



Master's thesis

March 25th – August 9th

Part 1. Critical review of waste management
in France
Part 2. Analysis of particulate matter emitted
by Waste-to-Energy plants

**Earth Engineering Center – Columbia
University**

500 West 120th Street

New York, 10027

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Acknowledgements

First of all, I would like to thank Professors Ange Nzihou, Nickolas Themelis and Marco Castaldi for introducing me to the subjects of this thesis and for giving me the opportunity to study at Columbia University. Both Professors Themelis and Castaldi helped me a lot throughout my research and took time to discuss any problems I encountered.

My colleagues at the Earth and Environmental Engineering Department of Columbia University, Marcella Lusardi, Rob Van Haaren, Thomas Nikolakakis, Timothy Sharobem and Jiao Ziang were very helpful and it was a pleasure to work with them.

Finally, I would like to thank Charles Mussche for his support, his patience and his advice during the writing of this thesis and my family for supporting my academic studies.



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Introduction

Growing population, industrial development and consumerism in current society have led to a sharp increase in Municipal Solid Waste (MSW) generation. As a result, many countries try to improve their waste management. For example, the European Union decided to act and provided a directive to phase out landfilling. Some E.U. members seem really advanced concerning waste management, like Germany that doesn't landfill its MSW anymore. However, other European countries are not as good in this way. France continues to landfill a large part of its MSW. A good way to reduce the amount of MSW without landfilling is by combustion or gasification. However, pollutant emissions of these processes are still considered to be harmful for health and environment by the public.

In October 2007, the government of France convened the "Grenelle Environnement" to consider how to deal with present and future environmental challenges. Concerning waste management, the first goal of the Grenelle was *waste reduction and increased recycling*. The second goal was *clear reduction in the health and environment impacts of waste policies*.

It is now interesting to study waste management in France to know the reason why landfilling is still high in this country and this is the first part of this study. The second part focuses on particulate matter emissions from waste-to-energy facilities.

For this, the different forms of waste management in France were studied to obtain an overview of waste management in the country. Then, a comparison with Northern Europe was made by studying the ranking of some European countries on the waste management "ladder", with special focus on landfill taxes in various European nations.

In the second part of this thesis, Particulate Matter (PM) emissions from MSW gasification and combustion were characterized, before studying the impacts in total background PM of the WTE facilities operating near the city of New York.



I. Part 1: Critical review of waste management in France

1) Landfills in France

France continues to landfill over 40% of its municipal solid waste, despite the European Union directive to phase out landfilling. However, France has strict regulations concerning landfilling. As a result, there are 244 landfills in 2010 in France ^[1], all of which are sanitary. These landfills received 19.6 million tons of waste in 2010 ^[1], the first time that less than 20 million tons of waste were landfilled. It should also be noted that in the last ten years, 150 landfills were closed ^[1], which shows that the country is clearly improving its waste management.

Landfills are sources of CH₄ emissions a gas that is harmful to the environment. The comparative impact of CH₄ on climate change is over 20 times greater than CO₂ over a 100-year period. Thus, 210 landfills in France capture CH₄: 130 flare it and 80 use it for energy generation ^[1]. In 2011, about 1.2 billion Nm³ of biogas were produced in these 80 landfills ^[2]. Therefore, the biogas capture in France corresponded to roughly 60 Nm³ per ton landfilled in all French landfills.

In 2010, the landfill gas (LFG) was used to generate 858 GWh of electricity and 296 GWh of heat ^[1]. There are also biogas plants in France, specialized in capture of methane and compost. In 2010, 9 biogas plants collected 471 ktons of organic waste and produced 63 ktons of digestate suitable for fertilizing agricultural land. Seven plants use CH₄ for energy generation: 36.4 GWh of electricity and 15.8 GWh of heat were generated ^[1].

2) Overview of waste management

a. Fields in waste production in France

In this part, Municipal Solid Waste (MSW) is household waste and public waste generated in France. MSW represents around 5% of waste produced by the country ^[3]. The figure below (see [Figure 1](#)) shows percentage of the different fields in waste production in France.

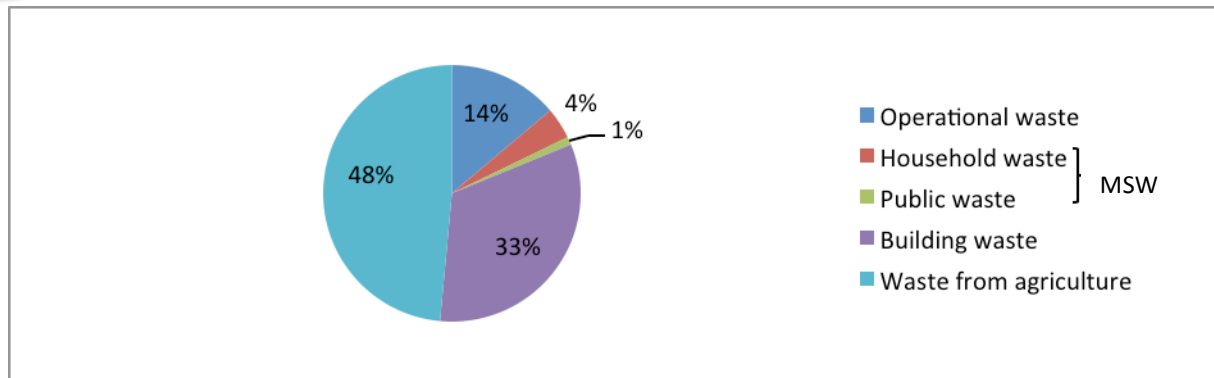


Figure 1 : Percentage of the different fields in waste production in France – 2009 (data based on ADEME 2012 ^[3])

Some waste needs special processes to avoid environment pollution, as building waste. However, there is no special process or transport for waste generated by agriculture, even if it represents the majority of all waste. Thus, different ways have to be considered, depending on type of waste.

b. Household waste production evolution in France

After 1960, population in France increased with the “baby-boom”. New technologies changed also the way of life in the country. Both facts led to a sharp increase in household waste production per capita.

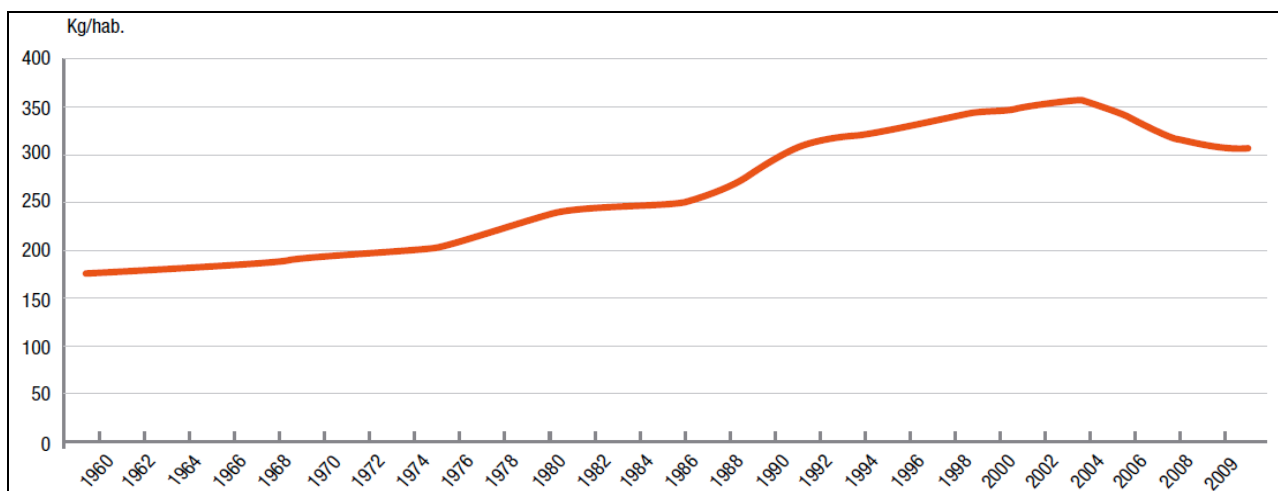


Figure 2 : Household waste production evolution between 1960 and 2009 in France (kg per capita) (ADEME 2012 ^[3])

As shown in Figure 2, waste generation per capita has more than doubled between 1960 and 2005 while population increased from 45 billion to 65 billion between 1960 and 2010 ^[3]. Distribution of new technologies (as cars, mobile phones etc.) on a large scale and new way of consumption in the society are the reason for this evolution. Since 2005, production per capita decreased but we have to consider the fact that waste reception centers receive more waste than before.



c. Characterization of MSW

MSW is the most heterogeneous fuel possible, as it is composed of all sorts of garbage from households. It is interesting to analyze waste streams to understand the different processes used in waste management in France. This analyze is given in the next figure (see **Figure 3**).

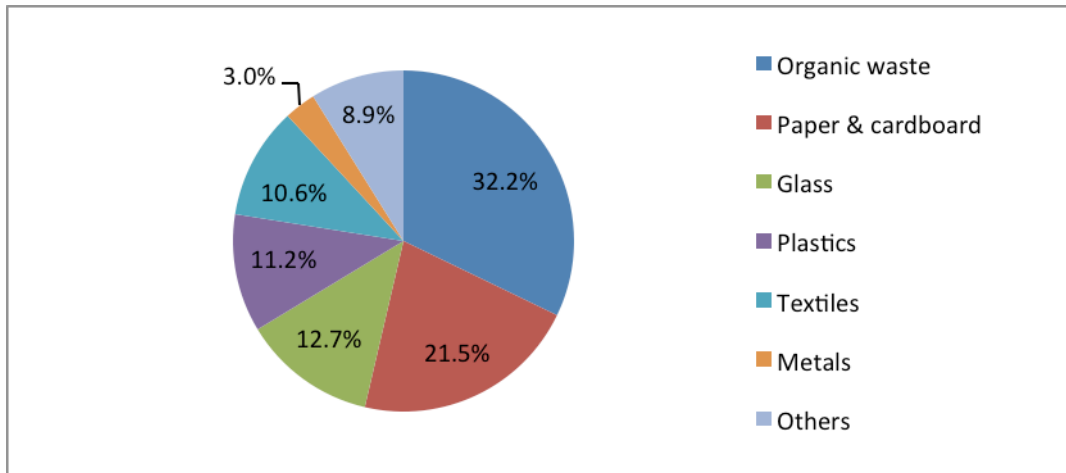


Figure 3: Composition of the waste stream in France (data based on Campagne MODECOM 2007-2008)

Two surveys were carried out for the characterization of MSW in France in the past 20 years. Both studies revealed that the composition of the waste streams does not show a lot of change over the years ^[3]. However, some differences are notable. The amount of beverage cartons for instance has decreased from 39% in 1993 to 32% in 2007 ^[2] as the result of recycling campaigns in France.

d. The different fields of waste management in France

In 2010, France generated about 48.7 million tons of MSW (0.74 tons per capita) ^[1]. Landfills and Waste-to-Energy (WTE) facilities are the most used processes as waste management for MSW. Thus, landfilling represents over 40% (see **Figure 4**) of waste management and incineration around 28%. However, landfilling has decreased from 48% in 2006 to 40% in 2010 (19.6 million tons) ^[2], showing that the country is ion the way to improve its waste management.

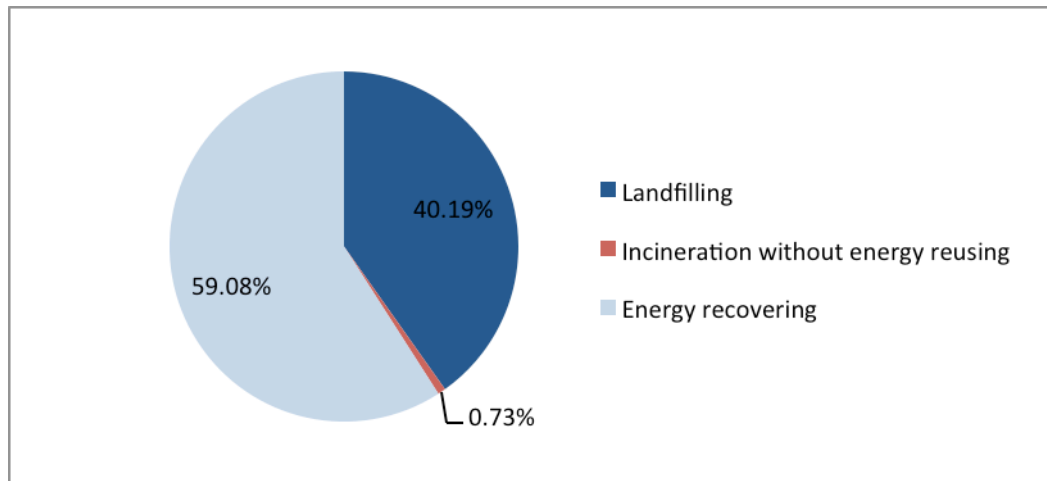


Figure 4: Waste management in France (data based on ITOMA 2010 ^[4])

Even though landfilling represents over 40% of waste management, it is important to notice that the percentage of energy recovering is around 59%. With only 0.73% incineration without energy recovery, the country is not doing a bad job (see Figure 5).

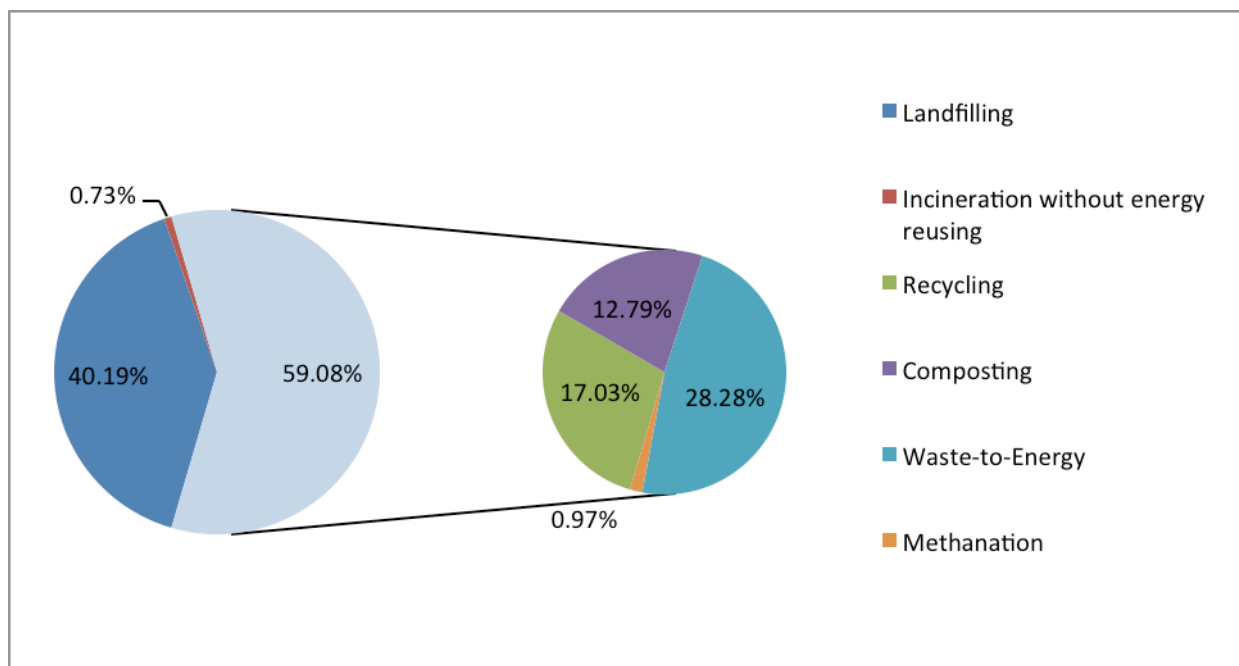


Figure 5: Waste management in France (data based on ITOMA 2010 ^[4])

Many ways are used to recover materials and energy from waste. Thus, recycling, composting, WTE and methane recovery facilities are present in the country. Energy recovering from WTE facilities represents around 28%, then recycling 17%, composting 13% and methanization less than 1% (see Figure 5).



There are 129 incinerators (114 WTE plants and 15 incinerators without energy reusing) that burnt 14.1 megatons of waste in 2010 ^[1]. These two types of incinerators do not have the same size characteristics:

- ❖ Incinerators without energy reusing are small plants. They burn on average 24 000 tons per year.
- ❖ WTE plants are bigger and they burn on average 121 000 tons of waste per year.

In the WTE facilities, 3657 GWh of electricity and 7589 GWh of heat were produced in 2010 (see [Table 1](#)).

Waste recovery form	WTE facilities number	Waste received (ktons)	Energy consumed (MWh)	Energy sold (MWh)
Electricity	42	4,494,655	254,928	1,428,098
Heat	29	1,661,453	96,180	1,791,758
Cogeneration:	42	7,610,530		
Cogeneration - Electricity			504,637	1,469,077
Cogeneration - Heat			692,835	5,007,780
No data	1			

Table 1: Energy recovering in WTE plants in 2010 (ITOMA 2010 ^[1])



In the same year, 366 recycling facilities received 8.3 megatons of waste and reused 5.7 megatons of waste. The number of recycling plants increased from 265 in 2000 to 366 in 2010, which represents an increase of 38%. On average, around 32% of this waste is not accepted in these facilities and is sent to landfills (around 62%) and WTE plants (around 31%) ^[1].

Composting plants are also numerous in France accounting for 593 facilities in the country. In 2010, these plants received 6.2 megatons of waste and produced 2.1 megatons of compost. In comparison, 1.8 megatons of compost were produced in 2008 where 71% of composting refusals are sent to landfills. However, the not accepted waste reduced considerably and represented only 377,000 tons in 2010 while it was more than 600,000 tons ten years ago ^[1].

Nine biogas plants collected 471 ktons of waste and produced 63 ktons of compost. Seven plants use CH₄ for energy generation: two plants generate electricity; one generates heat and four do cogeneration. Thus, 36.4 GWh of electricity and 15.8 GWh of heat were generated in 2010 ^[1].

3) Comparison between France and Northern Europe

In 2012, the European Commission evaluated European countries about quality of their waste management. The best countries are in Northern Europe and they landfill less than 5% of their waste. Austria and Netherlands are at the very top, then Denmark, Germany, Sweden and Belgium. It is useful to make a comparison between these countries, to understand why France is not as good as Northern Europe.

a. Amount of MSW generated in Europe

In Europe, some countries generate more MSW than others. Differences are really significant: minimum is 316 kg/capita/year and maxima 833 kg/capita/year ^[3] (see [Figure 6](#)).

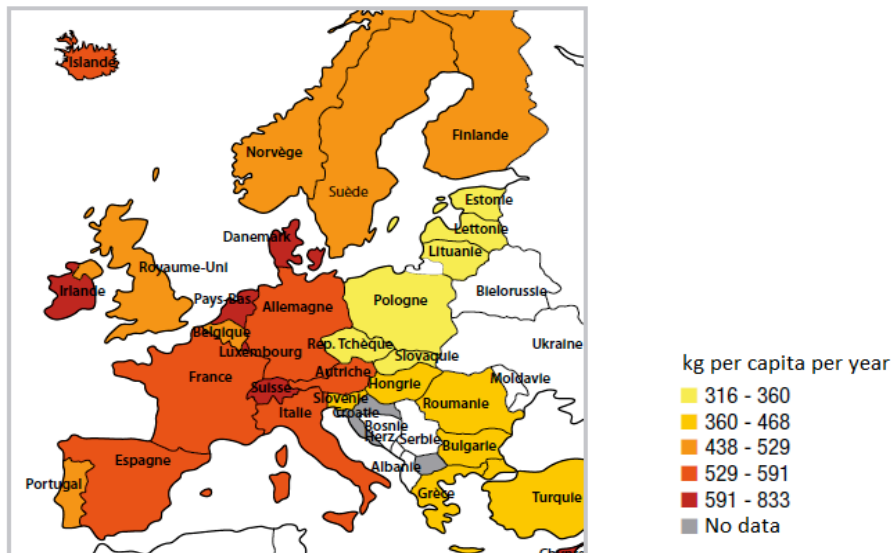


Figure 6: MSW generated in Europe in 2009 (Eurostat ^[3])

The previous figure shows that Eastern Europe generates less MSW than the other countries. However, most of these countries send all their MSW to landfills. Also, in seven countries there are no restrictions concerning landfilling and the law does not discourage this way of waste management.

b. France compared to Europe

The Earth and Engineering Center (EEC) in Columbia University has introduced the concept of the “Ladder of Sustainable Waste Management” (see Figure 7) on which cities and nations can climb up by increasing their recycling, composting and WTE, while decreasing landfilling.

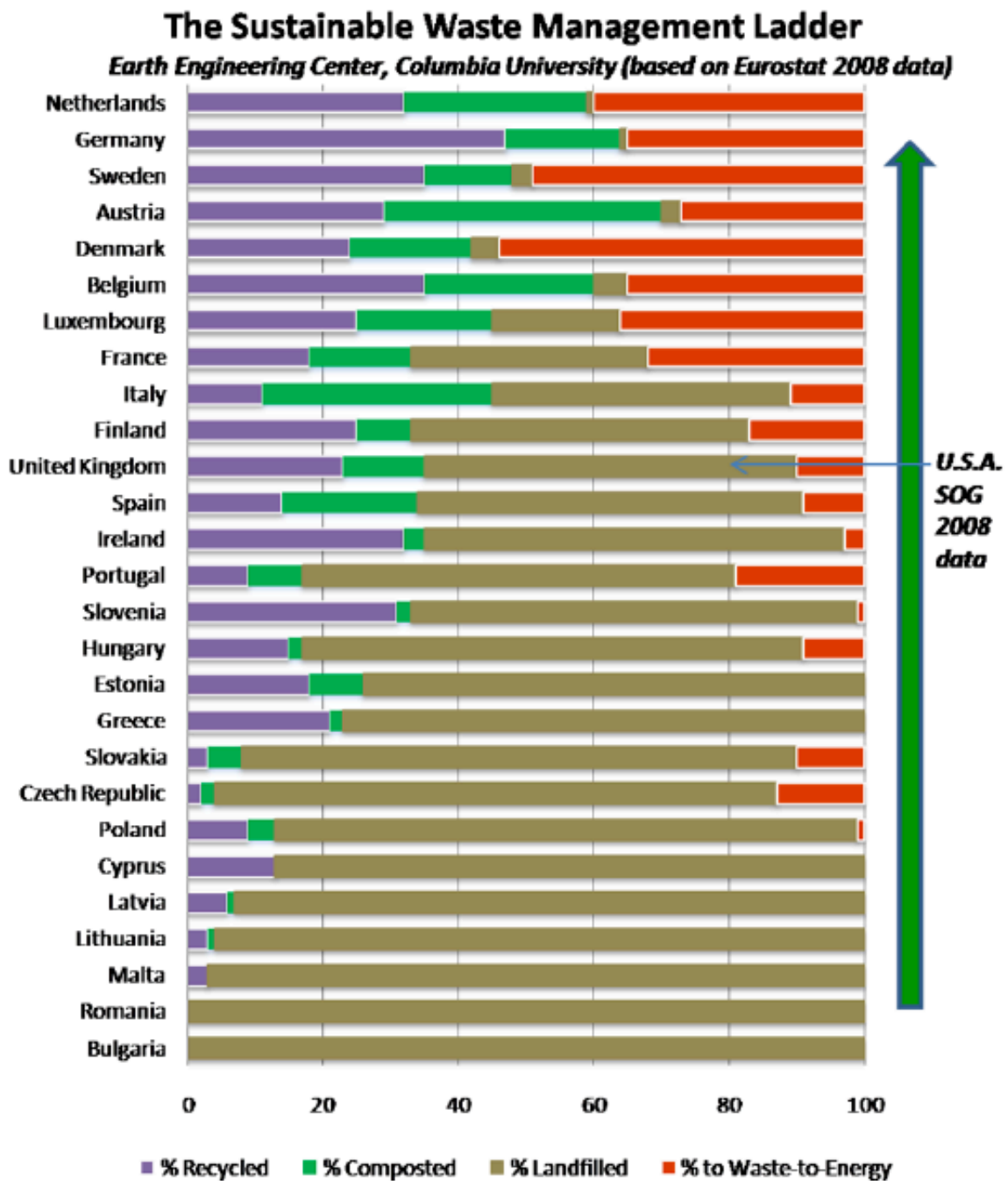


Figure 7: The Sustainable Waste Management Ladder for Europe (EEC)

France is No. 8 on the E.U. Ladder of Sustainable Waste Management. We can see considerable differences with the best countries, all in Northern Europe, especially concerning landfilling.

The European Commission has also evaluated European countries in 2012, with other criteria as the amount of recycled MSW, the amount of landfilled organic MSW etc. With 18 criteria, the European Commission gave good or bad points to European countries and ranked them [5]. Results are similar to the Sustainable Waste Management Ladder: Northern European countries are at the very top, before France (see Table 2).



1.	Austria (39 points)	15.	Ireland (19)
2.	Netherlands (39)	16.	Czech Republic (18)
3.	Denmark (37)	17.	Poland (18)
4.	Germany (36)	18.	Estonia (17)
5.	Sweden (35)	19.	Slovakia (17)
6.	Belgium (34)	20.	Italy (15)
7.	Luxembourg (33)	21.	Latvia (14)
8.	United Kingdom (32)	22.	Cyprus (11)
9.	Finland (31)	23.	Romania (11)
10.	France (31)	24.	Lithuania (9)
11.	Slovenia (25)	25.	Malta (9)
12.	Spain (21)	26.	Bulgaria (8)
13.	Portugal (21)	27.	Greece (3)
14.	Hungary (19)		

Table 2: Position of European countries according to the EC and its criteria (Eurostat ^[5])

Austria and Netherlands are at the very top, with 39 on 42 points. France and Finland are No. 9 in this ranking. Since we now know where France is situated in comparison with the other E.U. countries, it should be interesting to see the regional “best in class” within France itself.

c. French waste management

i) *The Sustainable Solid Waste Management Ladder for France - Regions*

France is divided in 27 regions: 22 in mainland France and 5 overseas departments. With the same criteria than the Sustainable Waste Management Ladder for Europe, a ladder for France and its regions has been made. Actually, each region has its own waste management. So it is useful to see differences and to rank all regions. Data for Mayotte are unknown, that is why only 26 regions were analyzed in this part.

The SINOE database ^[4] provides useful data about waste management for each region in France. The latest data dates from 2010, after ITOMA 2010 survey. This survey gives information about the amount of recycled, composted, landfilled and incinerated (with and without energy reusing) waste and also waste sent in methanization plants. The “Sustainable Solid Waste Management Ladder for regions of France” was constructed by the author on the basis of these data (see [Figure 8](#)).



The Sustainable Solid Waste Management Ladder for France - Regions

Earth Engineering Center, Columbia University (based on ITOMA 2010 data)

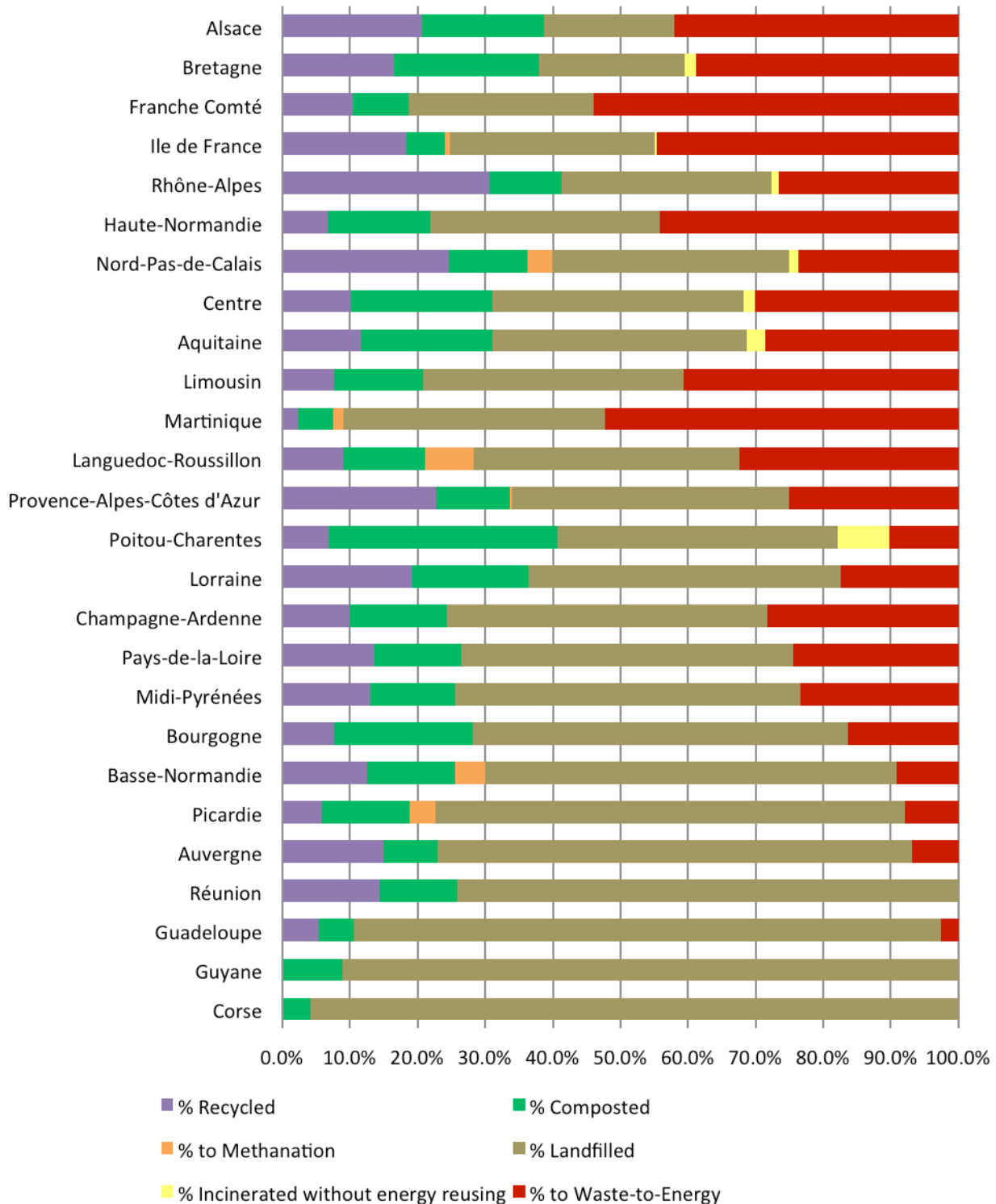


Figure 8: The Sustainable Waste Management Ladder for France - 2010

Alsace is at the very top of this ladder with 19.3% of landfilling, 42% of WTE, 20.6% of recycling and 18.1% of composting. At the bottom, there is Corsica which landfills 95.9% and composts 4.1% of its waste.



France landfills around 40% of its MSW but 14 regions are higher than this average. East of France is better than other places in the country. But actually, there are no specific places which are the best: percentage of waste management, especially landfilling, is really divided in the country (Figure 9).

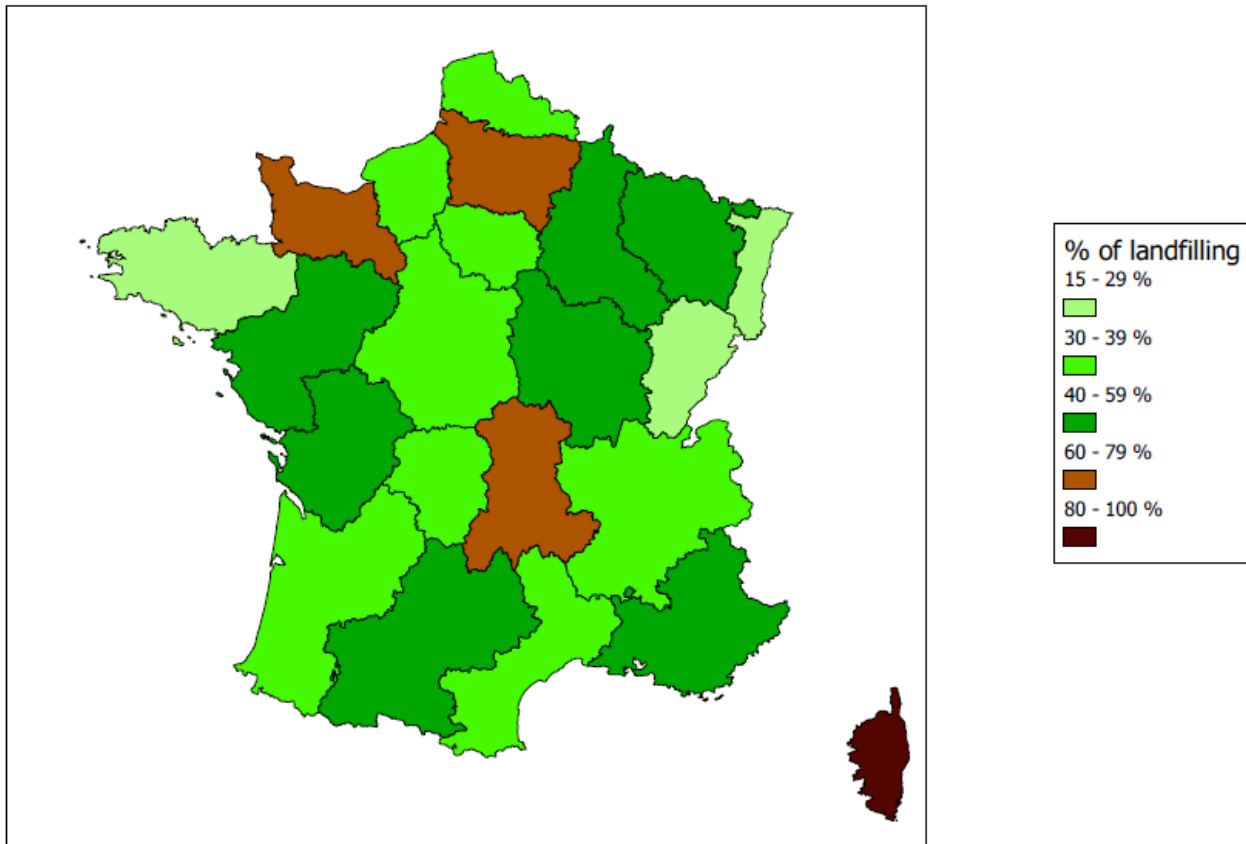


Figure 9: Waste management in France - Landfilling around the country

There are 3 regions below 30% of waste landfilling, then 9 below 40% (with Martinique), 7 below 60%, 4 below 80% (with La Réunion) and 3 over 80% (Corsica, Guyane and Martinique). The previous figure shows that regions are not working together in France: there are many differences between each region even if they follow the same Government directives. This is due to different waste management chosen by elected representatives in each region.

ii) *Matrix of sustainable waste management*

It is interesting to know if waste management and the amount of money earned in each region are linked. A matrix was made with sustainable waste management for Y-axis and GDP per capita of regions in X-axis.

At first, regions were ranked according their sustainable waste management rating. This one is defined as the percentage of all waste management, landfilling excluded (that means WTE, incineration, recycling, composting and methanization). The listing is the same as the sustainable waste management ladder (see Table 3).



A GDP weighted was calculated for each region: this is the ratio of GDP per capita of regions on average GDP per capita of France. The average GDP per capita of France (€29,784, defined as 100% ^[6]) and average sustainable waste rating management for France (59.8%) are the reference points for the matrix (see **Figure 10**).

Regions were positioned on the matrix with their rank to recognize them.

Rank	Region	Sustainable waste management rating	GDP weighted
1	Alsace	80,7%	94,0%
2	Bretagne	78,4%	83,2%
3	Franche Comté	72,7%	79,6%
4	Ile de France	69,7%	162,4%
5	Rhône-Alpes	69,1%	100,9%
6	Haute-Normandie	66,1%	86,0%
7	Nord-Pas-de-Calais	65,1%	81,7%
8	Centre	62,8%	84,7%
9	Aquitaine	62,4%	89,4%
10	Limousin	61,4%	77,3%
11	Languedoc-Roussillon	60,8%	79,5%
12	Provence-Alpes-Côtes d'Azur	59,0%	93,1%
13	Poitou-Charentes	58,5%	79,9%
14	Lorraine	53,9%	78,7%
15	Champagne-Ardenne	52,5%	88,2%
16	Pays-de-la-Loire	50,9%	89,1%
17	Midi-Pyrénées	48,9%	89,7%
18	Bourgogne	44,6%	85,5%
19	Basse-Normandie	39,1%	78,3%
20	Picardie	30,5%	76,3%
21	Auvergne	29,8%	80,7%
22	French overseas departments	26,4%	61,5%
23	Corse	4,1%	83,9%

Table 3: Regions ranked by sustainable waste management rating (based on ITOMA 2010 ^[4] and INSEE 2010 data ^[6])