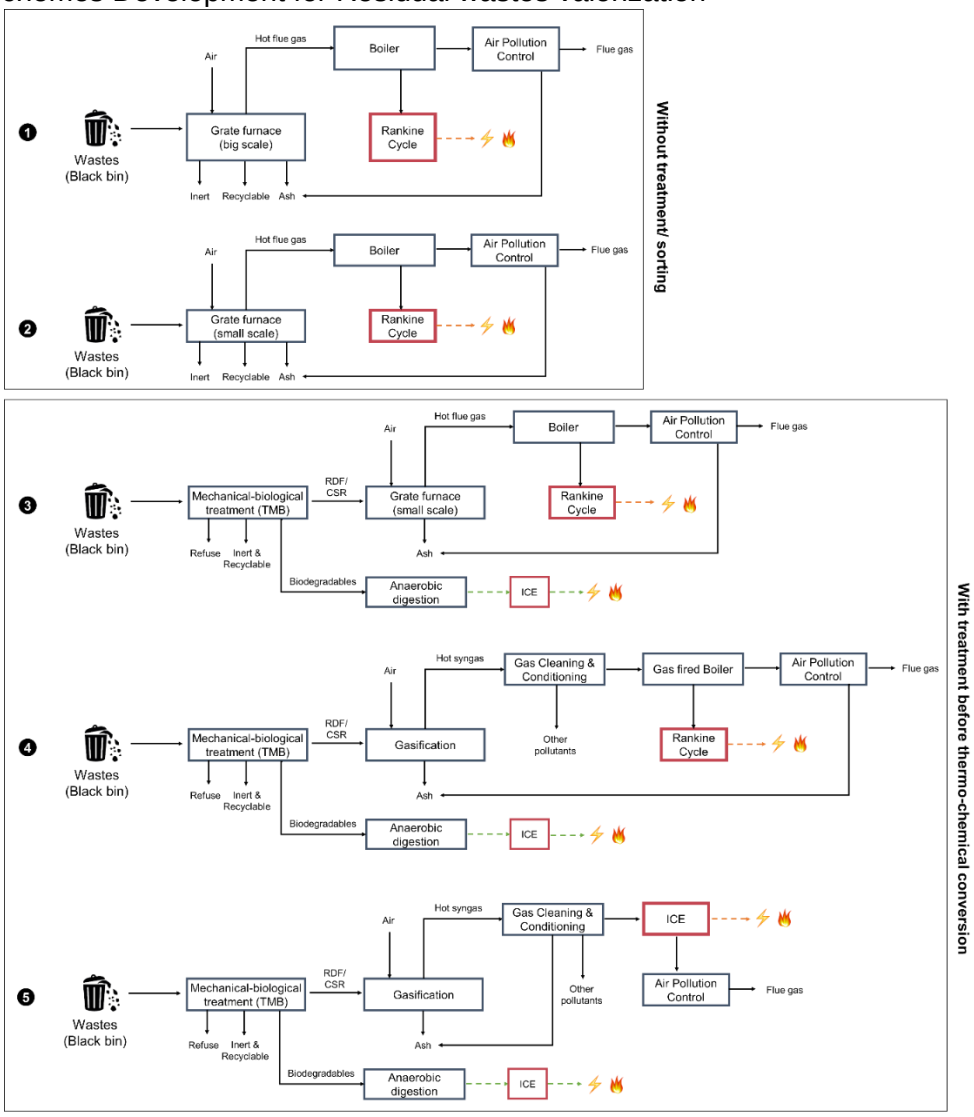
Supplier	Country	Technology	Input	Capacity	Products	Application/ Context	Installed Units	TRL	Reason of exclusion
JFE	Japan	Horizontal Stoker	MSW	4 – 20 t/h	Heat and Electricity	Waste disposal	~120	9	Retained
Babcock & Wilcox	Denmark	Dyna grate, Volund grate	MSW	4 – 55 t/h	Heat and Electricity	Municipal solid waste treatment	50	9	Retained
Martin Gmbh	Germany	Reverse reciprocating	MSW	50 t/h	Heat and Electricity	Municipal solid waste treatment	565	9	Retained
Hitachi Zosen	Switzerland	Forward acting	MSW	4 – 44 t/h	Heat and Electricity	Municipal solid waste treatment	500	9	Retained
Martin Gmbh	Germany	Reverse reciprocating	MSW, CSR	50 t/h	Heat and Electricity	RDF processing	565	9	Retained
Foster Wheeler	UK	BFB	CSR		Heat and Electricity	Medium scale waste conversion	136	9	Retained
LLT	France	BFB and CFB	CSR	3 – 15 t/h	Heat and Electricity	Medium scale waste conversion	~200	9	Retained
Outotec	Finland	BFB	CSR	5-60 t/h	Heat and Electricity	Medium scale waste conversion	~110	9	Retained
Nippon Steel	Japan	Blast furnace	Waste/ CSR	10-60 MWth, <20 Mwe	Heat and Electricity	Medium application	28	9	Retained
JFE	Japan	Blast furnace	Waste/ CSR	10-60 MWth, <20 Mwe	Heat and Electricity	Medium application	40	9	Retained
Kobelco	Japan	Fluided bed + combustion chamber	Waste/ CSR	5-40 MWth	Heat and/ Electricity	Medium application	30	9	Retained
Ebara	Japan	Fluided bed + combustion chamber	Waste/ CSR	<60 Mwth	Heat and/ Electricity	Medium big application	24	9	Retained
Valmet	Finland	Fluidized bed	Biomass/ Waste	20-140 MWth	Heat and/ Electricity	Medium big application	170	9	Retained
Mitsubishi	Japan	Reverse acting	MSW	1 – 50 t/h	Heat and Electricity	Municipal solid waste treatment	~250	9	Can be retained
Kawasaki	Japan	Horizontal water cooled	MSW	~20 t/h	Heat and Electricity	Municipal solid waste treatment	300	9	Can be retained
Fisia Babcock	Germany	Forward acting	MSW	40 t/h	Heat and Electricity	Municipal solid waste treatment	60	9	Can be retained
Keppel Seghers	Singapore	Dyna grate, Volund grate	MSW	1.5 – 30 t/h	Heat and Electricity		60	9	Can be retained
LLT	France	Rotograte	MSW	9 – 20 t/h	Heat and Electricity	Incineration grate	200	9	Can be retained

Ebara	Japan	TIF Fluidized Bed	CSR	20 t/h	Heat and Electricity	Waste to energy plant	90	9	Can be retained
Metso Power/ Valmet	Finland	BFB – Hybex	CSR	2 – 80 t/h	Heat and Electricity	Medium scale waste conversion	170	9	Retained
Metso Power/ Valmet	Finland	CFB – Cymic	CSR	10 – 200 t/h	Heat and Electricity	Medium-big scale waste conversion	70	9	Over capacity
Foster Wheeler	UK	CFB	CSR		Heat and Electricity	Medium-big scale waste conversion	>100	9	Over capacity
GE(formerly Alstom)	USA	CFB	CSR		Heat and Electricity	Medium-big scale waste conversion	~50	9	Over capacity
Steinmuller	Germany	CFB	CSR	5 – 30 t/h	Heat and Electricity	Medium-big scale waste conversion	~30	9	Over capacity
TBU Stubenvol	Germany	BFB	CSR	1 – 20 t/h	Heat and Electricity	Medium scale waste conversion	~20	9	less installed units
Teri	India	Fixed bed	Biomass	10 - 100 kWe	Electricity	Rural application	>600	9	Too small
Spanner Re²	Germany	Fixed bed	Biomass	30 - 45 kWe	Heat and Electricity	Small application	~500	9	Too small
Ankur	India	Fixed bed	Biomass/ CSR/ Waste	5-500 kWe	Electricity	Rural application	>100	9	Too small
Berkes	Uruguay	Fixed bed	Biomass/ Waste	2.1 Mwe/ 9 MWth	Heat and Electricity	Small industrial	80	9	Too small
All Power Labs	US	Fixed bed	Biomass	15-150 kWe	Electricity	Small application	~500	9	Too small
PRME	US	Fixed bed	Biomass/ Waste	4 - 35 MWth	Heat	Medium application	22	9	Only heat production
ESPE	Italy	Fixed bed	Biomass	49 kWe, 110 kWth	Heat and Electricity	Small application	~15	9	Too small
Urbas	Austria	Fixed bed	Biomass	70-300 kWe, 150 - 620 kWth	Heat and Electricity	Small application	14	9	Too small
Volter	Finland	Fixed bed	Biomass	40 kWe	Heat and Electricity	Small application	13	9	Too small
Bioneer	Finland	Fixed bed	Biomass	4-5 MWth	Heat	Medium application	9	8	Only heat production
B&W Vølund	Denmark	Fixed bed	Biomass	1-5 Mwe (<20 MWth)	Heat and Electricity	Medium application	>5	8	Too small
Gasek	Finland	Fixed bed	Biomass	500 kWe	Electricity	Small application	3	8	Too small
Xylowatt AB	Belgium	Fixed bed	Biomass/ Waste	1-4 MWth, 0.3-1 Mwe	Heat and Electricity	Medium application	3	8	Too small
Cogébio	France	Fixed bed	Biomass	0.3 - 1 Mwe, 1.5-4 MWth	Heat and Electricity	Medium application	2	8	Too small
Nexterra	Canada	Fixed bed	Biomass/ Waste	2-15 Mwe, 2-40 MWth	Heat and Electricity	Medium application	2	8	less installed units
Xylogas	Austria	Fixed bed	Biomass	400 - 900 kWe	Electricity	Small application	1	8	less installed units
Enerxyl	France	Fixed bed	Biomass	300-900 kWe	Electricity	Small application	0	6 or 7	not mature
Mini Green Power	France	Fixed bed	Biomass	0.5-2.5 Mwe	Electricity	Medium application	0	6 or 7	not mature
IWT	US	Blast furnace	Waste/ CSR	20-60 MWth, <15 Mwe	Heat and Electricity	Medium application	15	9	Can be retained
Alter NRG / WPC	US	Blast furnace	Waste/ CSR	8-30 MWth	Heat	Medium application	8	8	Only heat production
Sierra Energy	US	Blast furnace	Waste/ CSR	1 Mwe	Heat and/ Electricity	Small medium application	1	8	Too small
Burkhardt	Germany	Fluidized bed	Biomass	200-550 kWth	Heat	Small application	140	9	Too small
AMEC Foster Wheeler	UK	Fluidized bed	Biomass/ Waste	~40 MWth	Heat and/ Electricity	Medium application	9	8	less installed units
Outotec	Finland	fluidized bed bubbling Gasification	Biomass/ Waste/ CSR	20-90 MWth	Heat and/ Electricity	Medium big application	110	9	advanced combustion is preferred
Andritz	Austria	Fluidized bed	Biomass	10-150 MWth	Heat and/ Electricity	Medium big application	6	8	less installed units

Eqtec	Spain	Fluidized bed	Biomass/ Waste	3-20 MWth	Heat and/ Electricity	Medium application	11	9	less installed units
Repotec	Austria	Fluidized bed	Biomass	8-14 MWth, 2-5 Mwe	Heat and/ Electricity	Medium application	4	8	less installed units
Necer	Spain	Fluidized bed	Biomass/ Waste	1-16 MWth	Heat	Medium application	3	8	less installed units
Ortner Anlagenbau	Austria	Fluidized bed	Biomass	8-15 MWth, 3 Mwe	Heat and/ Electricity	Medium application	2	8	less installed units, inappropriate fuel
Enerkem	Canada	Fluidized bed	Waste/ CSR	60-100 MWth	Chemical synthesis	Chemical production of methanol	2	8	Producing chemicals only
TPS	Sweden	Fluidized bed	Waste/ CSR	15 MWth	Heat	Medium application	2	8	less installed units
Leroux & Lotz	France	Fluidized bed	Biomass/ Waste	12 MWth	Heat and/ Electricity	Medium application	2	8	Slightly less than desired capacity
TRI	US	Fluidized bed	Waste/ CSR	50-100 MWth	Jet fuel production	Medium big application	1	8	too big, unwanted products
Royal Dahlman	Netherlands	Fluidized bed	Biomass/ Waste	?	Heat and/ Electricity	-	0	6, 7	less mature
Inerco	Spain	Fluidized bed	Biomass/ Waste	?	Synthesis of gasoline	Synthesis of fuel	0	6, 7	less mature

**shaded cells are the pre-selected technologies*

- Schemes Development for Residual wastes valorization



**TMB from ZAK supplier*

Figure 46 Finding the Selected Schemes for Further Assessments (Residual wastes valorization in Metropole)

- Small scale technologies for SEI study case (< 1 MWe)

Table 23 Technology screening and selection for SEI case studies

Supplier	Country	Technology	Input	Capacity	Products	Application/ Context	Installed Units	TRL	Reason of exclusion
HomeBiogas	Israel	AD	Food wastes	12 Liter of food organic waste/ day or 36 liter of animal manure/ day	Biogas for cooking, fertilizer	Home scale	>100	9	Retained
Flexi Biogas	Kenya	AD	Biowastes	8-18 people capacity	Gas engine for electricity	Modular for rural application (no complex installation)	>50	9	Retained
Puxin	China	AD	Organic wastes	Max 25 kg/ day	Biogas stove	Domestic biogas plant	>100	9	Retained
Synod Bioscience	India	AD	Household waste (organic)	3-30 kg/ day	Biogas stove	Portable biogas plant	>50	9	Retained
Biogas SA	South Africa	AD	Organic wastes	Up to 100 kg/ day	Biogas for cooking and electricity	rural and domestic biogas solutions	>120	9	Retained
BioBowser	Australia	AD	Biowastes	50 - 20 000 kg/ day	Gas engine for heat/ electricity	Small medium application	>50	9	Retained
Novatech Gmbh	Germany	AD	Biowastes	up to 100 kW	Electricity	Small scale biogas plant	6	8	low TRL
Ankur	India	Fixed bed gasification	Biomass/ Waste	18-1000 kWe	Electricity (gas engine)	Rural area energy generation	100	9	Retained
Biolectric	Belgium	AD	Animal manure, organic wastes	11 - 44 kWe	Biogas for CHP	Micro small scale digester	>80	9	Retained
Enogia	France	ORC	Power cycle	5-100 kWe	Electricity through expander	Modular ORC concept	>50	9	Retained
BTS Biogas	Italy	AD	Biowastes	25kw - 1.5 MW	Electricity	Small medium application	~100	9	Retained
Bio4Gas	France	AD	Organic wastes	50-300 kW	Electricity	Small medium application	16	9	Retained
Concord Blue	US	Other type gasification	Waste	250 kWe - 6 Mwe	Electricity (gas engine)	Compact power production	5	8	Retained
Xylowatt	Belgium	Fixed bed gasification	Biomass/ Waste	200-1000 kWe	Electricity (gas engine)	Small medium application	3	8	Retained
				500-1200 kWth	CHP				
BioFERMenergy	US	AD	Multiple organic wastes	2000 - 6000 ton organics/ year	Biogas for CHP	Small scale digester	450	9	Retained
Turboden	Italy	ORC	Power cycle	Smallest 0.5 Mwe	Electricity through expander	Medium scale ORC concept	>300	9	Retained
Welltec Biopower	UK	AD	Biowastes	Smallest 200 kW	Electricity	Small medium application	300	9	Retained
SimGas	Netherlands	AD	Organic wastes	2 - 20m3	Biogas for cooking	Small scale digester	~600	9	Can be retained for cooking purpose
Durr Cyplan	Germany	ORC	Power cycle	smallest 40 kWth	Heat and electricity	Electricity generation from waste heat	14	9	Can be retained
Enertime	France	ORC	Power cycle	Smallest 100 - 5000 kWe	Heat and electricity	Electricity generation from waste heat	11	9	Can be retained
Ukatilai	Lithuania	Waste combustion	wood wastes, wood chips, coal, wastes	50 - 1000 kW	Hot flue gas	Burning/ combustion of wastes for disposal	>100	9	To be coupled with ORC
Herz Boiler	Austria	Combustion	wood wastes, wood	10 - 10000 kW	Hot flue gas, hot water (if necessary)	Burning/ combustion of wastes for disposal	>200	9	To be coupled with ORC

			chips, coal, wastes						
Inciner8	UK	Combustion	General wastes, incl. MSW	5 kW - 2500 kW	Hot flue gas, hot water (if necessary)	Burning/ combustion of wastes for disposal	>100	9	To be coupled with ORC
Teri	India	Fixed bed gasification	Biomass	10-100 kWe	Electricity (gas engine)	Rural area energy generation	600	9	Inappropriate fuel
					Heat				
Spanner Re2	Germany	Fixed bed gasification	Biomass	30-45 kWe	Electricity (gas engine)	collectivity, forestry, agricultural residues	500	9	Inappropriate fuel
				80-120 kWth	CHP				
Mothermik	Germany	Fixed bed gasification	Biomass	250 kWe	Electricity (gas engine)	Rural area energy generation	100	9	Inappropriate fuel
All Power Labs	All PowerLabs	Fixed bed gasification	Biomass	15-150 kWe	Electricity (gas engine)	Rural area energy generation	500	9	Inappropriate fuel
Holzenergie Wegscheid	Germany	Fixed bed gasification	Biomass	65-125 kWe	Electricity (gas engine)	Rural area energy generation	34	9	Inappropriate fuel
				110-250 kWth	CHP				
ESPE	Italy	Fixed bed gasification	Biomass	49 kWe	Electricity (gas engine)	Compact power production	15	9	Inappropriate fuel
				110 kWth	CHP				
Urbas	Austria	Fixed bed gasification	Biomass	70-300 kWe	Electricity (gas engine)	Small application	14	9	Inappropriate fuel
				150-620 kWth	CHP				
Volter	Finland	Fixed bed gasification	Biomass	40 kWe	Electricity (gas engine)	Small application	13	9	Inappropriate fuel
					CHP				
Gasek	Finland	Fixed bed gasification	Biomass	500 kWe	Electricity (gas engine)	Small medium application	3	8	Inappropriate fuel
					CHP				
Cogebio	France	Fixed bed gasification	Biomass	500 kWe	Electricity (gas engine)	Small medium application	2	8	Inappropriate fuel
				1200 kWth	CHP				
Xylogas	Austria	Fixed bed gasification	Biomass	400-900 kWe	Electricity (gas engine)	Small medium application	1	8	Inappropriate fuel
					CHP				
Enerxyl	France	Fixed bed gasification	Biomass	300-900 kWe	Electricity (gas engine)	Small medium application	0	6 to 7	Inappropriate fuel
					CHP				
Burkhardt	Germany	Fluidized bed gasification	Biomass	200-550 kWth	Electricity (gas engine)	Small medium application	140	9	Inappropriate fuel
					CHP				
Recor WtE solutions	South Africa	Pyrolysis	Municipal wastes	>100 kW	Pyrolysis gas to gas engines (heat, electricity)	Small to medium waste valorization	?	?	Fuel moisture limit
Desi Power	India	Gasifier	Biomass	20 - 135 kg/h	Syngas for CHP	Small to medium waste valorization	16	9	Inappropriate fuel
BETEL Gasifier	India	Gasifier	Biomass	19 - 1200 kWe	Electricity (gas engine)	Small to medium waste valorization	32	9	Inappropriate fuel
Biogen	Dominican Republic	Gasifier	Biomass	smallest 250 KW	Syngas for CHP	Small to medium waste valorization	4	8	Inappropriate fuel
Envitec biogas	France	AD	Agrowastes	smallest 200 - 800 kWe	Biogas for CHP	Small to medium anaerobic digestion on site	>350	9	Suitable for agrowastes
Ibert Biogas	South Africa	AD	Waste	<30 kW	Biogas for CHP	DIY digester	7	8	low TRL
Cogent Energy Systems	Canada	Gasifier	All wastes	Max 1 Mwe	Syngas for electricity, heat, chemicals	medium scale gasifier	0	7	not mature enough
PowerHouse Energy	UK	Gasifier	All wastes	5 ton/ day input	Multiple uses of syngas	Modular gasification	0	7	not mature enough
EcoFys Plastic Bag Digester	Netherlands	AD	Biowastes	Very small, TRL 7	Biogas for cooking	Home scale biogas system	0	7	Project discontinued

**shaded cells are the pre-selected technologies*

- Schemes Development for SEI Case Study

Some possible scenarios based on the available data are proposed in Figure 47.

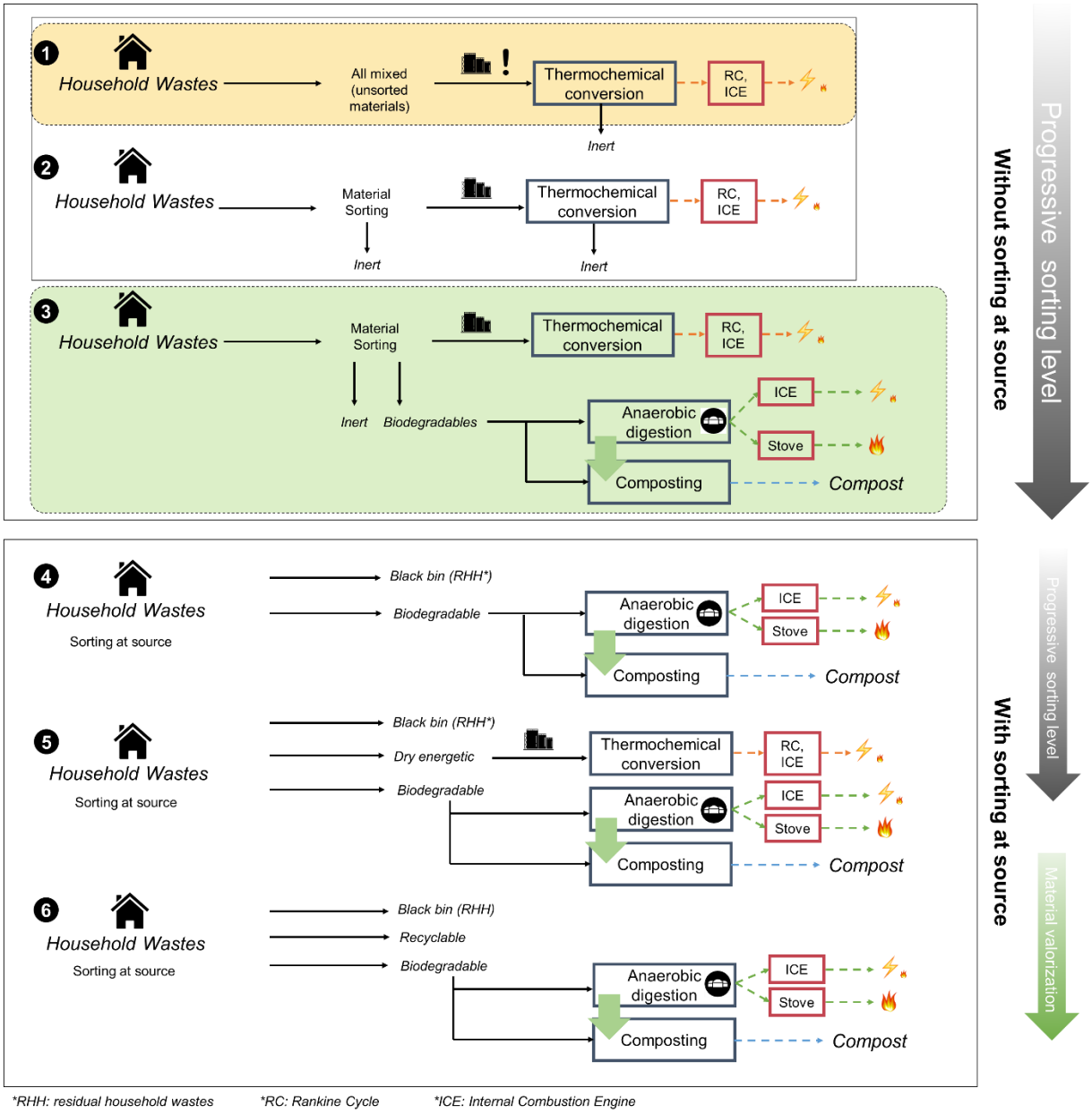


Figure 47 Finding the Selected Schemes for Further Assessments (SEI)

- Anaerobic Digestion Benchmarking for SEI Case Study

Table 24 Techno-economic Assessments of AD Process (100 and 10 000 inhabitants size)

Case	Developer	Application	Acceptable feed input	Energy yield (Mweh/ ton of input)	Biodigester CAPEX (EUR/ kWe)	Treatment cost (EUR/ ton of input)	Complexity of operation
100 inh.	Biobowser	Electricity	Animal manures, effluent, abattoir residues or food waste	0.15	20 417 €	166 €	-
	Biogas SA	Electricity	manure of: • grown pigs • cattle • chickens	0.40	19 798 €	183 €	+

			and vegetable waste				
	Novatech Gmbh	Electricity	liquid pig manure, corn silage, grass silage, food wastes	0.38	16 162 €	143 €	+
1000 inh.	Biolectric	Electricity	Cow manure	0.58	16 102 €	121 €	+
	BTS Biogas	Electricity	Various liquid and solid manure (farm)	0.51	13 553 €	96 €	+
	Bio4gas	Electricity	Cereal residues, whey, green residues, food wastes, slurry, manure	0.57	10 229 €	136 €	+

Based on this case, two suppliers of anaerobic digestion technologies are selected (highlighted by the yellow shade). The data for CAPEX and treatment cost have also been compared with the cost analysis from several studies such as IRENA [24] and related journal to techno-economic study of AD [40] [41]

- Treatment Cost of each scheme and case study for SEI

Table 25 Exhaustive Treatment Cost Data for All Cases with Different Schemes

Case	Scheme	CAPEX Combustor	CAPEX RC	CAPEX Gasifier + ICE syngas	CAPEX Biodigester + ICE biogas	Fixed O&M	Variable O&M	Revenue from electricity	Treatment cost (total)
20	Reference	-	-	-	-	10 €	-	-	10 €
	Scheme 1*	-	-	-	-	-	-	-	-
	Scheme 1	-	-	-	-	-	-	-	-
	Scheme 3	-	-	-	-	-	-	-	-
100	Reference	-	-	-	-	10 €	-	-	10 €
	Scheme 1*	105 €	-	-	-	25 €	17 €	-	147 €
	Scheme 1	105 €	118 €		-	46 €	31 €	- 33 €	266 €
	Scheme 3	-	-	-	-	-	-	-	-
1000	Reference	-	-		-	10 €	-	-	10 €
	Scheme 1*	73 €	-	-	-	16 €	11 €	-	99 €
	Scheme 1	73 €	78 €	-	-	27 €	18 €	- 37 €	158 €
	Scheme 3	-	-	152 €	49 €	49 €	8 €	- 42 €	217 €
10000	Reference	-	-	-	-	10 €	-	-	10 €
	Scheme 1*	51 €	-	-	-	11 €	7 €	-	69 €
	Scheme 1	51 €	65 €		-	19 €	13 €	- 42 €	106 €
	Scheme 3	-	-	107 €	42 €	32 €	16 €	- 61 €	135 €

Appendix 10 Mass and Energy Balances for Filtered Technologies

All the technical performance and data which are used for the calculation mainly gathered from supplier's websites, unless stated otherwise.

- Case studies of residual wastes energy valorization
  a) Scheme 1: Large scale incineration (100 MWth input)
  b) Scheme 2: Medium scale incineration (50 MWth input)
  c) Scheme 3: Mechanical-biological treatment (TMB) + combustion and rankine cycle (RC)
  d) Scheme 4: Mechanical-biological treatment (TMB) + gasification and rankine cycle (RC)
  e) Scheme 5: Mechanical-biological treatment (TMB) + gasification and internal combustion engine (ICE)

- Case Studies of SEI
  a) Scheme 0 (raw household open burning)
  b) Scheme 1 (raw household wastes combustion)
  c) Scheme 1a (raw household wastes combustion without energy valorization)
  d) Scheme 3 (light sorting, anaerobic digestion, and gasification)

- The complete sources of calculation are presented in: https://epolytechnique-my.sharepoint.com/:x:/g/personal/lugas-raka_adrianto_polytechnique_edu/Ee3dW-AZtVpEkjq5EDYaLNkBw0BhdvEQ6XcWTtE1BdVCgw?e=WSK3jC

Appendix 11 Air Pollution Control in Municipal Solid Waste Combustion/ Incineration

Municipal solid waste (MSW) faces a strong opposition in terms of social acceptance, even though it offers the solution to reduce the considerable amount of wastes. This appendix gives an overview of the MSW pollution problems during incineration/ combustion and devices used to prevent leakage of emission to the environment. The main focus is on the key air pollutants, such as dioxins and furans. At the end, the impact of emission on health risks is also briefly considered. Main resources for the creation of this appendix are BREF report [33], Dioxin comprehensive review journal by McKay [37] and Intechopen air pollution control Chapter 16 summary [34].

The general block chart of MSW conversion (1-ton mass basis) into energy can be clearly shown in Figure 48.

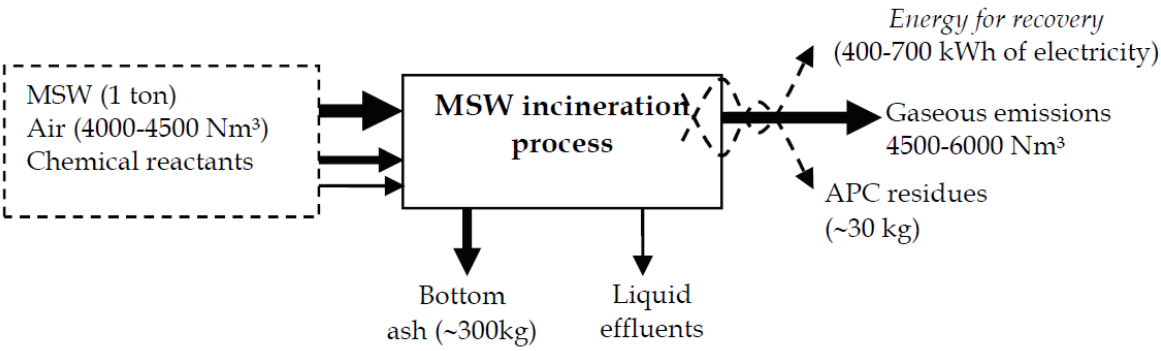


Figure 48 Main inputs and outputs of MSW incinerators [33]

The gas mixture leaving the incineration furnace has three main types of components that have to be removed to the possible extent before the exit at the stack:

- **Fly ash** which is composed by particles pneumatically transported by the gaseous flow;
- **Acids and acids precursors**, such as Sulphur dioxide, nitrogen oxides, hydrochloric acid;
- **Dioxins and analogues** that are compounds formed by radical recombination with structures such as polychloro dibenzodioxins and the respective furan analogues.

This collection of pollutants poses some problems as there is a strict limit of concentration before being emitted at the exhaust (shown in Table 26.

Table 26 Required efficiency to remove pollutants from MSW incineration

Pollutant	Concentration in raw gas from boiler (mg/ Nm^3)	Max admissible at exhaust (mg/ Nm^3)	Removal efficiency required (%)
Fly ash	1500 - 2000	10	99.9
HCl	300 - 2000	10	>99
SO_2	200 - 1000	5	99.5
NO_x	200 - 500	70	86
HF	2 - 25	1	96
Hg	0.2 – 0.8	0.01	99
Cd + other metals	2 – 15	0.05	>99.5
Dioxins, Furans	0.5 – 5	0.1	98

A large number of unit operations based on primary separation processes can be used for the gas cleaning of the flue gas generated in waste incineration systems. Table 27 for each type of flue gas pollutant, a combination of unit operations is indicated with the respective typical range of reduction.

Table 27 Gas cleaning processes and typical range of emission reduction by combination of unit operations

Pollutant	Process Steps	Reduction (%)
SO_x	Wet scrubber or dry multicyclone	50 - 90
HCl, HF	Wet scrubber or semi-dry	75 – 95
NO_x	Selective catalytic reduction/ non-catalytic	10 – 60
Heavy metals	Dry scrubber + electrostatic precipitator	70 – 95
Fly ash	Electrostatic precipitator + fabric hose filter	95 – 99.9
Dioxins & Furans	Activated carbon + fabric hose filter	50 – 99.9

The following subchapters will discuss briefly about the nature of each pollutant, how it is formed, and the potential risk of leaking it to the environment.

A. SO_x

Sulphur dioxide is a reaction product of S-compounds contained in the waste with oxygen and its concentration in the flue-gas is proportional to the amount present in the waste:

$$C_xH_yS + w\ O_2 \rightarrow CO_2 + H_2O + SO_2$$

Regardless of whether in organic or organic forms, most of the Sulphur oxides end up in stack gases as SO2. This pollutant can be removed by the reactions:

$$SO_2 + Ca(OH)_2 \rightarrow CaSO_3 + 1/2\ H_2O$$

It is important to note that SO2 is a highly reactive gas with short half-life indoors. Other issue that might pose a threat is the formation of acid rain. Acid rain results when sulfur dioxide (SO_2) and nitrogen oxides (NO_X) are emitted into the atmosphere and transported by wind and air currents. The SO_2 and NO_X react with water, oxygen and other chemicals to form sulfuric and nitric acids.

B. Acid chloride and fluoride

Chlorine and fluorine may be present in MSW in significant quantities. The main sources of chlorine are plastics such as PVC, salty food waste and other inorganic chlorides. Fluorine can arise into plastics such as PTFE, fluorinated textiles and other inorganic fluorides. Under the furnace conditions chlorine and fluorine are mostly converted into acid hydrogen halides, HCl

and HF, and part of these may react to form metal chlorides. In general, HCl and HF are removed by the same technology, by adding neutralization agents, for instance lime (Ca(OH)2), sodium hydroxide (NaOH), or calcium carbonate (CaCO3). The following reactions show the separation of acid pollutants with $Ca(OH)_2$:

$$2\ HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2\ H_2O$$
$$2\ HF + Ca(OH)_2 \rightarrow CaF_2 + 2\ H_2O$$

C. NO_x

Nitrogen oxides, NOx, are well known acidic and global warming gases, and during incineration process three main different mechanisms can lead to their formation. Indeed, part of the air nitrogen and part of the nitrogen contained in the waste (or fuel) may be oxidized to NOx. The nitrous oxides produced from air are known as **thermal NOx**, and the ones originated from waste as **fuel NOx**. These reactions can significantly occur for temperatures above 1300 ºC and whenever oxygen is not a limiting reagent. In WtE plants, thermal NOx is often much greater than fuel NOx. The formation of nitrogen oxides through radical reactions with organic compounds is known as **prompt NOx** and has little contribution in WtE incineration plants.

The main primary techniques can involve both over supply air and excessive high furnace temperatures. Secondary measures may demand injection of reduction agents such as ammonia (as 25% aqueous solution) or urea, for promoting SNCR as indicated in Table 27.

D. Heavy metals

Mercury is by far the most thermally mobile metal, highly toxic, and at 357 ºC it is all volatilized into the flue gas. Although restriction in uses of Hg, some peak loads of MSW with batteries, electrical devices, thermometers and specific wastes may lead to incompliance with the regulatory threshold of 0.05 mg/Nm3. For this element, the primary measures are those which avoid as much as possible to introduce in the furnace contaminated wastes that contain Hg. Nevertheless, secondary techniques are usually implemented in order to comply with the regulatory limit at stack emissions. The lowest emissions of Hg are observed when sulphur doped activated carbon is used.

Cadmium is an environmental problematic toxic element that may arise in air emissions of MSWI due to its thermal mobility. Although some countries restrict applications of Cd, frequent sources in MSWI are electronic devices (including accumulators), paints, Ni-Cd batteries, and cadmium-stabilised plastics. Under the conditions usually observed in the furnace, Cd is mainly converted into $CdCl_2$.

During the main stages of incineration, combustion temperatures attained in the furnace determine the evaporation degree of heavy metals and most of inorganic salts. Indeed, besides Hg, Cd and Tl also Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V must be under control in stack emissions. These are very toxic metals since they are carcinogenic or may provoke respiratory damages. Most of these metals are in flue-gas as oxides or chlorides, which condense onto dust particles as the gases cool down downstream of the boiler. Therefore, it is expected that the part of these metals that vaporize in furnace, probably ends as condensed phases in APC residues.

E. Fly ash (dust)

During the incineration process, part of the waste is incombustible and removed from the incinerator as solid wastes, usually referred as bottom ash or slag (particulate matter). They exist as APC residues and contain very low quantity of residual particles in the flue gas. The

matrix compounds of these particles are mainly aluminum and silicon oxides. Particulate matter is often grouped into categories based on their diameters (e.g. $PM_{2.5}$ with a diameter less than 2.5 µm). For example, $PM_{2.5}$ may persist in the atmosphere for long periods, travelling long distances and they are capable to penetrate deep into the respiratory tract. Their toxicity is normally correlated with the respective chemical composition.

F. Dioxins and Furans

In combustion, dioxins/furans are formed by either (1) so-called “de novo” synthesis from dissimilar non-extractable carbon structures, and (2) by precursor formation/reactions via aryl structures derived from incomplete aromatic oxidation or cyclization of hydrocarbon fragments. Generally, formation may take place given the presence of a carbon surface or structure (e.g. fly ash), organic or inorganic chlorine copper or iron metal ions (serving as catalysts), an oxidizing atmosphere, and, ideally, a temperature ranges of 250 - 450 C. Dioxin/furan emissions depend on many factors, including:

- Chemical and physical characteristics of the waste (e.g., organic carbon, chlorine, ammonia, amines, metals, moisture, sulfur, ash contents).
- Process/combustion conditions (e.g. The availability of oxygen, chlorine, other precursors/catalysts, temperature, time, mixing/turbulence, reactor materials).
- Downstream conditions (e.g., temperature, residence time, precursor concentrations, the quantity and specific surface area of flyash).
- Presence and efficiency of air pollution control devices (e.g., wet scrubbing, dry absorption using lime, carbon, etc.)

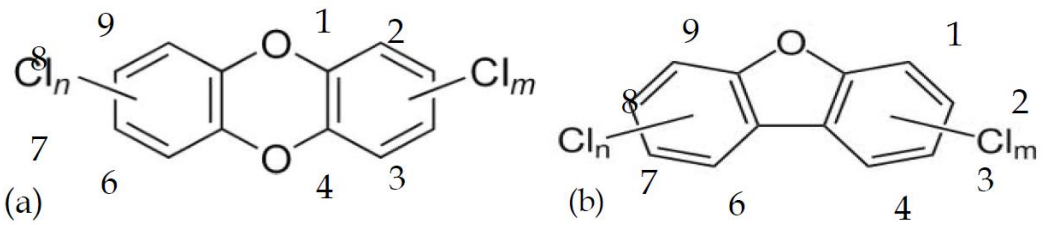


Figure 49 Generic structure of (a)- polychlorinated dibenzo-p-dioxin (PCDD), (b)-polychlorinated dibenzofurans (PCDF).

Indeed, in addition to PCDD/PCDF originally present in the furnace feedstock, three formation theories of dioxins should be considered:
- precursor compounds such as chlorinated hydrocarbons already in the MSW feed or formed in furnace by reacting rapidly with other groups (e.g. chlorobenzene)
- de-novo synthesis of smaller and relatively innocuous chemical molecules combining together in the low temperature range;
- radical recombination with prevalence of the structures with longer life-span (more symmetrical and more stable).

While the understanding of dioxin/furan formation conditions is incomplete, some statements are generally supported, e.g., formation is roughly proportional to the post-combustion residence time in 200 – 400 C environment. Even in high temperature incinerators (>800 C), temperatures may not be uniform, and dioxins and furans can form in cooler pockets or during start-up or shut-down periods. Dioxin/furan formation is minimized by ensuring that incineration only takes place at temperatures above 800 C.

Therefore, two strategies have been adopted for complete destruction in combustion and for minimize their formation. In this scope, it is very important that the combustion temperature

should be above 1000 ºC, the residence time should exceed 2 s, and high turbulence in the combustion chamber should be promoted (Reynolds number higher than 50,000). As an end-of-pipe treatment, it should be assured that a very rapid gas cooling from 450 to 250 ºC is able to occur. Currently, semi-dry lime scrubbing, and bag filters coupled with activated carbon injection have been playing an important role in prevention or minimization of dioxins in stack gas emission to the environment [35].

Appendix 12 The Classification of Municipal Solid Wastes Managed by Public Authority

CSR can be produced from different sources of wastes, according to the following Figure 50.

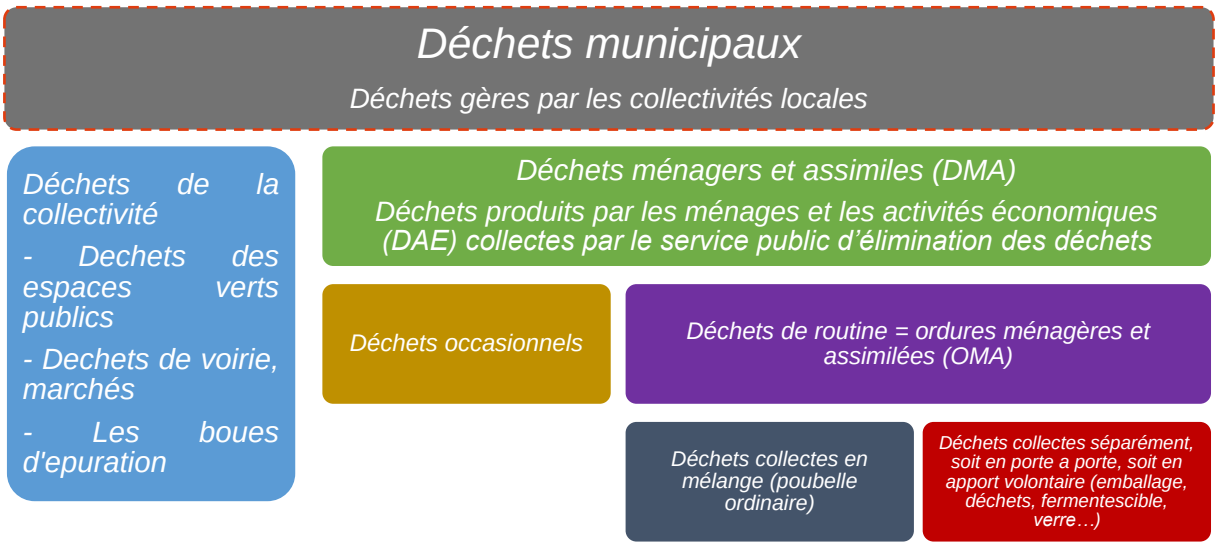


Figure 50 Classification of municipal solid wastes [13]

Appendix 13 The Energy Potential of Waste Matrix Data

The summarized results waste potential to draw the matrix in Chapter 3 are presented in Table 28.

Table 28 List of Wastes with Its Energy Potential in 2050

Type of wastes and non-wastes	Potential Energy in 2050 (TWh)
CSR* (9Mt potential) - CSR from HH wastes (refuse) - CSR from EA wastes - CSR from used furnitures - CSR from pre-sorted HH wastes - CSR from used tires	35,8 8,2 16 7,8 3,1 0,7
Wood wastes	19
Green wastes (parks, gardens)	36
Black liquor from paper industry	61
Crop residues	31
Intermediate crops	51
Grass and fodder	13
Animal excrement	27
Agro-food industry residues	5

Energy calculated by its HHV or LHV

Type of bio wastes	Potential Energy in 2050 (TWh)
Organic fraction of household wastes	2,5
Sanitation	2,5
Markets	0,2
Commercials/ Shops	0,1
Restaurants	0,4
Roadside grass	2,1
Total	7,8

Type of non-wastes	Potential Energy in 2050 (TWh)
Wood energy from the forest	112
Algae	14
Coal	-
Oil	-
Natural gas	-

*Source: ADEME, 2018 and *EIFER, 2016 (projection in 2025)*