CONTRIBUTION OF NON-HAZARDOUS WASTE LANDFILLS TO THE ACHIEVEMENT OF GHG EMISSION REDUCTION TARGETS IN THE EU

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READER'S NOTE

By presenting this study and the associated recommendations to operators and policy makers, Suez, Veolia and WAGA Energy follow the ambition to secure and reinforce the contribution of non-hazardous waste landfill facilities to the EU decarbonisation and energy sovereignty targets, while minimizing the impact of the sector on the environment.

The effects highlighted and measured in this study in terms of decarbonisation and energy production have been calculated in addition to the effects of the current regulatory framework, essentially focused on reducing the amount of future waste (and its organic share) sent to landfills. This regulatory framework has been taken as a baseline scenario for all projection works performed in the study.

EXECUTIVE SUMMARY

The European context on waste management presents important challenges regarding design and operation of non-hazardous waste landfill facilities, with:

- **The necessity to adapt to a strong decrease in the total volume of waste landfilled** (reaching a maximum of 10% of Municipal Solid Waste landfilled by 2035) **and to the changing nature of such waste** (mainly due to the increasing diversion of biodegradable waste from landfills).
- **The requirement to better measure methane emissions** (as strong uncertainties and technical challenges remain today) and to **better control methane emissions**, **accompanying the reduction target.**
- **An opportunity to significantly contribute to the Repower EU Targets for biomethane[1],** as landfill biomethane is currently one of the most competitive biomethane production solutions, thus important to tackle both decarbonization and energy sovereignty challenges.

In this context, three key players of the European landfilling sector[2] have performed a study to:

- Analyse with a rigorous methodology, associated with the expertise of experienced market operators, the performance of "best-in-class" landfill installations in terms of direct and indirect emissions and in terms of energy recovery.
- Estimate the additional potential contribution of the landfill sector to EU GHG emission reduction objectives and to the 35bcm biomethane production target, and the associated cost (or profit) for the community, if the existing landfilling reduction targets were accompanied with the proper economic tools and regulatory measures to effectively spread good practices in terms of biogas capture, measurement, and energy recovery across European landfill installations.
- Provide concrete recommendations to operators and public policy makers to achieve such results.

The results above have been computed at the French perimeter where the contributors to the study were in position to provide detailed data on landfill operating conditions. Extrapolations have been made at a European level. The extrapolation calculations should be furtherly refined at each country level.

The main findings and conclusions of this study are summarized below:

1) **Currently achievable good operating practices, reaching a high level of methane capture (~80%) and energy recovery, allow operators to reduce by ~50% the total direct and indirect emissions generated with "average" operating practices, and to increase biomethane**

[1] Biomethane Action Plan (within Repower EU) targeting 35bcm by 2030 (~350TWh).
[2] Suez, Veolia and Waga Energy

production (generating +50% in terms of avoided emissions through the replacement of fossil natural gas)

- Modelized[3] for the current average French waste mix[4], total direct[5] and indirect[6] GHG emissions generated in a landfill implementing "best-in class" operating practices amount to ~300-310kg$_{CO2eq}$/t$_{waste}$, compared to >600kg$_{CO2e}$/t$_{waste}$ for a landfill operated under "average" practices and close to 900kg$_{CO2e}$/t$_{waste}$ for landfills operated under "bad" practices.
- In addition to enhance methane capture rate, "best-in-class" operating conditions enable to increase biogas recovery. Its injection into the gas network can generate "avoided emissions" up to ~110kgCO2eq/t$_{waste}$ by replacing fossil gas while contributing to the national production of renewable gas (compared to ~80kgCO2eq/t$_{waste}$ for "average" operating conditions)
    - In France, landfill biomethane could contribute to ~5-10% of the 2030 biomethane injection targets (~2-3TWh depending on production practices); extrapolated at the EU level, it could represent ~15-20TWh, or ~5 to 10% of the 2030 production target[7].
    - The production of renewable biomethane contributes to the energy independency of the European Union.
- The corresponding "good practices"[8] are realistic operating conditions today, effectively put in place in ~25 to 30% of Suez and Veolia's French landfills:
    - Implementation of an anticipated capture system during the operation phase[9], and immediate implementation of the capture system and final cover at the end of operations.
    - Implementation of an impermeable final cover with a bioreactor system properly operated for maintaining the right humidity rate in the long-term, allowing to optimize methanisation conditions and degradation until the stabilisation of the waste and the landfill waste body (no more settlement or leachate produced requesting a strong treatment).
    - Optimization of the rate of energy recovery for the captured biogas, consistent flaring of the non-recovered biogas in the long term[10] and adequate implementation of additional treatment processes (natural oxidation, biofilters etc.)

2) While pursuing the landfill decrease objective, by putting in place the conditions to better monitor and control fugitive emissions and to support a general upgrading of landfilling operations, the waste sector would be able to additionally reduce its 2030 emissions by

[3] Using an IPCC Tier2 model. For more details, refer to report APPENDIX N°2 describing the modelling methodology and hypotheses retained for this study.
[4] Based on a French mix reconstituted from MODECOM 2017 data, C&I regional data, ADEME data on waste entering landfills. This French mix is composed of ~24% of food waste, ~4% garden, ~20% of paper waste, ~11% of wood waste. More details are given in APPENDIX N°7 describing the average mix reconstitution (incl. MSW and C&I waste) used in this study. These proportions can be variable in European countries.
[5] Direct emissions: GHG emissions generated by lost CH4 for 30 years post-operation and residual CO2 that will be lost in the following 50 years post-surveillance until reaching the total decomposition of waste.
[6] Indirect emissions: GHG emissions generated during the construction and operation of the treatment installation.
[7] The extrapolation has been made assessing the volume of waste that would be landfilled at the European level from 2024 and 2035, if all countries would decrease the volume of waste landfilled from now to 2035 in order to respect the target of 10% of MSW landfilled by 2035. The methane potential generated by a tonne of waste in France over this period has been extrapolated at a European level. This analysis should be refined at each country level.
[8] On the other hand, average practices refer to landfill where – in comparison to "good practices" – no anticipated capture system is installed during the operational phase, there is no (or poorly exploited) bioreactor, and the level of maintenance is moderate. Further details regarding "average practices" are given in part I.C.
[9] Period of ~2 years when the cell is being filled with waste.
[10] Note: this can require a reinvestment in a flaring equipment to adapt to the gas flow evolution over time.

~30% (reduction of ~0.4Mt$_{CO2eq}$/year in France) at a reasonable average abatement cost of ~€20/tCO2e, partly financed by additional energy recovery.

- Even in the most ambitious scenarios, the volume of landfilled waste will take time to decrease in the coming decade, as several countries are facing massive challenges to implement the EU waste reduction, sorting and recovery policies[11].
- The existing and future landfilled waste will continue to be degradable[12] and to be biogas emitters. At the French perimeter, in a "business-as-usual" scenario considering that operating practices are maintained in the next ten years as they are today[13], all waste landfilled between 2024 and 2035 have a potential of generating ~58Mt$_{CO2e}$ into the atmosphere (cumulated over their whole degradation period), including ~1.5Mt$_{CO2e}$/year in 2030-35.
- If, while pursuing the landfilling decrease objective, the conditions to support a general upgrading of landfilling operations were put in place (corresponding to a widespread adoption of good practices), the corresponding fugitive emissions in France would be significantly reduced to:
    - ~37Mt cumulated over the whole degradation period (-21Mt$_{CO2e}$ compared to the "business-as-usual" scenario)
    - ~1.1Mt$_{CO2eq}$/year in 2030-35, corresponding to a decrease of ~28% of landfilling emissions due to fugitive methane[14] from 2030 to 2035.
- *N.B. The results above have been computed at the French perimeter where the contributors to the study were in position to provide detailed data on landfills' operating conditions. Considering that France represents average practices among European countries, similar results (-30% of emissions in 2030-35 due to fugitive methane emissions) could be expected at the European perimeter[15].*
- Such improvement could come at a reasonable cost for the community and be partly financed by the resulting energy recovery:
    - Expressed in terms of € per tonne of CO2e avoided: the total cost to implement the corresponding actions result into a **CO2e abatement cost of ~€20/tCO2e, which is in the low range of publicly supported actions such as renewable electricity assets or renewable thermal energy supported by the *Fonds Chaleur* in France[16]**.
    - Expressed in terms of €/tonne of landfilled waste: the corresponding cost would represent **a few euros per tonne of waste (~2 to 3€)**[17]
- It should be noted that the capture of gas from closed landfills is considered as a sustainable activity by the Taxonomy.

3) **The costs associated to the "generalisation of good practices" could be financed by revenues from energy recovery if the adequate investment conditions are in place.**

    - **Additionally, the cost of energy recovery makes it one of the most competitive sources of renewable gas on the market and could cover the upgrading expenses**

[11] In 2021, France ~18Mt were landfilled in France, with ~15Mt coming from residual municipal waste and C&I waste. The rest was composed of compost refusal, sorting refusals and residuals from MBT. In France in 2020, ~25% of municipal waste was sent to landfills and ~31% to WtE plants.
[12] In France, ~42% organic waste (food, garden, wood, paper) would still be landfilled in 2035, coming from residual waste, sorting refusals, residuals from MBT, compost refusals. This share may differ in other European countries.
[13] Which is uncertain in a context of decreasing volumes.
[14] Considering that all landfills operated without methane recovery are upgraded to follow at least the "average" operating practices, and that landfills currently operating under "average" practices upgrade to "good" operating practices – *See the detailed study for more information on the categorization of landfill practices and underlying hypotheses.*
[15] The extrapolation should be refined to better assess each country's potential.
[16] The French Fonds Chaleur provides public financial support for the development of renewable heat production.
[17] i.e. lower than the current gap between the various landfill TGAP (tax) regimes.

without additional public support if good conditions to encourage investment are in place.

  - While the smallest installations still require either public support or a high market price, most of the landfills producing more than 1.000 Nm3/h will be able to sign offtake agreements directly with consumers, as demonstrated by the first European examples[18]. On average, landfill biomethane is the production source requiring the smallest amount of public support expressed in €/MWh.

- In "central" gas and EU-ETS market conditions generating a "network" mix of gases at ~€60/MWh[19], landfill biomethane production units with a minimum capacity of 1.500-2.000 Nm3/h (typically accessible on an "average" landfill site of 150.000 to 250.000 t_{waste}/year of capacity) would generate competitive biomethane with a profitability level compliant with project financing ratio, and integrating a revenue transfer to operators of €2-3/tonne of waste, able to cover the above mentioned costs.
- While the RED II Directive clearly flags Landfill gas as a renewable source, the "green value" of the Biomethane from Landfills shall be undoubtedly supported by the EU Taxonomy. A few ambiguities in the criteria to be met for the landfill biogas recovery to be considered an eligible activity under the European taxonomy shall be then corrected, both in the French version and in the other EU versions of the taxonomy. This simplification would prevent the risk of confusion, enhance the appetite for biomethane from landfill sites and sending positive signals to operators.

The companies that commissioned this study support the waste treatment hierarchy and thus the reduction of landfilling (disposal) in Europe. In addition, they wish to highlight the critical importance of adequately accompanying this decrease across Europe with the proper measures to better:

- **Control and measure methane fugitive emissions for the remaining volumes of landfilled waste.**
- **Recognise and optimise the accessible biomethane potential and other relevant forms of energy recovery.**

The contributors to this study support the vision of a 2030 landfilling landscape respecting the EU targets[20], centred around large and high performing landfills, equipped with the proper methane measurement tools and operated according to the highest quality standards including full optimization of their energy recovery potential.

4) **To reach this objective, several recommendations in terms of technical, regulatory and operational evolutions are presented in this study.**
   - Reaching better practices and an average level of methane capture rates corresponding to widespread good practices (N.B. France targets 85% of capture rate by 2030 in the *"France Nation Verte"* Circular Economy Plan[21]) requires overcoming several types of obstacles – *illustration for the French case*:
     - A **technical** challenge to properly measure real methane fugitive emission levels:

[18] In June 2023, a biomethane production unit of ~70GWh/year has been launched by Waga Energy on a Spanish landfill site operated by PreZero (Can Mata site); the biomethane will be commercialized through a long-term unsubsidized Biomethane Purchase Agreement contract.
[19] Hypotheses: long-term gas prices based on market futures up to 2026 then stagnating at ~€40/MWh in the longer term; EU-ETS CO2 prices at €100/tCO2e (corresponding to ~€18/MWh of natural gas) from 2025 up to €105/tCO2e (€19/MWh) in 2040 and raising to €180/tCO2e (€33/MWh) in 2050 corresponding to the EU Commission's central scenario. Those price scenarios lead to a gas sourcing cost of ~€60/MWh over 10 or 15 years starting in 2024.
[20] The total volume of landfilled waste has already significantly decreased in France historically: -31% between 1999 (landfill directive) and 2020 (last reliable available data); the French landfill sector is pursuing efforts to accompany this continuous decrease up to the achievement of the EU target of 10% landfilled MSW.
[21] See the « France Nation Verte » working document (link)

- Landfill sites are not equipped with methane emissions' continuous monitoring, which is an emerging technology being developed in priority for the oil & gas industry. High seasonal and local variations make one-off measures globally unreliable unless conducted on a regular basis.
- This leaves operators dependent on theoretical biogas production and capture modelling, which are an insufficient basis to build proper result-based incentive mechanisms or to build reliable business plans to engage significant investment.
  - *N.B. Additionally, the quickly changing climate conditions and waste mixes are making the current modelling tools like IPCC framework increasingly unreliable year-on-year.*

o A **lack of recognition** of good practices and a **lack of incentive to improve the performance of methane capture and energy recovery**, both in national reporting and in the fiscal framework:
- **The level of landfill emissions declared at the national level** are estimated with highly variable methodologies and high levels of uncertainties, discrediting the operators' practices.
- **Fiscal incentives are not always effectively encouraging improved operations[22].**

- Considering those elements, the collaborators in this study propose a series of **concrete recommendations for policy makers and private and public market players, to revamp the existing landfill sector to maximise their opportunities and lessen their impact on the environment**.
  - o Build a **Best Available Techniques Reference Document (BREF)** dedicated to non-hazardous waste landfills to harmonize, spread and detail good operating practices.
  - o Engage in a **review of the "Monitoring, Reporting and Verification" methodologies.** First ideas include:
    - Review the national reporting methodologies and better articulate them with corporate ones that, for many operators, are done using sophisticated internal tools and expertise to reach higher degrees of reliability in estimates.
    - Review and standardize measurement methodologies including, for the biggest sites, some rules in terms of actual fugitive emission measures (standardization of frequencies and number of measures), propose a certification system.
    - Promote a **European harmonization of MRV[23] methodologies**, for example through the launch of an EU program involving several States and operators.
  - o **Review the Landfill Directive** to integrate the above changes and (1) **impose a measurement system for fugitive emissions** and (2) **impose a target for methane capture rates** (with an adapted timeline to achieve the target depending on each country's situation).
  - o **Adapt some key regulations** to operating needs – in particular: give more flexibility to operators to maintain the adequate humidity levels of waste masses by enabling re-injection more largely than for bioreactors and increasing the sources of water available for re-injection (leachate from other sites, industrial wastewater…), in accordance with the humidity and the composition of the accepted waste.
  - o **Encourage biomethane landfill production through adequate support mechanism, regulatory consistency and continuity over time to produce**

[22] e.g. in France: (1) the energy recovery criteria is based on the share of captured biogas flared and recovered without considering the actual capture rate performance (2) the operating mode criteria is based on the nature of the equipment – the bioreactor – without considering whether this equipment is adequately operated and reaches good results in terms of capture rates. Additionally, the decision to progressively reduce and cancel this fiscal advantage instead of reshaping it to better target efficient criteria generates a risk to see further degradation of global operating practices and a reduction of operators' investment in the landfill sector.
[23] Monitoring, Reporting and Verification.

significant volumes at market price and without subsidies (except for the smallest installations) and thus generate financial flows for operators to finance the actions above. Among other, provide stability in the status of landfill biomethane and in the ability for consumers to recover it as a decarbonised energy in the regulatory systems like EU-ETS.

- **Rethink the fiscal and support framework to incentivize concrete operational and methane capture performance improvements, tending to encourage results (as far as measurable) rather than means**.
- **Harmonize EU Taxonomy with RED II:** while both the RED II Directive n°2018/2001 and the Commission Delegated Regulation (EU) 2021/2139 on Taxonomy clearly identify Landfill gas as a renewable energy, the latter introduces some ambiguity that may jeopardize the strategy of better capture and valorise landfill gas.
- **Integrate the landfill sector in the European projects to develop continuous fugitive methane emissions measuring technologies** (Copernicus Sentinel Program, CoCO2 project) to prepare the longer-term, when continuous measure on large landfill installations will allow a proper emission-based incentive system to be implemented.

TABLE OF CONTENT

TABLE OF CONTENT

INTRODUCTION 11

I. The good operating practices currently achievable in French storage facilities enable operators to significantly reduce the total direct and indirect emissions generated by "average" operating practices, and to increase the volume of energy recovered and associated avoided emissions. 13

A. Total direct and indirect emissions vary widely depending on the operating practices of landfill operators 13

B. Landfill properly managed is a relevant solution in terms of energy recovery 14

C. “Good practices” are realistic operating conditions today, effectively put in place in ~25 to 30% of Suez and Veolia’s French landfills 16

II. While pursuing the landfilling decrease objective, by achieving a general upgrading of landfilling operations, the sector would be able to reduce by ~30% the 2030 GHG emissions compared to current average practices, at a reasonable abatement cost of ~20€/tCO2e, partly financed by additional energy recovery 20

A. Even in a context of drastic reduction of waste volume landfilled, landfills will continue to be biogas emitters 20

B. If conditions to support a general upgrading of landfilling operations were put in place, the corresponding fugitive emissions could be reduced by at least ~30% 26

C. The abatement cost to avoid GHG emissions enabled by the improvement of landfill practices appears to be reasonable at ~€20/t_{CO2eq} 28

D. The costs associated with a “generalisation of good practices” could be largely financed by revenues from energy recovery if the adequate investment conditions are in place 31

III. To accompany emission reduction in the landfill sector, several recommendations in terms of technical, regulatory and operational evolutions can be studied. 35

A. There are circumstantial reasons constraining a switch to “good practices” 35

B. To overcome existing obstacles and reach the emission reduction potential, the collaborators in this study propose a series of concrete recommendations for policy makers and private and public market players, to reposition the landfill sector in a trajectory of continuous improvement in a context of decreasing volumes. 36

APPENDIX 39

APPENDIX N°1: Modelling waste decomposition and GHG emissions in landfills 39

APPENDIX N°2: Link between defined practices and modelling 40

APPENDIX N°3: Methodology and main hypotheses for the calculation of avoided emissions 42

APPENDIX N°4: Larger environmental impact of landfills 43

APPENDIX N°5: Technical performance considered for landfill energy recovery (injection, cogeneration) 45

APPENDIX N°6: Reconstitution of French average mix of practices in SWDS 45

APPENDIX N°7: Reconstitution of current waste mix sent to French landfills 46

APPENDIX N°8: Reference scenario of the waste tonnage and mix sent to landfills in 2035 48

APPENDIX N°9: Alternative mix scenario – France 2035 ... 49
APPENDIX N°10: Alternative volume scenario – France 2035 ... 50
APPENDIX N°11: Economical modelling of changes in landfill management practices ... 51
APPENDIX N°12: Spanish analysis ... 51
GLOSSARY ... 55
BIBLIOGRAPHY ... 56

TABLE OF ILLUSTRATIONS

Figure 1 - Comparison of direct and indirect emissions generated by SWDS in 2020 ... 14
Figure 2 - Comparison of avoided emissions by SWDS equipped with an injection installation and a cogeneration, in the reference mix, under "good" practices. ... 15
Figure 3 - Comparison of the emissions avoided for a ton of waste treated with "bad", "average" and "good practices" in SWDS equipped with an injection system in 2020 ... 15
Figure 4 - Description of "good practices" in landfill ... 18
Figure 5 - Waste mix landfilled in 2020 and in 2035 in the reference scenario. ... 21
Figure 6 - Waste mix landfilled in 2035 in the mix sensitivity scenario ... 22
Figure 7 - Waste mix landfilled in 2020 and in 2035 in the volume sensitivity scenario ... 23
Figure 8 - Estimated French mix of practices in SWDS in 2023 ... 24
Figure 9 – Direct GHG emissions generated by waste landfilled in SWDS between 2024 and 2035, if SWDS would be operated under current French practices ... 25
Figure 10 - Total emissions generated by waste landfilled between 2024 and 2035 in the Reference scenario, the sensitivity analysis on waste mix and sensitivity analysis on volume landfilled ... 26
Figure 11 - Impact of generalisation of good practices on the French standards practices in SWDS ... 26
Figure 12 - Emission reduction that could be generated through the generalisation of "good practices" ... 27
Figure 13 - Emission reduction that could be generated through the generalisation of "good practices" [Alternative scenario on the waste mix] ... 28
Figure 14 - Emission reduction that could be generated through the generalisation of "good practices" [Alternative scenario on the waste volume] ... 28
Figure 15 - Assessment of the cost needed to switch from "bad" / "average" to 'average" / "good" practices ... 29
Figure 16 - Abatement cost linked to the implementation of switch from bad and average practices to average or good practices in SWDS ... 30
Figure 17 - Comparison of the abatement cost switching to "good practices" with abatement costs of renewable energy deployment for the public service ... 30
Figure 18 - Biomethane selling price depending on the biogas production size ... 31
Figure 19 - Biomethane production potential in "Current French practices" vs "Generalized good practices" ... 33
Figure 21 – Modelling assumptions for bad, average and good practices ... 42
Figure 22 - Quantity of carbon sequestered and emitted per tonne of waste according to waste typology ... 44
Figure 23 - Estimation of carbon sequestered and emitted for a ton of waste landfilled in France [kgCO2/twaste, 2020] ... 44
Figure 24 - Breakdown of waste volumes depending on the current practices used in the landfills ... 46
Figure 25 - Breakdown of the waste mix landfilled in 2020 by sources and by waste components. ... 47
Figure 26 - MODECOM 2017 – Municipal Solid Waste mix ... 47
Figure 27 - Average regional C&I mix ... 47

Figure 28 - Projection of the volume of waste sent to landfill in 2035 48
Figure 29 - FNADE waste mix 2050 49
Figure 30 – Reference scenario and alternative scenario mix for 2035 50
Figure 31 - Volume landfilled in alternative scenario 51
Figure 32 - Comparison of French and Spanish mix landfilled in 2020 52
Figure 33 - Comparison of direct and indirect emissions generated by SWDS in 2020 in Spain 53
Figure 34 - Comparison of avoided emissions by SWDS in the Spanish mix 53
Figure 35 - Projection of the volume of waste sent to landfill in 2035 in Spain 54

INTRODUCTION

EU context

The European context on waste management presents important challenges regarding design and operation of non-hazardous waste landfill facilities, with:

- **The necessity to adapt to a strong decrease in the total volume of waste landfilled and to the changing nature of such waste**. The EU has set a target to reach a maximum of 10% of Municipal Solid Waste landfilled by 2035, which on average requires to divide by 2 the total amount of landfilled MSW in the coming decade (EU-27average currently at ~23%), and in some countries by up to 4 or more (e.g. in Poland the current share is ~40%, in Portugal ~51%, in Spain ~52%[24]). Additionally, the increasing diversion of biodegradable waste from landfills imposes adaptation for operators to maintain the optimum level of humidity in their installations[25];
- **The requirement to better measure and control methane emissions**. The waste sector has been estimated to represent 26% of total EU anthropogenic methane emissions, targeted by the EU Strategy to Reduce Methane Emissions published in October 2020. The strong reduction of such emissions by 2030-35 can only be partly achieved by the diversion of biodegradable waste and the landfilled waste reduction target, as historically landfilled waste as well as the amount of biodegradable waste that will still be landfilled between today and 2035 while progressing towards the target will continue to emit methane in the atmosphere for decades[26]. Thus, **the waste reduction target must be accompanied with proper measures to encourage a better measurement** (strong uncertainties remain today linked to measurement and reporting practices and technological challenges) **and capture** (through a global improvement of average operational practices among European operators) **of methane emissions** in the meantime.
- **An opportunity to significantly contribute to Repower EU Targets for biomethane[27].** Landfills can be important sources of energy recovery when the captured methane is efficiently recovered. Landfill biomethane is currently one of the most competitive biomethane production solutions and has the potential to significantly contribute to the EU renewable gas production targets, thus tackling both decarbonization and energy sovereignty challenges. While the business case for biomethane production becomes increasingly favourable (without public subsidies for a large share of landfill gas produced by EU installations), the investment context to maximize this potential remains challenging for operators (lack of reliable methane production projections, unfavourable fiscal mechanisms[28]).

Objectives of the study

In this context, three key players of the European landfilling sector[29] have performed a study to:

- Analyse with a rigorous methodology, associated with the expertise of experienced market operators, the performance of “best-in-class” landfill installations in terms of direct and indirect emissions and in terms of energy recovery.

[24] Source: CEWEP, Municipal waste treatment in 2020
[25] Landfill’ “good” operating practices are to maintain a certain level of humidity in the cell for the waste to express the largest part of its methane potential early in the degradation process, at a time when good operational conditions are ensured to capture and recover this methane. As the biodegradable fraction of waste decreases over time (an increasing amount of organic waste being diverted to paper/cardboard recycling, composting & biogas installations etc.), landfill cells become dryer and therefore more complicated to operate. Although decreasing in absolute value, the total amount of methane generated in future landfills will become more complicated to control and capture (the biogas decreases in quality for recovery, generating higher filtration costs to deal with increased H2S concentration).
[26] Ten to twenty years according the degradation factor and weather conditions and composition of the mix waste received.
[27] Biomethane Action Plan (within Repower EU) targeting 35bcm by 2030 (~350TWh).
[28] E.g. in France, the fiscal advantage of ensuring the energy recovering of the captured biogas is decreasing year-on-year and will be suppressed from 2025.
[29] Suez, Veolia and Waga Energy

- Estimate the additional potential contribution of the landfill sector to EU GHG emission reduction objectives and to the 35bcm biomethane production target[30], and the associated cost (or profit) for the community, if the existing landfilling reduction targets were accompanied with the proper economic tools and regulatory measures to effectively spread good practices in terms of biogas capture, measurement, and energy recovery across European landfill installations.
- Provide concrete recommendations to operators and public policy makers to achieve such results.

Caveat

- Most analyses performed in this report are based on an average waste mix in France. The results might not reflect the disparities between facilities, although sensitivity analyses have been conducted in order to highlight the impact of major disparities on final results.
- The analysis has been carried out converting the methane emissions in CO2eq emissions using the GWP value for 100-year horizon (28). This indicator is aligned with the CO2 lifetime, for which the resulting warming is mainly due to an accumulation effect. In the case of methane, which only has a lifetime of around 12 years, the warming effect is determined by its short-term concentration. On a 100-year basis, the effect of methane would therefore be underestimated in the first years of the period.
- Hypotheses used in the analysis (technical & operational data, economic data…) come from public sources or from landfill operators.
    - These data **have not been audited by E-CUBE Strategy Consultants**.
    - References are explicitly quoted in the document.
- The results above have been computed at the French perimeter where the contributors to the study were in position to provide detailed data on landfills' operating conditions. Extrapolations have been made at a European level. The extrapolation calculations should be furtherly refined at each country's level.

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[30] Repower EU Targets for biomethane

I. The good operating practices currently achievable in French storage facilities enable operators to significantly reduce the total direct and indirect emissions generated by "average" operating practices, and to increase the volume of energy recovered and associated avoided emissions.

A. Total direct and indirect emissions vary widely depending on the operating practices of landfill operators

For an average waste mix landfilled in France, good operating practices in waste storage facilities allow GHG emissions generated per tonne of waste to be almost halved compared with "average" operating practices

Direct emissions are generated by the methane released in the atmosphere during the waste decomposition. Its amount reflects the methane capture performance of the waste storage facility. Methane is generated during the operating years[31] of the SWDS and beyond, until total decomposition of the waste.

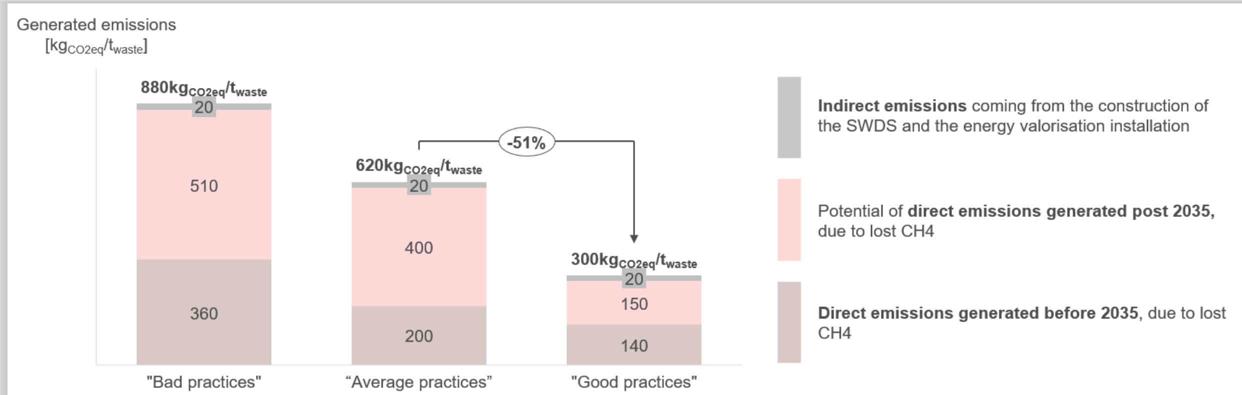
Indirect emissions refer to the emissions linked to the construction and operation of the facilities (SWDS[32] and energy recovery installations). They represent ~20kg_{CO2eq}/t_{waste}[33]**.** Those emissions are relatively low, representing about 5% to 10% of the total emissions generated.

When a landfill installation is properly managed to achieve high capture performance[34] (referred below as **"good operating practices"**), the current average French waste mix[35] generates total direct[36] and indirect[37] GHG emissions amounting to **~300kg_{CO2eq}/t_{waste}**[38]**.**

It can be compared to more than 600kg_{CO2e}/t_{waste} for a landfill operated under "average" practices and close to 900kg_{CO2e}/t_{waste} for landfills operated under "bad practices" (i.e. without biogas capture among others).

The level of emissions generated by non-hazardous waste landfills is highly dependent on the practices implemented by the site operator. "Good operating practices" in waste storage facilities allow GHG emissions generated per tonne of waste to be almost halved compared with "average" operating practices.

31 The operating years refer to the 2 years where the landfill cell is being filled in with waste, before installing the final cover of the landfill cell.
32 SWDS : Solid Waste Disposal Sites
33 Corresponding to indirect emissions coming from SWDS at approximatively 50%, and energy recovery installation at approximatively 50%.
34 Detailed below in the I.C paragraph
35 See APPENDIX N°7 describing the average mix reconstitution (incl. MSW and C&I waste) used in this study.
36 Direct emissions: GHG emissions generated by lost CH4 for 30 years post-operation and residual CO2 that will be lost in the following 50 years post-surveillance until reaching the total decomposition of waste.
37 Indirect emissions: GHG emissions generated during the construction and operation of the treatment installation.
38 See APPENDIX N°2 describing the modelling methodology and hypotheses retained for this study.



- Direct emissions generated by lost CH4 until reaching the total decomposition of waste
- Indirect emissions linked to the construction and operation of the SWDS and the energy recovery installation

Figure 1 - Comparison of direct and indirect emissions generated by SWDS in 2020

A sensitivity analysis on the industrial waste mix landfilled was carried out, with no significant impact on direct and indirect landfill emissions. Uncertainties relating to the industrial waste mix can generate a variation of -5%/+5% of the emission factor of waste treated under “good” and “average” practices.

Indeed, there can be major gaps in the composition of industrial waste sent to landfill, depending on the SWDS and the French regions. It is also difficult to obtain a precise characterisation of this waste[39], which can generate uncertainties at a SWDS level, and at a national level.

Therefore, a sensitivity analysis was carried out to study the impact of variations in the composition of the waste mix on the overall emissions generated by landfilled waste in France. Differences were studied on historical C&I[40] waste mix landfilled in different regions of France[41] with:

- a lower (22%) and higher (35%) share of “food and garden” waste (vs. 30% in average)
- a lower (28%) and higher (58%) share of “paper & wood” waste (vs 46% in average).

Direct and indirect emissions induced by these different waste mix ranged from ~290 to 320kg_{CO2eq}/t_{waste} for landfills managed with “good” operation practices, and from ~580 to 645kg_{CO2eq}/t_{waste} for landfill operated with “average” practices.

These variations in the composition of the C&I waste mix have an impact of more or less ~7% on the direct and indirect emissions from landfill waste recovered by injection or cogeneration.

B. Landfill properly managed is a relevant solution in terms of energy recovery

Avoided emissions generated by landfills operated under “good” practices are 50% higher than the avoided emissions generated by landfills operated under “average” practices

The methane generated in landfills can be recovered through biomethane injection or heat & electricity cogeneration and thus enable to **avoid emissions** (by replacing energy that would have been produced by more carbon-intensive means). By comparing the energy produced with the respective emission factors for

39 See APPENDIX N°7
40 C&I : Commercial and Industrial
41 Source of data used: ORDEEC PACA 2020, ORDECO Occitanie 2017, TEO Pays de La Loire

natural gas, heat and electricity in France (in kg_{CO2eq}/MWh)[42], these avoided emissions would **reach ~110kg_{CO2eq}/t_{waste} for a landfill with injection** and ~**30kg_{CO2eq}/t_{waste} for a landfill with cogeneration**[43]. Avoided emissions could be higher in other countries where the renewable share of electricity / heat production is lower than the French one.

NB: Energy recovery solutions – injection or cogeneration installations – are complementary. In some cases, installing a biomethane injection system may not be possible or profitable

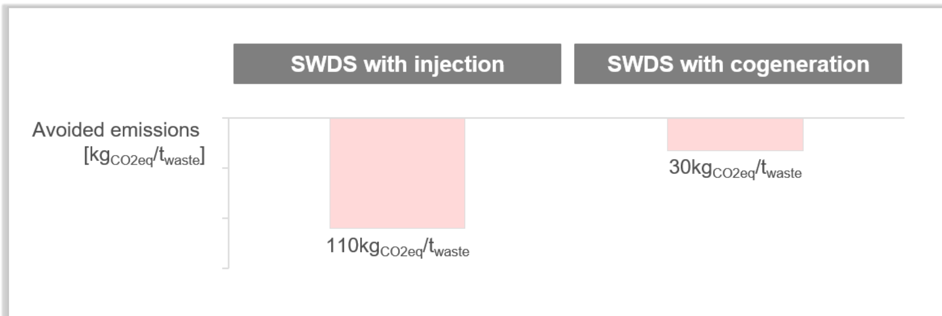


Figure 2 - Comparison of avoided emissions by SWDS equipped with an injection installation and a cogeneration, in the reference mix in 2020, under "good" practices.

Moreover, avoided emissions generated by **landfills managed with good practices are 50% higher than emissions avoided through landfills managed with "average practices**", and more than double what could have been avoided through "bad practices".

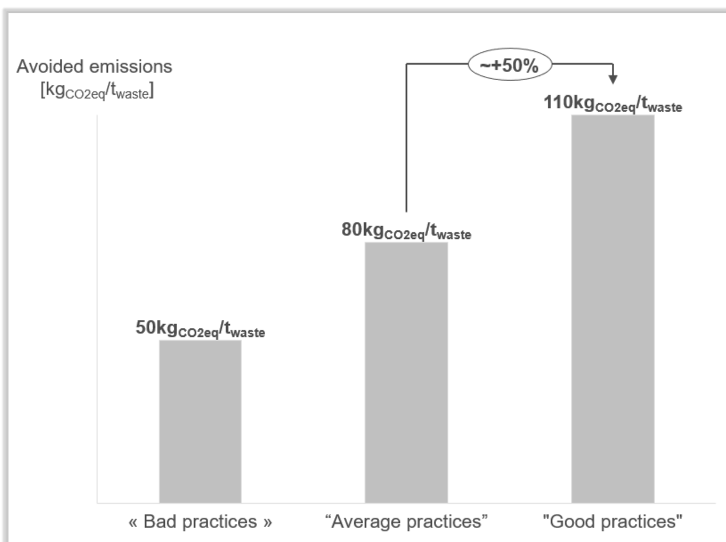


Figure 3 - Comparison of the emissions avoided for a ton of waste treated with "bad", "average" and "good practices" in SWDS equipped with an injection system in 2020

[42] Calculated with 2021 emission factor for electricity: 57kgCO2eq/MWh, and heat: 125kgCO2eq/MWh. See APPENDIX N°5 for more details.
[43] See APPENDIX N°5

A sensitivity analysis on the industrial waste mix landfilled was carried out, showing a similar impact on avoided emissions

A sensitivity on the C&I mix in the mix landfilled has been carried out. The composition of the C&I mix has a similar impact on the avoided emissions. The avoided emissions for the two alternative industrial waste mix treated in SWDS vary by **more or less ~6%** compared with the emissions avoided for the reference mix.

Landfill biomethane could contribute to 5 to 10% of the French and European biomethane injection targets

In Europe, landfill is the second largest source of biogas production (representing ~14% of production in 2021)[44]. In France, ~16 installations were injecting biomethane in 2023 and ~27 installations are expected to be injecting in 2024. In other European countries this number may be higher; in Spain ~40 landfill plants were injecting biomethane in 2021, in Portugal 42 plants.

In the future, **landfills could fulfil a strategic additional supply for biomethane to Europe**. Indeed, as stated by the European Commission, the biomethane potential should be achieved by pulling different types of waste feedstock streams, ensuring the sustainability of the use of feedstocks (food/feed) and limiting the land-use change-risk[45].

In France, landfill biomethane could contribute to ~7 to 10% of the 2030 biomethane injection targets (~2-3TWh depending on production practices – *see Part II-D of the report*); **extrapolated at the EU level, it could represent ~15-20TWh, or ~5 to 10% of the 2030 production target.**

NB: The extrapolation has been made assessing the volume of waste that would be landfilled at the European level from 2024 and 2035, if all countries would decrease the volume of waste landfilled from now to 2035 in order to respect the target of 10% of MSW landfilled by 2035[46]. No assumption has been made on waste characterization at a European level. The methane potential generated by a tonne of waste in France over this period has been extrapolated at a European level.

C. “Good practices” are realistic operating conditions today, effectively put in place in ~25 to 30% of Suez and Veolia’s French landfills

As it was previously illustrated through emissions factor and emission avoidance performance, practices have a major impact on landfills direct GHG emissions.

To better illustrate current practices in place in France, two categories of less efficient operational practices have been considered: an “**average**” practice reflecting standard French practice, and a "**bad**" practice characterising the operational practices of the least well-managed landfills. For those “average” and “bad” practices, a smaller share of the methane is captured, meaning that a larger share of the methane is released into the atmosphere.

“Good” practices distinguish themselves from “average” and “bad” practices mainly from:

- Implementation of an anticipated capture system during the operation phase[47], and immediate implementation of the capture system and final cover at the end of operations.

[44] European Biogas association (EBA) statistical report 2022 – *Ther Biomethane and biogas markets*

[45] European Commission (2022). Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria https://eur-lex.europa.eu/eli/reg_impl/2022/996

[46] A linear decrease of waste landfilled in each country has been computed from EUROSTAT 2021 data to 2035, in order to reach the target of 10% of MSW landfilled by 2035. No assumption has been made on waste characterization at a European level. The methane potential generated by a tonne of waste in France over this period has been extrapolated at a European level.

[47] Period of ~2 years when the cell is being filled with waste.

- Implementation of an impermeable final cover with a bioreactor system properly operated for maintaining the right humidity rate in the long-term, allowing to optimize methanisation conditions and degradation until the stabilisation of the waste and the landfill waste body (no more settlement or leachate produced requesting a strong treatment).
- Optimization of the rate of energy recovery for the captured biogas, consistent flaring of the non-recovered biogas in the long term[48] and adequate implementation of additional treatment processes (natural oxidation, biofilters etc.)

The corresponding "good practices" are realistic operating conditions today, effectively put in place in ~25 to 30% of Suez and Veolia's French landfills.

Details of the technical and operational choices that are referred to as "good", "average" and "bad" practices in this study

Different factors impact performance of methane capture from landfilling until total decomposition of waste. Eight operational and technical practices can illustrate the latitude of choices given to operators, which are:

1. The installation of a temporary capture system during the operating phase (or not),
2. The installation of a definitive capture system with or without delay once the landfill is closed,
3. The use of a high-performant cover (impermeable) or a less performant cover (semi-permeable cover),
4. The use of a bioreactor (or not),
5. If a bioreactor is installed: the performance of the bioreactor,
6. The level of quality of reporting and maintenance operations,
7. The implementation of an energy recovery system for the captured methane (or not),
8. The quality of management of residual methane emissions throughout the life of the waste.

The "good practices" scenario depicted in this study corresponds to the good existing practices to limit emissions as much as technically possible, based on different performances on the 8 operational and technical practices developed above.

Therefore, "good practices" refer to a landfill where:

1. An anticipated capture system is installed as soon as technically feasible during the operating phase,
2. The final cover and capture system are installed without delay when a landfill cell is closed,
3. The cover used is impermeable, enabling a theoretical capture rate of 90% of methane emissions,
4. The landfill is equipped with a bioreactor,
5. The bioreactor is keeping 60% of wastes at an optimal humidity level,
6. Important maintenance and reporting operations are carried out,
7. Captured gas is recovered instead of being flared,
8. Residual methane emissions are limited by the use of treatment processes (natural oxidation, biofilters, etc.) throughout the waste decomposition process.

"Average practices" refer to a landfill where:

1. No anticipated capture system is installed during the operational phase of a landfill,
2. The final cover and capture system are installed without delay when a landfill cell is closed,

[48] Biogas that cannot be captured nor recovered has to be flared in order to convert it into CO2 that has a lesser environmental impact (due to a lower global warming potential). This can require a reinvestment in a flaring equipment to adapt to the gas flow evolution over time.

3. The cover in place is impermeable, enabling a theoretical capture rate of 90% of methane emissions,
4. The landfill is not equipped with a bioreactor or is equipped with a bioreactor not or poorly exploited,
5. No waste is therefore kept at an optimal humidity level thanks to a bioreactor,
6. Moderate maintenance and reporting operations are carried out on the installation during surveillance period,
7. Captured gas is recovered through cogeneration or injection instead of being flared,
8. Leakage of residual methane emissions is partially limited by the use of treatments (natural oxidation, biofilters, etc.) until the total decomposition of the waste.

Finally, "Bad practices" are defined as follow:

1. No anticipated capture system is installed during the operational phase of a landfill,
2. A delay of 2 year is taken between the final cover installation and an additional year of delay for the capture system installation[49],
3. The cover in place is semi-permeable, enabling a theoretical capture rate of 85% of methane emissions,
4. The landfill is not equipped with a bioreactor,
5. No waste is therefore kept at an optimal humidity level thanks to a bioreactor,
6. Poor maintenance and poor reporting operations are carried out on the installation during surveillance period,
7. Captured gas is flared,
8. Lack of treatment on the residual methane emissions, leading to significant leakage until the total decomposition of the waste.

The link between the defined practices and the waste degradation model is defined more precisely in APPENDIX N°2: Link between defined practices and modelling

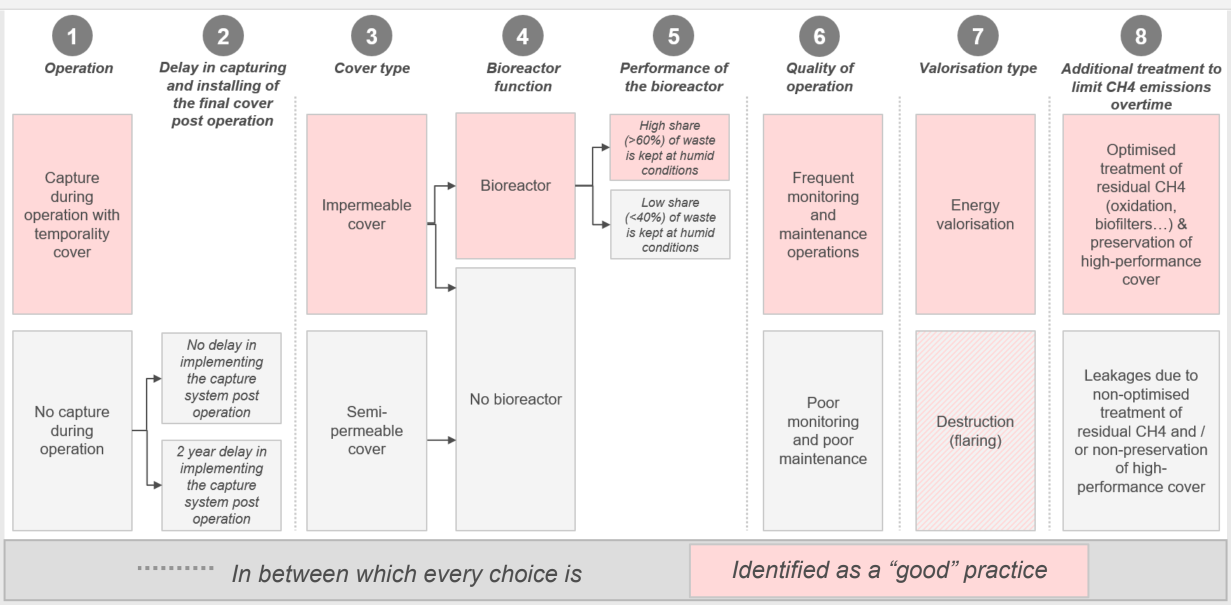


Figure 4 - Description of "good practices" in landfill

[49] *Arrêté du 15 février 2016 relatif aux installations de stockage de déchets non dangereux* [Link to the legislative text]

Conclusion:

Landfill operating conditions are a determining factor regarding their environmental impact. Currently achievable good operating practices, reaching a high level of methane capture (~80%) and energy recovery, enable operators to reduce by ~50% the total direct and indirect emissions generated with "average" operating practices and to increase biomethane production (generating +50% in terms of avoided emissions through the replacement of fossil natural gas).

Therefore, the study further analysed the environmental impact at a country level (France) of a potential evolution of the landfill operating practices, complementary to waste volume reduction in landfills.

II. While pursuing the landfilling decrease objective, by achieving a general upgrading of landfilling operations, the sector would be able to reduce by ~30% the 2030 GHG emissions compared to current average practices, at a reasonable abatement cost of ~20€/tCO2e, partly financed by additional energy recovery

A. Even in a context of drastic reduction of waste volume landfilled, landfills will continue to be biogas emitters

Even in the most ambitious scenarios, **the existing and future landfilled waste will continue to contain a share of degradable waste and to be biogas emitters**.

As an illustration, the exercise of estimating the volume and mix of waste landfilled in 2035 in France has been conducted during the study, considering a scenario respecting the European and French waste management targets (i.e. maximum of 10% of MSW landfilled by 2035, objectives in terms of recycling of various waste types, separate collecting and valorisation of organic waste etc.)

- This reference scenario leads to a total remaining amount of **organic waste[50] landfilled in 2035 of 3Mt** (42% of total landfilled waste) on an annual basis.
- **Cumulated over 2024-2035, a total of 63Mt of organic waste would be landfilled in the reference scenario and would therefore generate fugitive methane emissions in the coming decades.**

[50] Organic waste refers to food, garden, paper and cardboard waste.

The evolution of the **waste volume and mix** to be landfilled between 2024 and 2035 has been scenarized at the French perimeter to assess the future emissions that would be generated from landfills. The waste mix has been scenarized projecting:

- A municipal waste mix **aligned with FNADE's voluntarist scenario**[51].
    - The 2035 mix has been calculated computing an exponential decrease from MODECOM 2017 to FNADE 2050[52].
- A C&I waste mix that evolves according to each waste mix evolution projected in municipal waste mix evolution.

The waste tonnage to be landfilled in 2035 has been scenarized projecting:

- FNADE's voluntarist scenario, foreseeing ~7Mt of waste to be landfilled in 2035.
  That **10% of municipal waste would be landfilled in 2035, in compliance with the Landfill directive**[53]

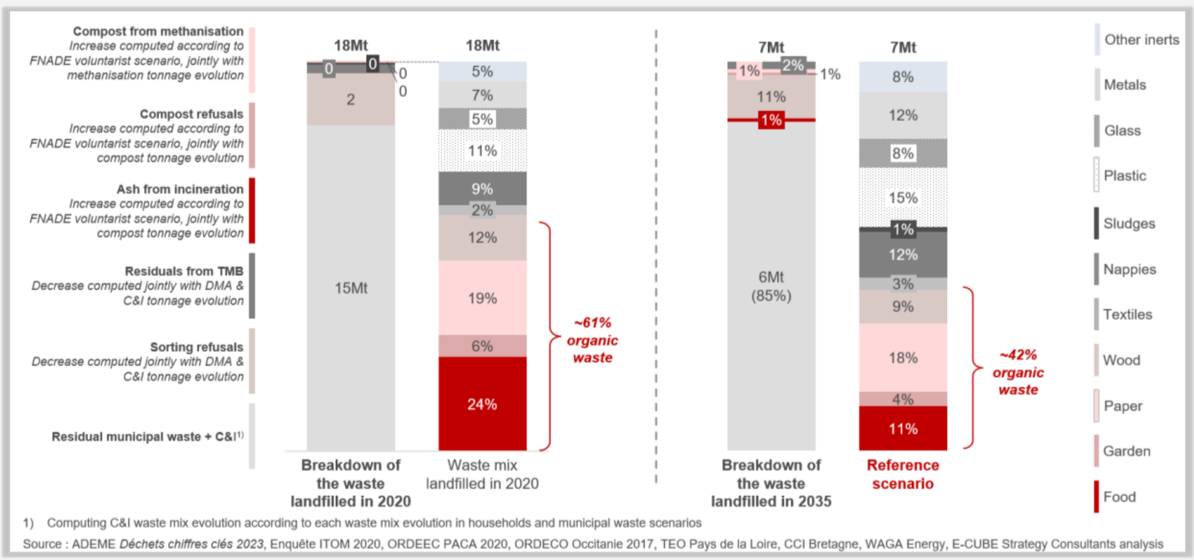


Figure 5 - Waste mix landfilled in 2020 and in 2035 in the reference scenario.

	2020 *Reconstituted from ADEME & FNADE's data*	**2035** *Reference scenario*
Tonnage of waste landfilled	~18Mt	~7Mt of which ~4Mt will come from municipal waste
Share (and tonnage) of organic waste landfilled	~61% (~11Mt)	~42% (~3Mt)

Table 1 - Summary of key assumptions relating to Reference Scenario

[51] FNADE "Voluntarist scenario", was established by the FNADE within the framework of the construction of the 3rd edition of the SNBC and referred to as a voluntarist trajectory of evolution of tonnages and waste flows sent towards different modes of treatment. The scenario has been communicated to main players of the sector, and to public authorities. It has been made public at the beginning of August 2023 : https://www.fnade.org/fr/kiosque-agenda/publications/4860,Analyse-prospective-FNADE-de-la-gestion-des-dechets-a-horizon-2050
[52] See APPENDIX N°7 describing the waste mix reconstitution used in this study.
[53] Landfill directive: council Directive 1999/31/EC of 26 April 1999 on the landfill of waste

Sensitivity on a mix with a higher organic share:

Only ~20% of the French population is currently covered by a solution for sorting bio-waste separately. Among these, 2/3 are covered because they compost it themselves at home. In view of the delay in generalizing separate sorting of household waste[54], 2035 mix risks to be composed of a higher share of biowaste than the one projected in the Reference mix.

Therefore, a sensitivity on the share of biowaste has been studied. For this purpose, an alternative mix scenario has been constructed to consider a projection where the bio-waste reduction is less efficient, resulting in a more organic landfill mix in 2035.

- This scenario leads to a total remaining amount of organic waste landfilled in 2035 of ~4Mt (54% of total landfilled waste) on an annual basis.
- Cumulated over 2024-2035, a total of 72Mt of organic waste would be landfilled in this scenario and would therefore generate fugitive methane emissions in the coming decades.

The alternative mix has been scenarized as follows:

- A municipal waste mix aligned with FNADE's voluntarist scenario. The 2035 mix has been calculated computing a linear decrease from MODECOM 2017 to FNADE 2050. (cf APPENDIX N°8)
- A C&I waste mix that evolves according to each waste mix evolution projected in municipal waste mix evolution.

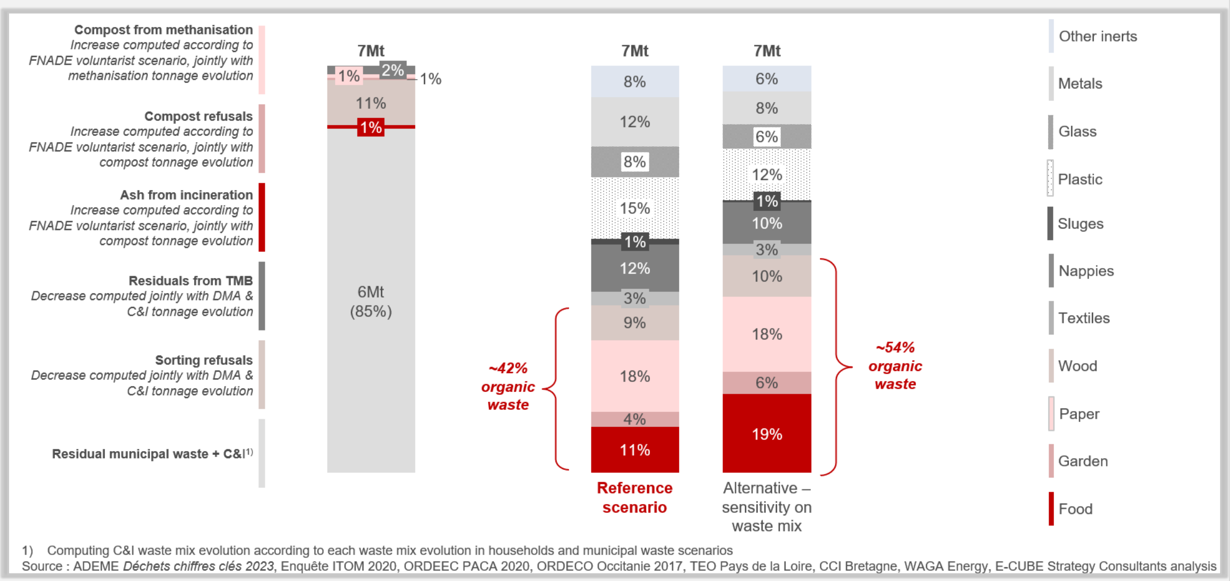


Figure 6 - Waste mix landfilled in 2035 in the mix sensitivity scenario

In this alternative scenario ~7Mt of waste would be landfilled in 2035, with the organic share representing ~54% (vs ~42% in the reference scenario).

[54] Vincent Coissard, Deputy Director in charge of waste and the circular economy at the French Ministry of Ecological Transition, acknowledges that a delay of "one, two, or even three years could be necessary" to generalise separate bio-waste collect during a symposium organised by Amorce in June 2023.

	2020 *Reconstituted from ADEME & FNADE's data*	**2035** *Reference scenario*	**2035** *Mix sensitivity scenario*
Tonnage of waste landfilled	~18Mt	~7Mt of which ~3.6Mt will come from municipal waste	~7Mt of which ~3.6Mt will come from municipal waste
Share of organic waste landfilled	61% (~11Mt)	~42% (~3Mt)	54% (~3.8Mt)

Table 2 - Summary of key assumptions relating to Alternative mix scenario

Sensitivity on higher volume of waste landfilled by 2035:

A second sensitivity has been studied considering a situation in which the target of reducing the tonnages sent to landfill is not achieved (i.e. the more than 10% of municipal waste is sent to landfill in 2035).

- This scenario leads to a total remaining amount of organic waste landfilled in 2035 of ~3.3Mt (42% of total landfilled waste) on an annual basis.
- Cumulated over 2024-2035, a total of 63Mt of organic waste would be landfilled in this scenario and would therefore generate fugitive methane emissions in the coming decades.

The alternative mix has been scenarized as follows:

- A municipal waste and C&I mix similar to the reference scenario mix
- A municipal waste tonnage for 2035 calculated computing a linear decrease from MODECOM 2017 to FNADE 2050. (see APPENDIX N°8)

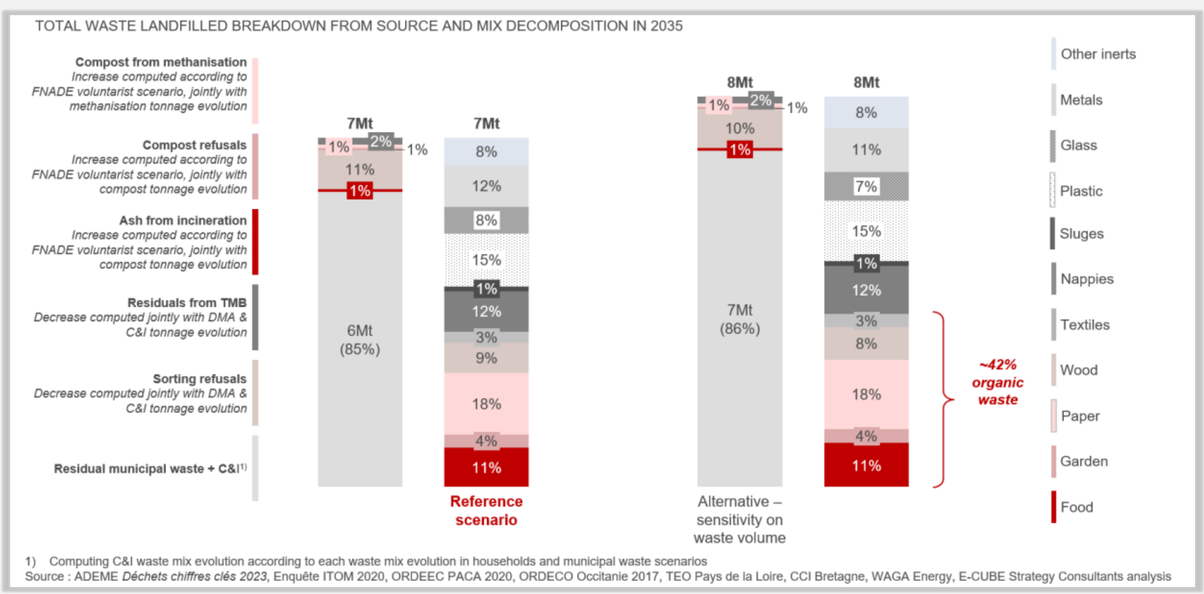


Figure 7 - Waste mix landfilled in 2020 and in 2035 in the volume sensitivity scenario

In this alternative scenario ~8Mt of waste would be landfilled in 2035. The total volume of municipal waste generated remains the same as in the reference scenario, i.e. ~36.5Mt in 2035. In this scenario, **~12% of municipal waste** is landfilled in 2035.

	2020 *Reconstituted from ADEME & FNADE's data*	**2035** *Reference scenario*	**2035** *Volume sensitivity scenario*
Tonnage of waste landfilled	~18Mt	~7Mt of which ~3.6Mt will come from municipal waste	~8Mt of which ~4.5Mt will come from municipal waste
Share of organic waste landfilled	61% (~11Mt)	~42% (~3Mt)	42% (~3.4Mt)

Table 3 - Summary of key assumptions relating to Alternative tonnage scenario

Emissions from landfilled waste between 2024 and 2035 based on current practices in France

Based on this scenario of changes in the mix and volume of waste landfilled between 2024 and 2035, and on average practices to date in France, it is possible to calculate the emissions involved in landfilling waste over this period.

The "average practices to date in France" have been modelized as a distribution of the three cases of operating practices defined in *paragraph I-C* (referred to as "good", "average" and "bad"). This distribution has been made on the basis of Veolia and Suez' analysis of their own portfolios and extrapolated to all French landfills using national reporting databases.

With the above methodology, it can be considered that ~38% of French landfilled waste is currently treated with "good" practices, ~49% with "average" practices and ~14% with "bad" practices. (See APPENDIX N°6)

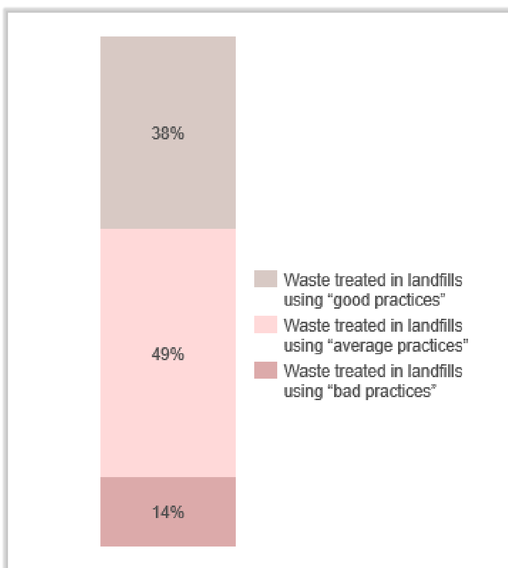


Figure 8 - Estimated French mix of practices in SWDS in 2023

This makes it possible to calculate the average direct, indirect and avoided emissions for one tonne of waste landfilled in France: **direct GHG emissions[55] of an average mix of waste landfilled between 2024 and 2035 represents ~460kg$_{CO2eq}$/t$_{waste}$,**

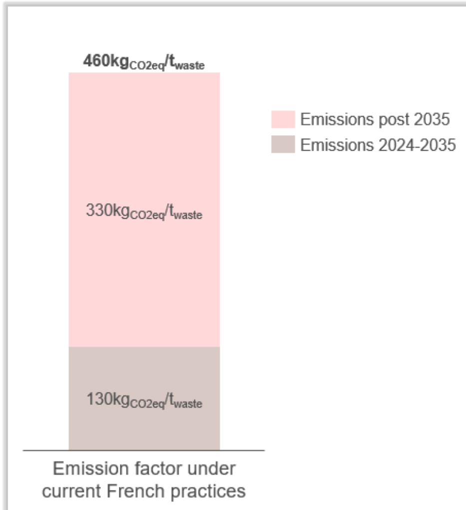


Figure 9 – Direct GHG emissions generated by waste landfilled in SWDS between 2024 and 2035, if SWDS would be operated under current French practices

*Even with a strong ambition to reduce the volume of waste landfilled, organic waste that will be landfilled over the period 2024-2035 will emit **~58Mt$_{CO2eq}$** over their entire lifetime in the reference scenario, **~30%** of which will be expressed over the first 12 years, generating in average **~1.5Mt$_{CO2eq}$/year** over 2030-2035.*

At the French perimeter, considering that operating practices are maintained in the next ten years as they are today[56], all waste landfilled between 2024 and 2035 have a potential of generating **~58Mt$_{CO2eq}$** into the atmosphere (cumulated over their whole degradation period), representing in average **~1.5Mt$_{CO2eq}$/year between 2030 and 2035**.

For both sensitivity analyses – scenarizing a higher share of organic waste or a higher volume of waste landfilled in 2035 – the emission generated would be higher than in the reference scenario

- *Sensitivity on waste mix:* If the mix of waste landfilled were to be **more organic** than the one forecasted in the reference trajectory, emissions generated by waste landfilled between 2024 and 2035 would amount **~62Mt$_{CO2eq}$ (+8% vs reference scenario)**.
- *Sensitivity on waste volume:* If the volume of waste landfilled were to be **more important** than the one forecasted in the reference trajectory, emissions generated by waste landfilled between 2024 and 2035 would amount **~59Mt$_{CO2eq}$ (+2% vs reference scenario)**.

[55] Direct emissions refer to CH4 emissions in the atmosphere during surveillance period of landfill operators and post-surveillance period until total waste degradation. Indirect emissions refer to emissions linked to the construction of the landfill.
[56] Which is uncertain in a context of decreasing volumes.

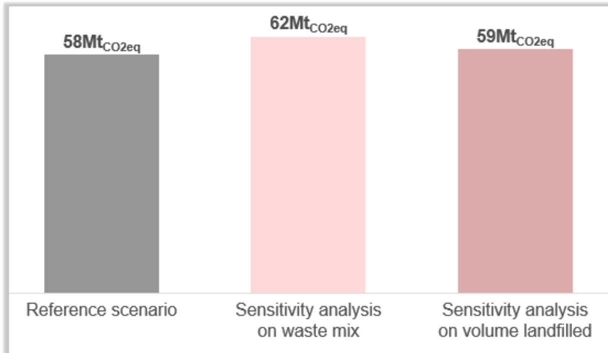


Figure 10 - Total emissions generated by waste landfilled between 2024 and 2035 in the Reference scenario, the sensitivity analysis on waste mix and sensitivity analysis on volume landfilled

Conclusion:

Until 2035 and onwards, biowaste will still be sent to disposal and landfills will still be fuelled by organic waste generating biogas production. In the long term, landfill may also remain the outlet of compost refusals or municipal waste refusals.

B. If conditions to support a general upgrading of landfilling operations were put in place, the corresponding fugitive emissions could be reduced by at least ~30%

Putting in place the conditions to support a general upgrading of landfilling operations (while pursuing the landfilled waste decrease target) could allow the sector to reduce its 2030-35 emissions by ~30%

The widespread adoption of “good” practices has been modelled as follows:

- “Average” practices would be converted into "Good” practices,
- “Bad” practices would be converted into "Average” practices.

This generalisation of good practices in SWDS management would therefore represent a mix of **~86% of SWDS managed with good practices in 2035, and ~14% with average practices**, with bad practices tending to disappear.

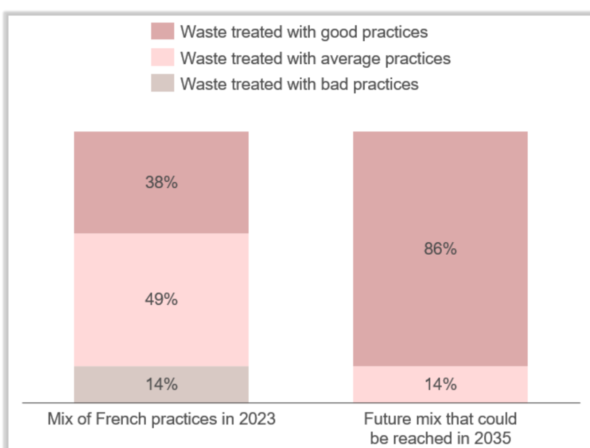


Figure 11 - Impact of generalisation of good practices on the French standards practices in SWDS

Switching from the actual mix of practice to this target mix of practice (later referred to as "Generalisation of good practices") would have a major impact on the emission of the landfilled waste. It could enable[57]:

- **A reduction of ~-21Mt$_{CO2eq}$ (-36%) of emissions due to the degradation of waste landfilled between 2024 and 2035**, compared to the "business-as-usual scenario". ~37Mt$_{CO2eq}$ would then been cumulated over the whole degradation period of the waste landfilled from 2024 to 2035 compared to ~58Mt in the scenario maintaining the current mix of French practices.
- **A reduction of ~28% the annual emissions generated by waste degradation at 2030-2035 horizon,** resulting in ~1.1Mt$_{CO2eq}$/year in 2030-35 (vs ~1.5Mt$_{CO2eq}$/year in the "business-as-usual" scenario)[58].

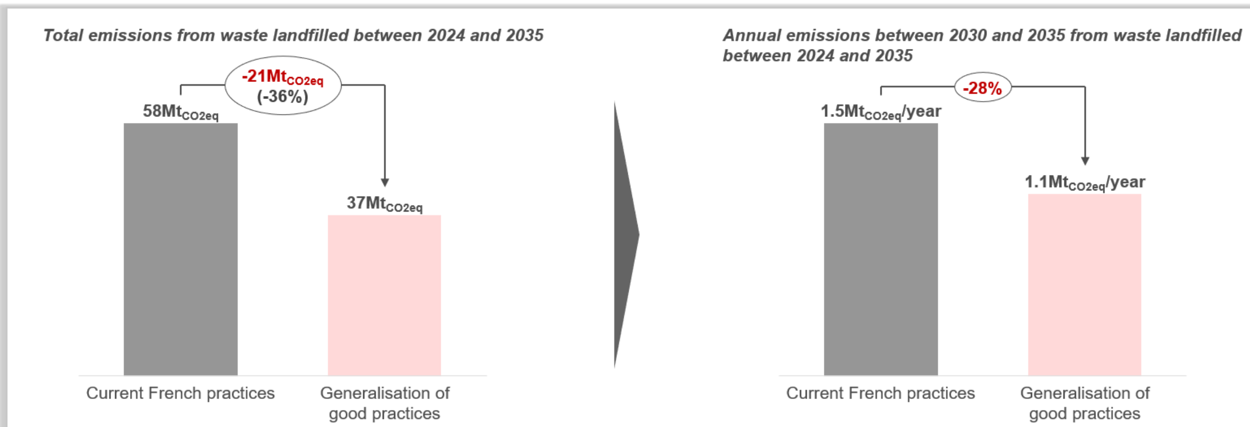


Figure 12 - Emission reduction that could be generated through the generalisation of "good practices"

For both alternative scenarios - a higher share of organic waste or a higher volume of waste landfilled in 2035 – the emission reduction potential would be higher than in the reference scenario

Sensitivity on a mix with a higher organic share	*Sensitivity on higher volume of waste landfilled by 2035:*
In the alternative scenario, the same volume of waste is landfilled until 2035, but 54% of organic waste compared to 42% in the reference mix[59]. Therefore, for an equivalent volume landfilled, emissions generated by waste landfilled from 2024 to 2035 would be higher, reaching **~62Mt$_{CO2eq}$** if current average practices were maintained. A generalisation of "good practices" would therefore	In the alternative scenario, the same waste mix is landfilled until 2035, but ~12% of municipal waste remain in landfills in 2035 instead of 10%. Therefore, for the same mix landfilled, total emissions generated by waste landfilled from 2024 and 2035 would be higher, reaching **~66Mt$_{CO2eq}$** if current practices were maintained. A generalisation of "good practices" would therefore enable to avoid **~22Mt$_{CO2eq}$** for waste landfilled between 2024 and 2035.

[57] Considering that all landfills operated without methane recovery are upgraded to follow at least the "average" operating practices, and that landfills currently operating under "average" practices upgrade to "good" operating practices – *See the detailed study for more information on the categorization of landfill practices and underlying hypotheses.*
[58] According to the CITEPA inventory data, the landfill sector emits every year ~12-13Mt$_{CO2eq}$. This figure refers to emissions from the total waste that has been landfilled in France (vs 1.5Mt$_{CO2eq}$/year estimated for the waste being landfilled between 2024 and 2035). These ~12-13Mt$_{CO2eq}$ represents ~60% of the emissions of the waste sector (excl. collect), ~81% of the emissions of the waste disposal sector, and ~3% of France total emissions. However, these values are still subject to high uncertainties due to the unreliability of measurements and emissions modelling.
[59] See Appendix N°7

enable to avoid **~23Mt$_{CO2eq}$** for waste landfilled between 2024 and 2035.

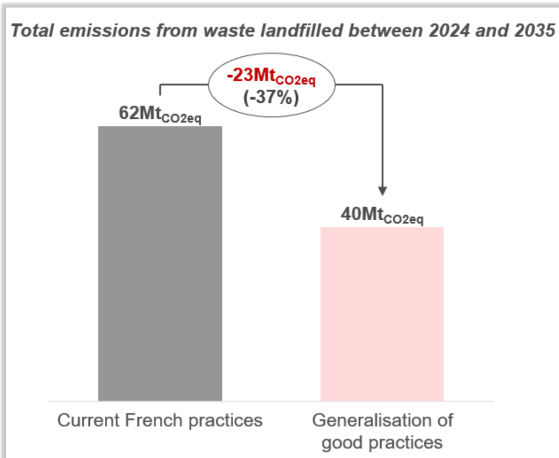


Figure 13 - Emission reduction that could be generated through the generalisation of "good practices" [Alternative scenario on the waste mix]

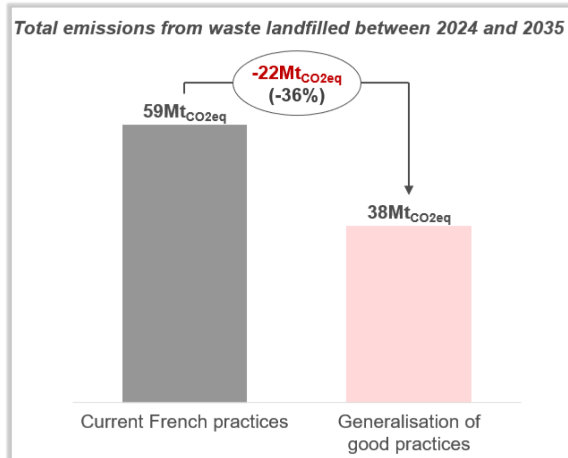


Figure 14 - Emission reduction that could be generated through the generalisation of "good practices" [Alternative scenario on the waste volume]

1) Direct GHG emissions from 2024 correspond to both emissions linked to CH4 lost between 2024 and 2065, and to CH4 lost after the surveillance period, until the waste is completely degraded
2) Emissions during the period 2024-2035
3) Emissions remaining after the latest waste is landfilled in 2035

The results above have been computed at the French perimeter where the contributors to the study were in position to provide detailed data on landfills' operating conditions. Taking the hypothesis that France represents average practices among European countries, **similar results (-30% of annual 2030-35 emissions due to fugitive methane emissions compared to a scenario <u>respecting the EU landfill reduction target</u> but not evolving in terms of landfill operational practices) could be expected at the European perimeter**.

*Note 1: The emission reduction potential presented in paragraphs II-B and C refer to a potential reachable if **the change in practices is achieved in 2024**. Each year of delay to implement those changes would decrease the reduction potential.*

*Note 2: The analysis has been carried out converting the methane emissions in CO2eq emissions using the GWP value for 100-year horizon (28). This indicator is aligned with the CO2 lifetime, for which the resulting warming is mainly due to an accumulation effect. In the case of methane, which only has a lifetime of around 12 years, the warming effect is determined by its short-term concentration. **The upcoming emissions will therefore have a strong impact in the short-term, intensifying the importance to act rapidly**.*

C. The abatement cost to avoid GHG emissions enabled by the improvement of landfill practices appears to be reasonable at ~€20/t$_{CO2eq}$

Switching from bad or average management practices to good practices entails additional OPEX and CAPEX for the SWDS operator[60]

Enhancing landfill's practices to reach "average" or even "good" practices generates additional CAPEX and OPEX to be borne by landfill operators. It includes the cost of high-performance temporary and permanent membranes, bioreactors, or even the cost of re-dimensioning the flare when a capture system is installed, as well as operating and maintenance costs over the period of operation of the landfill and the surveillance period.

These costs differ depending on the practices currently in place in the SWDS concerned. Conversion from a facility with "bad practices" to one with "good practices" requires more investment than transforming a SWDS with "average practices". The nature of the expenses also differs according to the management method in place in the facility.

As the treatment capacity varies significantly from an SWDS to another, ranging from more than one million tonnes treated per year in the biggest facility to less than 10,000 tonnes for the smallest ones, and as there are many different types of landfill cells, the economical values calculated are based on the tonne of waste landfilled[61].

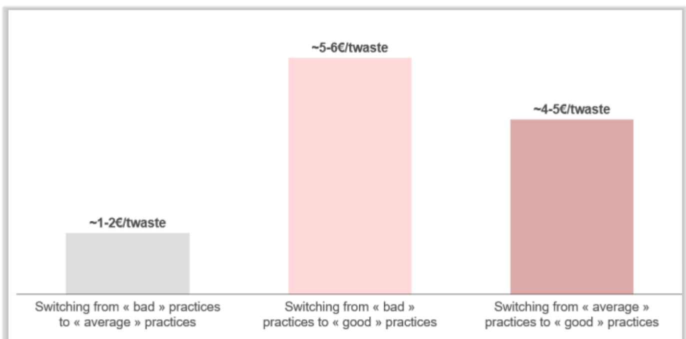


Figure 15 - Assessment of the cost needed to switch from "bad" / "average" to 'average" / "good" practices

Considering the overall changes required to transform SWDS in France from the "current mix of practices" towards a "generalisation of good practices", the average estimated cost would amount ~€3-4/t_{waste}[62]

In average, the abatement cost would represent ~€20/t_{CO2eq}

These investments can also be expressed in terms of emissions avoided through abatement costs, which can be determined for each switch in practice.

Thus, the abatement cost of converting a SWDS from "bad" management practices to one with "average" practices is **~€12/t_{CO2eq}**. Representing the most easily avoidable emissions, with a relatively low abatement cost, this transition represents the first effort to be made in order to limit the largest part of emissions.

Switching from a SWDS with "average" practices to "good" practices requires more cost to avoid the remaining GHG emissions that are more difficult to capture. The abatement cost per tonne of CO2 is therefore higher for this transformation, amounting **~€22/t_{CO2eq}**.

[60] Economic data relating to CAPEX & OPEX have been provided by landfill operators. These data have not been audited by E-CUBE Consultant Strategy.
[61] More details are given in APPENDIX N°13
[62] i.e. lower than the current gap between the various landfill TGAP (tax) regimes.

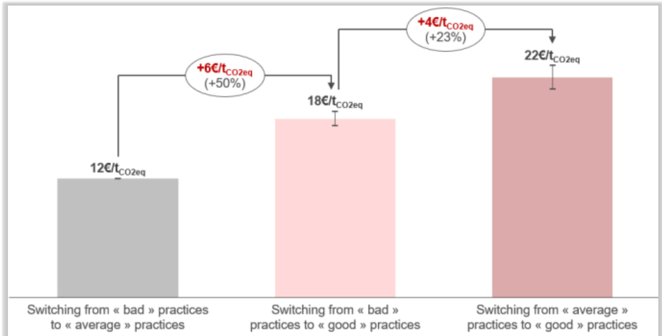


Figure 16 - Abatement cost linked to the implementation of switch from bad and average practices to average or good practices in SWDS

As regards the French mix of practices, the "generalisation of good practices" scenario (i.e. moving from SWDS with "bad" practices to "average" practices, and from "average" practices to "good" practices), would have an average abatement cost of ~€20/t_{CO2eq}.

Considering the alternative mix scenario (sensitivity analysis) affecting the emissions generated by the waste mix in landfill, the abatement cost is relatively lower by ~8%, reaching ~€18/t_{CO2eq}.

The average abatement cost to be deployed in order to reach the "generalisation of good practices" scenario **is in the low range of publicly supported actions such as renewable electricity assets or renewable thermal energy supported by the Fonds Chaleur in France**[63]. As an example, average abatement costs for Fonds Chaleur supported projects oscillate around **~€44-50/t_{CO2eq}**[64].

Encouraging a switch to "good practices" by investing these additional costs therefore appears to be an efficient and relevant solution for the community.

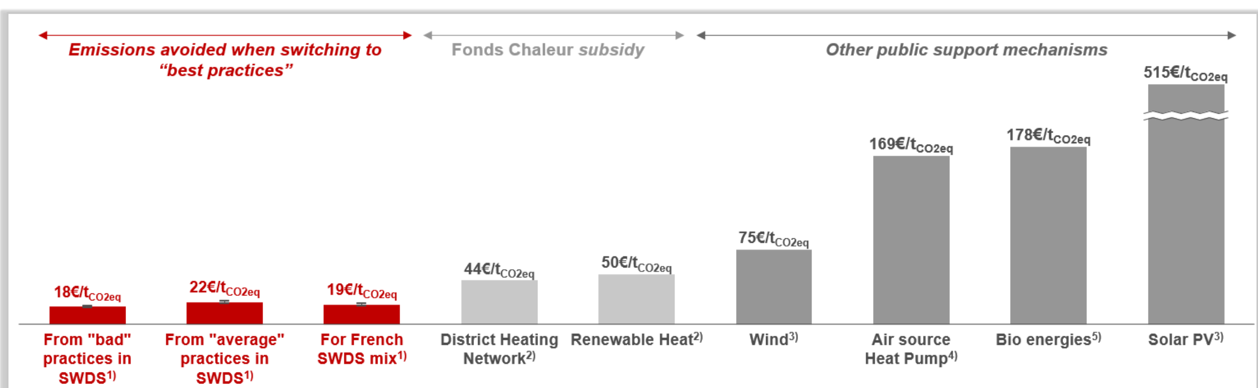


Figure 17 - Comparison of the abatement cost switching to "good practices" with abatement costs of renewable energy deployment for the public service

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[63] The French Fonds Chaleur provides public financial support for the development of renewable heat production.
[64] Calculated as the ratio between the total subsidies attributed and the avoided emissions during the project life.

1) Average value. Minimum and maximum value calculated from Suez and Veolia data differ from ~€1-2/tCO2eq.
2) Average abatement cost for Fonds Chaleur supported projects: total subsidy / avoided emissions in the project life (source: ADEME; Direction Générale du Trésor, « Les énergies renouvelables : quels enjeux de politique publique », Trésor-Eco n°162 03/16)
3) Abatement cost as the average public charge (purchase obligations 2012-2020, source: CRE) divided by avoided emissions (22Mt_{CO2eq}/yr avoided, according to RTE 'Bilan prévisionnel 2019)
4) Average Heat Pump (~4 MWh/yr) as a substitute to an old gas boiler (90% efficiency) in an individual housing, with ~€3.5k subsidy from MaPrime Rénov, for a 20-year duration (source: FEDENE; MaPrime Rénov 1st semester 2022)
5) Purchase obligations and investment support (average abatement cost according to Direction Générale du Trésor, 2016)

*Note: The emission reduction potential and associated cost presented in paragraphs II-B and C refer to a potential reachable if **the change in practices is achieved in 2024**. Each year of delay to implement those changes would decrease the reduction potential and increase the abatement costs.*

D. The costs associated with a "generalisation of good practices" could be largely financed by revenues from energy recovery if the adequate investment conditions are in place

Landfill biomethane is one of the most competitive sources of renewable gas production on the market; a large number of installations should be competitive without public support in 2024-2040 market conditions while generating additional revenue sources for operators to finance the upgrade of operating practices

In "central" gas and EU-ETS market conditions generating a "network" mix of gases at ~€60/MWh[65], landfill biomethane production units with a minimum capacity of 1.500-2.000 Nm3/h (typically accessible on an "average" landfill site of 150.000–250.000 t_{waste}/year of capacity) would generate competitive biomethane, integrating a revenue transfer to operators of €2-3/tonne of waste, able to cover the above mentioned costs.

Sensitivities show that, using the Wagabox© technology, a selling price of the biomethane in a range of 50 to 70 €/MWh would be sufficient to finance on a non-recourse basis, on a 15 year maturity, all CAPEX and OPEX required to implement the upgrading of biogas into biomethane and inject it into the gas grid, including a 3€ per ton of waste paid to the landfill owner to cover to cost for the better capture of the landfill gas.

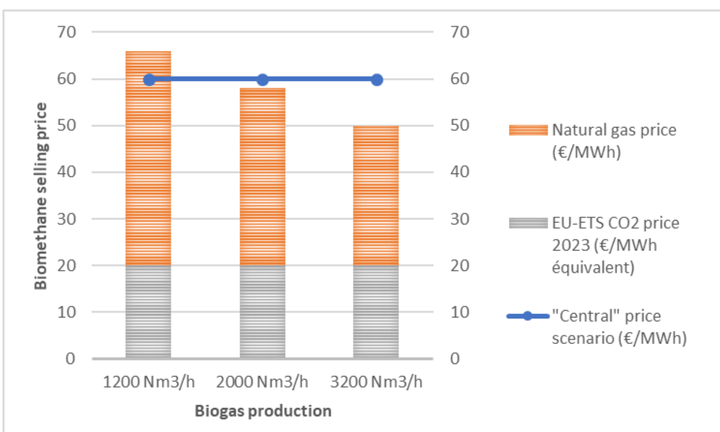

Figure 18 - Biomethane selling price depending on the biogas production size

[65] Hypotheses: long-term gas prices based on market futures up to 2026 then stagnating at ~€40/MWh in the longer term; EU-ETS CO2 prices at €100/tCO2e (corresponding to ~€18/MWh of natural gas) from 2025 up to €105/tCO2e (€19/MWh) in 2040 and raising to €180/tCO2e (€33/MWh) in 2050 corresponding to the EU Commission's central scenario. Those price scenarios lead to a gas sourcing cost of ~€60/MWh over 10 or 15 years starting in 2024.

While smaller installations will still rely on public support, the global envelope of public support required (expressed in €/MWh of produced energy) will be on average lower than other renewable gas production solutions.

It should also be noted that the capture of gas from closed landfills is considered as a sustainable activity by the Taxonomy. However, while both the RED II Directive n°2018/2001 and the Commission Delegated Regulation (EU) 2021/2139 on Taxonomy clearly identify Landfill gas as a renewable energy, the latter introduces some ambiguity that may jeopardize the strategy of better capture and valorize landfill gas. Harmonizing EU Taxonomy with RED II seem compulsory to easily and clearly flag biomethane from landfills as an eligible energy under both regulations.

Several cumulative criteria must be met for landfill biogas recovery to be considered an eligible activity under the European taxonomy rules. This complexity risks creating confusion in the market, reducing the appetite for biomethane from landfill sites and sending negative signals to operators.

The aim of the collaborators in this study is to steer efforts towards better capture of emissions through the implementation of BREF. However, this effort must be focused - and be recognised in the long term - both on landfills opened before 8 July 2020 and on those that may be opened after that date. Furthermore, limiting eligibility for the European taxonomy to "definitively closed" landfills or landfill cells risks calling into question the good practices presented in this study for capturing biogas during the operational phase on open cells - at the very moment when the highest concentration of methane is produced. Furthermore, the rule requiring that the "landfill or landfill cell ... is not taking in further biodegradable waste" may be open to several interpretations: for example, it is clear that a closed landfill cell, in which waste complying with the rules on the prohibition of biodegradable waste has been stored, which is in itself eligible for the taxonomy, may be in a landfill where another landfill cell does not comply with these rules on biodegradable waste. In this case, there is a risk that the eligibility of the "compliant" landfill could be called into question.

Additionally, the generalisation of good practices would optimize the biomethane production potential per ton of waste in a landfill by up to +26%, securing the above business model by adding production at a marginal cost of zero.

Indeed, the generalisation of “good practices” could be partly finance by additional revenues from energy recovery.

In France, **the generalisation of « good practices » could enable to increase by ~26% the biomethane production potential of France to more than ~2.6TWh in 2030.**

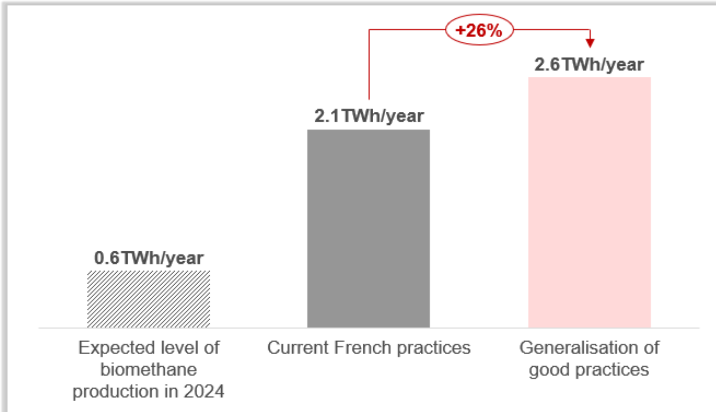

Figure 19 - Biomethane production potential in "Current French practices" vs "Generalized good practices"

This potential has been calculated considering:

- The current dynamic experienced on biomethane injection from SWDS:
  - ~600GWh of biogas should be produced from landfills in 2024 (vs ~440GWh in 2023).
  - In a reference scenario, it has been estimated that the penetration of injection installations would continue at the same rate, reaching ~2.1TWh/year production in 2030.
  - *NB: Reaching ~2.1TWh/year in 2030 is already a challenging target for France. Up to date, ~9TWh of biogas is produced in France every year, and the France Multi-Year Energy Program[66] targets ~24 to 32TWh of biogas produced by 2028.*
- The "generalisation of good practices" scenario does question this dynamic. It considers that landfills that did not have an energy recovery system would be equipped with an injection system. Moreover, all landfills managed with "average practices" would switch to "good practices". Biomethane production would therefore increases in conjunction with these two levers, reaching ~2.6TWh/year in 2030.

This potential may be limited in time, due to two factors:

- the decrease of waste sent to landfill sites up to 2035 (and post-2035),
- the profitability of the investments in energy recovery installations. As energy recovery installation are CAPEX intensive, landfills would need to have visibility on the mid/long term of the volume of waste to invest in energy recovery installations and benefit from.

This additional production of biomethane would therefore partly finance the cost induced by the generalisation of "good practices".

Conclusion :

In addition to the strategy of reducing volumes of waste landfilled, it is highly strategic, at a European scale, to support the « upscaling » of landfill practices according to national situations.

The companies that commissioned this study support the waste treatment hierarchy and thus the reduction of landfilling (disposal) in Europe. In addition, they wish to highlight the critical importance of adequately accompanying this decrease across Europe with the proper measures to better:

- **Control and measure methane fugitive emissions for the remaining volumes of landfilled waste.**
- **Recognise and optimise the accessible biomethane potential and other relevant forms of energy recovery.**

[66] *Programmation pluriannuelle de l'énergie (PPE)* published in 2019

The contributors to this study support the vision of a 2030 landfilling landscape respecting the EU targets[67], centred around large and high performing landfills, equipped with the proper methane measurement tools and operated according to the highest quality standards including full optimization of their energy recovery potential.

[67] The total volume of landfilled waste has already significantly decreased in France historically: -31% between 1999 (landfill directive) and 2020 (last reliable available data); the French landfill sector is pursuing efforts to accompany this continuous decrease up to the achievement of the EU target of 10% landfilled MSW.

III. To accompany emission reduction in the landfill sector, several recommendations in terms of technical, regulatory and operational evolutions can be studied.

A. There are circumstantial reasons constraining a switch to "good practices"

Reaching better practices and an average level of methane capture rates corresponding to a "generalisation of good practices"[68] requires overcoming several types of obstacles.

Regarding the French Case, several barriers have been identified by the major players of the sector, including:

- **A technical challenge to properly measure real methane fugitive emission levels:**
  - Landfill sites are not equipped with methane emissions' continuous monitoring, which is an emerging technology being developed in priority for the oil & gas industry. High seasonal and local variations make one-off measures globally unreliable unless conducted on a regular basis.
  - This leaves operators dependent on theoretical biogas production and capture modelling, which are an insufficient basis to build proper result-based incentive mechanisms or to build reliable business plans to engage significant investment. Difficulties for players to draw up a reliable "cost-benefit" analysis for their projects, slow down investment decisions including in energy recovery installations.
  - *N.B. Additionally, the quickly changing climate conditions and waste mixes are making the current modelling tools like IPCC framework increasingly unreliable year-on-year.*

- A **lack of recognition** of good practices and a **lack of incentive to improve the performance of methane capture and energy recovery**, both in national reporting and in the fiscal framework:
  - **The level of landfill emissions declared at the national level** are estimated with highly variable methodologies and high levels of uncertainties, discrediting the operators' practices.
  - **Fiscal incentives are not always effectively encouraging improved operations[69].** Indeed, the fiscal differentiation introduced by the TGAP attributes value to SWDS equipped with bioreactor or with a geo-membrane, valuing means, and not to the results achieved. It has therefore not been appropriate to encourage the development of "good practices".

- Several regulatory constraints, restraining a quick adaptation to climate changing conditions.
  - As an example, operators are facing increasingly dry waste, yet they do not have the flexibility to use wastewater (or other additional source of water) for leachate circulation, to counter waste dryness.
    - *NB: Monitoring humidity is a crucial challenge as it directly determines the waste degradation kinetic and the amount of biogas that can be produced. For a landfill operator, the challenge is to capture the maximum of the methane generated*

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[68] N.B. France targets 85% of capture rate by 2030 in the "France Nation Verte" Circular Economy Plan

[69] e.g. in France: (1) the energy recovery criteria is based on the share of captured biogas flared and recovered without considering the actual capture rate performance (2) the operating mode criteria is based on the nature of the equipment – the bioreactor – without considering whether this equipment is adequately operated and reaches good results in terms of capture rates. Additionally, the decision to progressively reduce and cancel this fiscal advantage instead of reshaping it to better target efficient criteria generates a risk to see further degradation of global operating practices and a reduction of operators' investment in the landfill sector.

during waste degradation and therefore concentrate this potential during operating & surveillance periods.

B. To overcome existing obstacles and reach the emission reduction potential, the collaborators in this study propose a series of concrete recommendations for policy makers and private and public market players, to reposition the landfill sector in a trajectory of continuous improvement in a context of decreasing volumes.

As the reduction of the potential of emission avoidance is significative overtime, it is highly important to implement these good practices as quickly as possible.

Considering those elements, the collaborators in this study propose a series of **concrete recommendations for policy makers and private and public market players, to reposition the landfill sector, as the complementary essential final treatment solution, in a trajectory of continuous improvement in a context of decreasing volumes**.

1. Build a **Best Available Techniques Reference Document (BREF)** dedicated to non-hazardous waste landfills to harmonize, spread and detail good operating practices.
2. Engage a **review of the "Monitoring, Reporting and Verification" methodologies**,
3. Review the Landfill Directive to integrate the above changes and (1) **impose a measurement system for fugitive emissions** and (2) **impose a target for methane capture rates** (with an adapted timeline to achieve the target depending on each country's situation),
4. **Adapt some key regulations** to operating needs,
5. **Encourage biomethane landfill production** through adequate support mechanism, regulatory consistency and continuity over time to produce significant volumes at market price and without subsidies,
6. **Rethink the fiscal and support framework to incentivize concrete operational and methane capture performance improvements, tending to encourage results** (as far as measurable) **rather than means.**
7. Integrate the landfill sector in the European projects to develop continuous fugitive methane emissions measuring technologies.
8. Harmonize EU Taxonomy with RED II.

1. Build a Best Available Techniques Reference Document (BREF) dedicated to non-hazardous waste landfills to harmonize, spread and detail good operating practices.
   - Up to date, there was no reference document on the Best Available Techniques (BREF) for landfill. The only reference document was the *Landfill directive*[70].
   - Since the revision[7], it has been discussed that landfill should have a specific BREF or be integrated in the BREF regarding waste treatment.
   - Yet, the role of the Best available techniques REFerence document (BREF) is of interest when fiscal incentives promote their application.

2. Engage a review of the "Monitoring, Reporting and Verification" methodologies. First ideas include:
   - Review the national reporting methodologies and tools and better articulate them with corporate ones that, for many operators, are done using sophisticated internal tools and expertise to reach higher degrees of reliability in estimates.
     - In France, interconnectivity between the group / company reporting and CITEPA reporting could be considered.

[70] Directive (EU) 2018/850 amending the Landfill Directive that entered into force on the 5th of July 2020.

    - Review and standardize measurement methodologies including, for the biggest sites, some rules in terms of actual fugitive emission measures (standardization of frequencies and number of measures), propose a certification system.
        - In France, Suez and Veolia are in favour of introducing a filling-in guide to simplify declarations and improve the quality of reporting.
    - Promote a **European harmonization of MRV[71] methodologies**, for example through the launch of an EU program involving several States and operators.
    - **Update the models in order to take into account the increasing dryness of the waste landfilled**, which implies the redefinition of the climatic zone taken into account in the model.

3. **Review the Landfill Directive** to integrate the above changes and (1) **impose a measurement system for fugitive emissions** and (2) **impose a target for methane capture rates** (with an adapted timeline to achieve the target depending on each country's situation).

4. **Adapt some key regulations to operating needs** – in particular: give more flexibility to operators to maintain the adequate humidity levels of waste masses by enabling re-injection more largely than for bioreactors and increasing the sources of water available for re-injection (leachate from other sites, industrial wastewater…), in accordance with the humidity and the composition of the accepted waste.
    - Enable reinjection more largely than for bioreactors, as reinjection could be more than useful to balance with the increasing dryness of waste. Injection could be enabled for open cells during operation, and for landfill cells equipped with a geo-membrane cover but not with a bioreactor.
        - However, such decision should be combined with measures guaranteeing that reinjection is carried out in conjunction with more stringent emission and environmental controls.
    - Seek to increase the sources of water available for re-injection, giving more flexibility in the possibility of using additional water sources and/or water recirculation options: leachate, industrial wastewater, rainwater, treated water, etc.
        - This should be accompanied with a proper monitoring of bioreactors' water balance by operators.

5. **Encourage biomethane landfill production through adequate support mechanism, regulatory consistency and continuity over time to produce significant volumes at market price and without subsidies** (except for the smallest installations) and thus generate financial flows for operators to finance the actions above.
    - There has been a great change in the way biomethane, and its market value are perceived. Today, there are market solutions enabling biomethane to be recovered without support. Market players will be ready to pay for the "renewable" value of gas in the next decade.
    - While public financial support should therefore be dedicated to small sites, the largest ones would require **stability in the status of landfill biomethane and in the ability for consumers to recover it as a decarbonised energy**..

6. **Rethink the fiscal and support framework to incentivize concrete operational and methane capture performance improvements, tending to encourage results (as far as measurable) rather than means**.

[71] Monitoring, Reporting and Verification.

7. **Integrate the landfill sector in the European projects to develop continuous or semi-continuous fugitive methane emissions measuring technologies (Copernicus Sentinel Program, CoCO2 project) to prepare the longer-term**, when continuous measure on large landfill installations will allow a proper emission-based incentive system to be implemented.
    - Under the **Copernicus Sentinel program**, ESA and EUMETSAT are developing a constellation of dedicated satellites that will measure concentrations of carbon dioxide and methane in the atmosphere with an unprecedented combination of coverage, detail, and accuracy. The system is expected to **be fully operational by 2026**.
    - The CoCO2 project, an EU-funded consortium, is currently developing the prototype system, which will be unique by integrating all available information streams in a globally consistent way. Until now, satellite systems measuring methane have been of insufficient resolution to attribute emissions from individual landfill sites. By combining satellite observations with the Earth System modelling and data assimilation capabilities of CAMS, it will provide consistent and reliable information that can be used to support policy- and decision-making with respect to anthropogenic CO2 emissions, at local, national and European level. The main elements of the prototype are expected to be delivered at the end of 2023.
    - Both the RED II Directive n°2018/2001 and the Commission Delegated Regulation (EU) 2021/2139 on Taxonomy clearly identify Landfill gas as a renewable energy and a sustainable activity. However, the latter introduces some ambiguity that may jeopardize the strategy of better capture and valorize landfill gas. Harmonizing EU Taxonomy with RED II seem compulsory to easily and clearly flag Biomethane from landfills as an eligible energy under both regulations.

APPENDIX

APPENDIX N°1: Modelling waste decomposition and GHG emissions in landfills

Waste decomposition in landfills is modelled using IPCC Tier 2 model (IPCC, 2019)[72], which has been updated in 2019, according to the type of organic waste considered ("food"; "garden"; "paper"; "wood"; "textile"; "nappies"; "sludges"). For each of these categories, IPCC takes into account the organic degradable carbon share per tonne of waste (DOC), the fraction of organic carbon that decomposes (DOCf), and the degradation kinetic constant (exp(-k))[73] to model waste decomposition over time. These constants vary according to the climatic conditions of a given geography.

The following tables shows the DOC, DOCf and k values from IPCC per type of waste.

	Food	**Garden**	**Paper**	**Wood**	**Textiles**	**Nappies**	**Sludge**
DOC	15%	20%	40%	43%	24%	24%	5%
DOCf	70%	70%	50%	10%	50%	50%	70%

Table 4 - DOC and DOCf values per waste type - IPCC values

	Temperate Climate					
	Dry			**Wet**		
Type of Waste	Default value	Min value	Max value	Default value	Min value	Max value
Food	0.06	0.05	0.08	0.185	0.1	0.2
Wood	0.02	0.01	0.03	0.03	0.02	0.04
Garden	0.05	0.04	0.06	0.1	0.06	0.1
Paper	0.04	0.03	0.05	0.06	0.05	0.07
Textile	0.04	0.03	0.05	0.06	0.05	0.07
Nappies	0.05	0.04	0.06	0.1	0.06	0.1
Sludge	0.06	0.05	0.08	0.185	0.1	0.2

Table 5 - Methane rate generation constant – IPCC values

For Western Europe, the values considered are those relating to a **'temperate' geography, with a dry climate,** reflecting a slower decomposition of waste than in a humid climate.

General modelling functioning:

- **Input data:**
  - Waste volume landfilled is computed annually.
  - Waste mix landfilled is computed annually.
- **Input parameters:**
  - An evolutive capture rate is entered annually from the year of first disposal until 30 years after the landfill is closed.
  - This capture rate is calculated from input parameters regarding the practices at stake.
- **Calculation**
  - The methane generation is calculated at **an annual step** from the Tier 2 IPCC model according to the waste mix and tonnage entered the same year, and to the waste entered the previous years still in decomposition.

72 IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories - Waste
73 IPCC, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

  - The methane recovered is calculated annual from the generated methane and the capture rate entered.
  - The methane lost is calculated from the difference between the methane generated and the methane recovered, excluding a part that has been oxidized (10% of the methane generated).
- **Output data :**
  - Methane recovered per year
  - Methane lost per year

APPENDIX N°2: Link between defined practices and modelling

The practices described in part one imply different modelling criteria regarding waste decomposition in SWDS:

- Firstly, practices have an impact the **generated methane** modelled
  - **"Use of a bioreactor":** a bioreactor enables leachate to be recirculated, which maintains optimum humidity in the decomposing waste. In this study, the bioreactor is modelled by a change in the moisture content of the waste. This condition is modelled by a change in the degradation kinetic constant k per waste typology, using the values of the IPCC Tier 2 model. It is assumed here that this will keep 60% of the waste moist. It thus affects the methane generated.

- They also influence the **methane recovered** from the methane generated:
  - **"Type of cover"**: Using an impermeable membrane enables a theoretical capture rate of 90% to be achieved.
  - **"Anticipated capture installation"** and **"No delay in installing the final cover and recovery system"**: the implementation of a capture system as soon as a cell is opened is modelled by a positive capture rate from the first year of operation. A ramp-up has been added to model the lower efficiency of a temporary cover during the operating period compared with a temporary cover once the landfill is closed. The capture rate is therefore 45% in year 1 and 90% from year 2 onwards.
  - **"Management of residual methane"**: Membranes deteriorate over time. This loss of impermeability is modelled by leaks, corresponding to a reduction in the capture rate of 1% per year from the 5th year after the opening of the landfill cell.
  - **"Maintenance and reporting"**: It is considered that good monitoring and maintenance practices can prevent a significant proportion of methane losses to the atmosphere. This aspect is modelled by reducing the degradation of the capture rate due to leaks by 10%.

- Finally, they have an impact on **emissions linked to the use of recovered methane**:
  - **"Energy recovery":** methane is recovered by injection or cogeneration instead of simply being flared. Recovered methane is calculated on the basis of the quantities of methane recovered and the technical characteristics of the various recovery methods.

The bad, average and good practices are modelled according to the following characteristics:

	Bad practices	**Average practices**	**Good practices**

Impact on **generated methane**	**“Use of a bioreactor”**	**No use of bioreactor:** Leaches are not recirculated. All wastes are considered as **dry**, with the associated IPCC kinetic k constants per typology of waste	**No use or misuse of bioreactor:** Leaches are not recirculated. All wastes are considered as **dry**, with the associated IPCC kinetic k constants per typology of waste	**Use of bioreactor:** Leaches are recirculated, keeping **60% of waste wet, and 40% dry**, with the associated IPCC kinetic k constants per typology of waste
Impact on **recovered methane**	**“Type of cover”**	Using a **semi-permeable membrane** allows a theoretical **capture rate of 85%** to be achieved	Using an **impermeable membrane** allows a theoretical **capture rate of 90%** to be achieved	Using an **impermeable membrane** allows a theoretical **capture rate of 90%** to be achieved
	“Anticipated capture” **“Delay in installing the final cover and recovery system”**	- **No temporary cover** is installed during the operation phase, meaning the capture rate is zero during the two years of operation. - A **two-year delay** is considered for the installation of the final cover and a supplementary year for the installation of the capture system. **The capture rate is therefore zero until the end of year 5, and 85% from year 6 onwards**	- **No temporary cover** is installed during the operation phase, meaning the capture rate is zero during the two years of operation. - The implementation of a final cover and capture system as soon as a cell is closed is modelled by a positive capture rate from the first year of post-operation. **The capture rate is therefore 90% from year 3** onwards	- **A temporary cover is installed** during the operation phase, which is modelled with a **ramp-up in the capture year reaching 45% the first year and 90% from year two** - The implementation of a final cover and capture system as soon as a cell is closed is modelled by a positive capture rate from the first year of post-operation. **The capture rate is therefore 90% from year 3** onwards
	“Management of residual methane”	Membranes deteriorate over time. This loss of impermeability is modelled by leaks, corresponding to a **reduction in the capture rate of 5% per year from the 5th** year after the opening of the landfill cell	Membranes deteriorate over time. This loss of impermeability is modelled by leaks, corresponding to a **reduction in the capture rate of 3% per year from the 5th year** after the opening of the landfill cell	Membranes deteriorate over time. This loss of impermeability is modelled by leaks, corresponding to a **reduction in the capture rate of** 1**% per year from the 5th year** after the opening of the landfill cell

	“Maintenance and reporting”	**No maintenance or reporting** operations are planned in the bad practices, leading to no specific reduction of the methane losses	Average monitoring and maintenance practices can prevent a proportion of methane losses to the atmosphere. This aspect is modelled by **reducing the degradation of the capture rate due to leaks by 5%**	Good monitoring and maintenance practices can prevent a proportion of methane losses to the atmosphere. This aspect is modelled by **reducing the degradation of the capture rate due to leaks by 10%**
Impact on **emissions from recovered methane**	**“Energy recovery”**	Recovered methane is immediately **flared** in bad practices	Methane is **recovered by injection or cogeneration** instead of simply being flared. Recovered methane is calculated on the basis of the quantities of methane recovered and the technical characteristics of the various recovery methods	Methane is **recovered by injection or cogeneration** instead of simply being flared. Recovered methane is calculated on the basis of the quantities of methane recovered and the technical characteristics of the various recovery methods

Table 6 - Modelling of good, average and bad practices

Those modelling characteristics are sum up in the following table

Operation duration : 2 years

n = year of the landfill cell closing

	A « Bad » practices	B « Average » practices	C « Good » practices
1 Capture rate during operation	0% (no capture & no temporary cover)		Ramp up from 0% to final capture rate (90%) i.e. 45% during year n+1 (considering a temporary cover)
2 Year of recovery starting	n+3	n	n-1
Delay in cover installation	*2 year*	*0 year*	*0 year*
Delay in recovery installation	*1 year*	*0 year*	*0 year*
3 Cover type	Semi permeable (85%)	Impermeable (90%)	Impermeable (90%)
4 5 Bioreactor	No	No	Yes (60% of waste humidify)
6 Avoided loss of CH4 due to monitoring and maintenance practices	**0%**	**5%**	**10%**
8 Leakage			
From year	n+3	n+3	n+3
% per year	5% per year	3% per year	1% per year

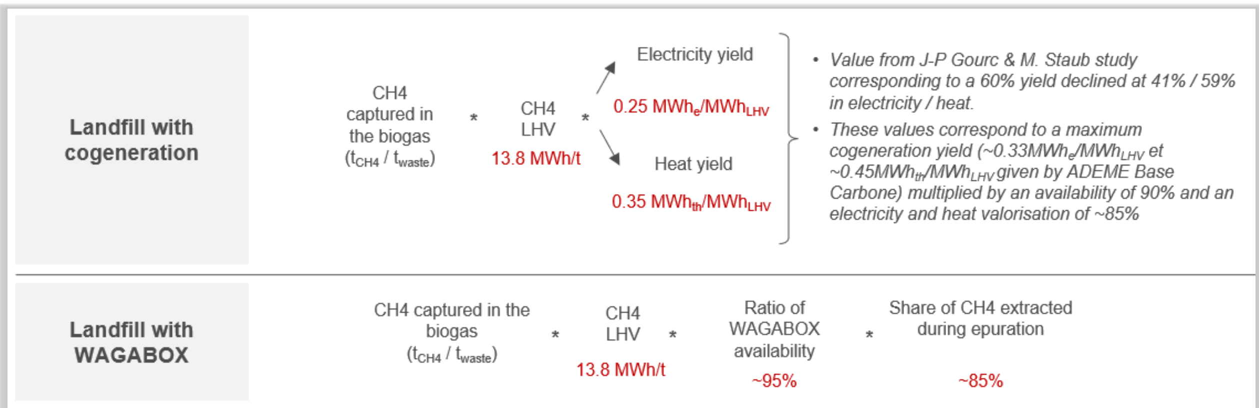
Figure 20 – Modelling assumptions for bad, average and good practices

APPENDIX N°3: Methodology and main hypotheses for the calculation of avoided emissions

The emissions avoided by a facility are the difference between the emissions generated by the production of one kWh of energy by the facility and the emissions generated by the production of one kWh of the relevant reference energy.

Avoided emissions [kg_{CO2e}/t_{waste}] =
[1] **Energy produced [MWh/t]**
x
[2] **CO2 contained in the energy replaced [kg_{CO2e}/MWh]**

[1] The energy produced was calculated as follows:



[2] The emissions factor of the energy replaced via injection and cogeneration are the following:

- Injection:
  - Natural gas: Average "Natural gas France value": 244kg_{CO2e}/MWh
    - *Source: ADEME Base Carbone 2023*
- Cogeneration:
  - Heat: Average French mix for heating networks in 2021: 125kgCO2/MWh
    - According to the FEDENE, in 2021 heat was produced at ~63% from renewable and recovered sources.
    - *Source: FEDENE / SNCU : « Enquête annuelle RCU 2021 »* (FEDENE & SNCU, 2021)
  - Electricity: Average French electricity emission factor in 2021: 57kgCO2/MWh
    - According to RTE, in 2021, total French electricity was generated at ~69% by nuclear power, ~12% by hydraulic power, ~7% by wind power, ~3% by solar power, ~6% by gas turbines, and the rest by bio-energies, coal, and fuel.
    - *Source: ADEME Base Carbone 2023*

APPENDIX N°4: Larger environmental impact of landfills

#1: Environmental impact on water and soils

More largely, a SWDS well managed is also a SWDS limiting its impacts on water and soils.

- SWDS are generally located on sites to be rehabilitated (former quarries, degraded areas, wasteland, etc.). Therefore, SWDS have no impact on the land available for urban development.
- Moreover, it is no longer common to create new sites rather than extend existing ones. No new sites have been created in the last 5 years.

- In the long term, and beyond regulations, these sites are often transformed into solar energy production site (that do not compete with agriculture land), and into biodiversity reservoirs.

#2: Long-term sequestration of organic carbon

Moreover, landfilling waste in SWDS enables long-term sequestration of organic carbon in soils. High uncertainties remain to assess the volume of organic carbon sequestrated. IPCC model considers a fraction of degradable organic carbon which decomposes (DOCf) in SWDS. This fraction varies widely depending on the type of organic waste materials being degraded.

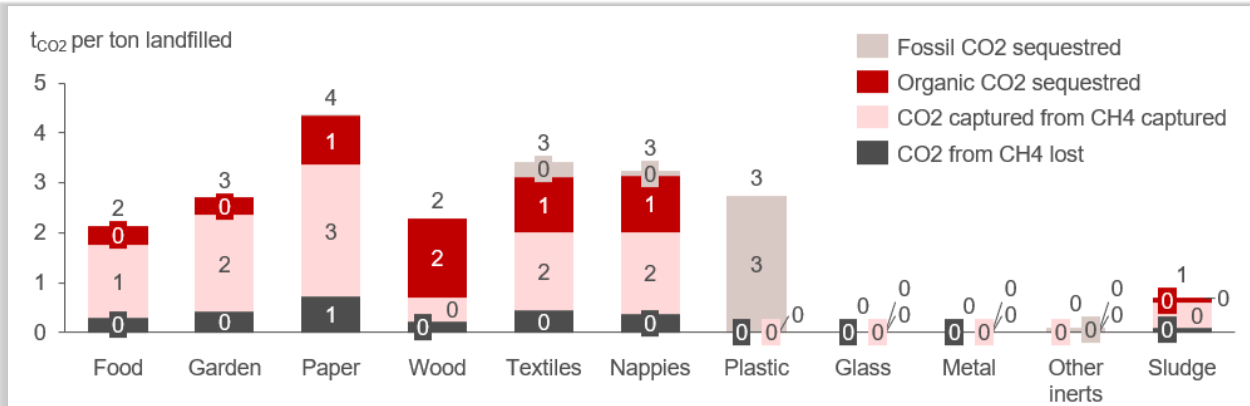


Figure 21 - Quantity of carbon sequestered and emitted per tonne of waste according to waste typology

It represents the part of the carbon that is not converted into methane will be stored underground: this is a biogenic carbon sink. This carbon storage is considered as a "benefit" for the atmospheric CO2eq balance.

The emissions factors used can then subtract from net methane emissions the equivalent of carbon sequestered in the soil.

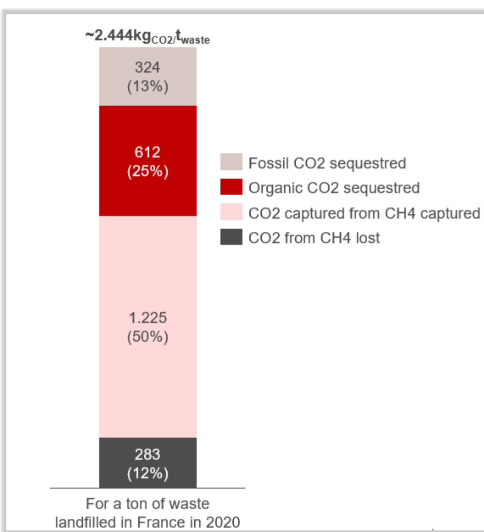


Figure 22 - Estimation of carbon sequestered and emitted for a ton of waste landfilled in France [kgCO2/twaste, 2020]

Considering the French mix of waste sent to landfills (see figure 6.), **the total carbon emitted per tonne of waste could amount ~2444kg$_{CO2eq}$/t$_{waste}$.**

Carbon stored for a tonne of waste landfilled in 2020 amounts ~610kg$_{CO2eq}$/t$_{waste}$. This represents a potential of **~11Mt$_{CO2eq}$** based on the volume total of waste landfilled in 2020.

APPENDIX N°5: Technical performance considered for landfill energy recovery (injection, cogeneration)

Calculation of cogeneration and injection performances and emissions are based on the following data:

- Cogeneration:
  - Yield heat landfill = 35%, yield electricity landfill = 25%
  - Low Heating Value (LHV) of CH4 = 0.0138MWh/kg[74]
  - Emission factor of electricity: 57kg$_{CO2eq}$/MWh[75]
  - Emission factor of heat: 125kg$_{CO2eq}$/MWh[76]

- Injection:
  - Emission factor of gas: 244kg$_{CO2eq}$/MWh[77]
  - WAGABOX availability[78]: 95%
  - WAGABOX yield: 85%
  - Quantity of biomethane injected by WAGABOX by tonne of CH4 recovered: 0.011MWh/kg$_{CH4}$

APPENDIX N°6: Reconstitution of French average mix of practices in SWDS

The mix of practices in French SWDS in 2023 was reconstituted on the basis of European Pollutant Release and Transfer Register (E PRTR) (EEA, 2007-2021)[79] emissions data, the French register of polluting emissions listing data on the tonnages of waste entering SWDS[80] each year, and the practices currently in place in the sites managed by Veolia and Suez.

The E PRTR database provides information on the **annual emissions** of a major part of the French SWDS. By combining this information with data on the **tonnages entering each facility each year** from the French register of polluting emissions, it is possible to calculate an annual **emission factor** for each facility. However, as the dataset is uncomplete, these emission factors have been computed as the ratio of the average tonnage on the average emissions over 4 years, from 2014 to 2017 on ~150 landfills in France.

Emission factor thresholds have been defined, above which facilities are considered to have average or poor practices. These thresholds were calculated using emission factors from Suez and Veolia facilities labelled as implementing good, average or bad practices.

On the basis of emission factors averaged between 2014 and 2017 and thresholds defined on the basis of Veolia and Suez data, **~38% of French facilities have an emission factor below the defined good** practice threshold, **and ~49% of them present an emission factor between the good practice and**

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[74] ADEME *Bilan GES ADEME documentation*
[75] ADEME *Base Carbone 2023* referring to 2021 emission factor. According to RTE, in 2021, total French electricity was generated at ~69% by nuclear power, ~12% by hydraulic power, ~7% by wind power, ~3% by solar power, ~6% by gas turbines, and the rest by bio-energies, coal, and fuel.
[76] FEDENE / SNCU *Enquête annuelle RCU 2021.* According to the study, in 2021 heat was produced at ~63% from renewable and recovered sources.
[77] ADEME *Base Carbone 2023*.
[78] WAGA Energy
[79] European Environment Agency https://sdi.eea.europa.eu/data/0e2e16ac-06e9-40b8-9aef-b3d228100564?path=%2FEXCEL
[80] Registre français des émissions polluantes https://public.opendatasoft.com/explore/dataset/registre-francais-des-emission-polluantes-traitement-dechets/table/?flg=fr.

average practice threshold, meaning the remaining **~14% installations are considered to have bad practices.**

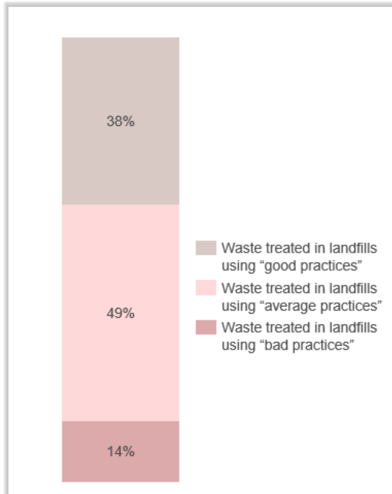

Figure 23 - Breakdown of waste volumes depending on the current practices used in the landfills

This distribution of practices will be considered in the study as the distribution of standards practices in landfill sites in France in 2023.

APPENDIX N°7: Reconstitution of current waste mix sent to French landfills

~18Mt of waste is landfilled every year in France, of which municipal waste represent ~8Mt, C&I waste ~7Mt, and the rest is composed of sorting refusals, residuals from TMB, ash from incineration, compost refusals, compost from methanisation.

This breakdown is displayed in *Déchets chiffres clés 2023* published by ADEME in 2023[81] on 2020 data.

[81] ADEME displays data from SWDS in ITOM perimeter (~95% of total waste landfilled). Data have been extrapolated to represent the totality of waste landfilled in 2020 ~18.136Mt, according to FNADE and GEREP data.

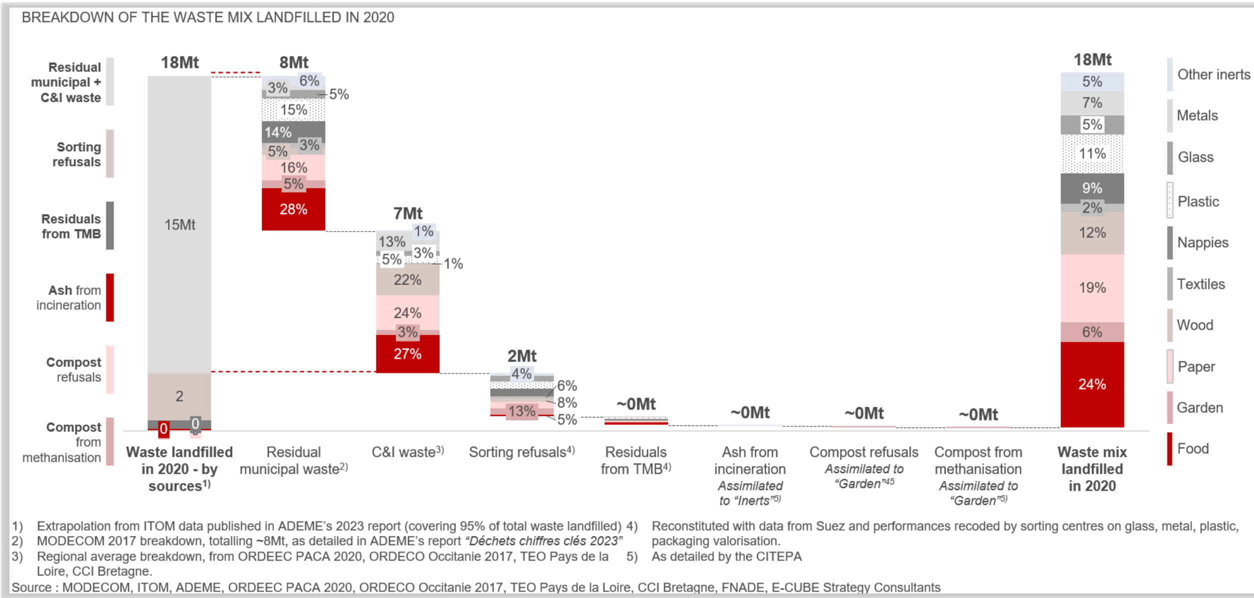

Figure 24 - Breakdown of the waste mix landfilled in 2020 by sources and by waste components.

The residual municipal waste mix for 2020 has been taken equal to MODECOM 2017 mix.

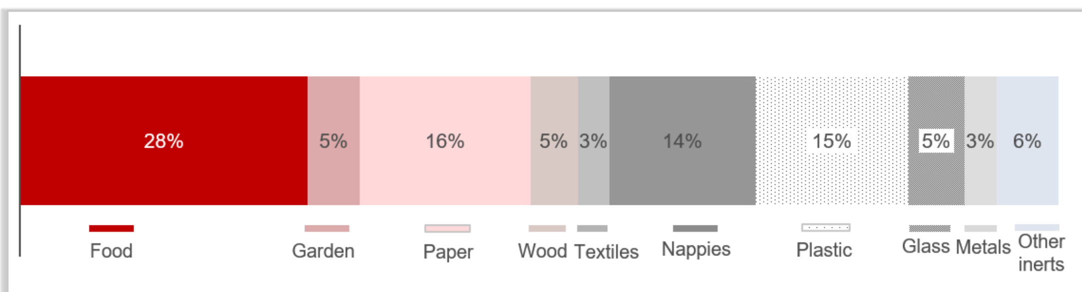

Figure 25 - MODECOM 2017 – Municipal Solid Waste mix

The C&I mix for 2020 has been calculated as an average of French regional C&I mix (Provence-Alpes Côte d'Azur, Occitanie, Pays de la Loire and Bretagne)[82].

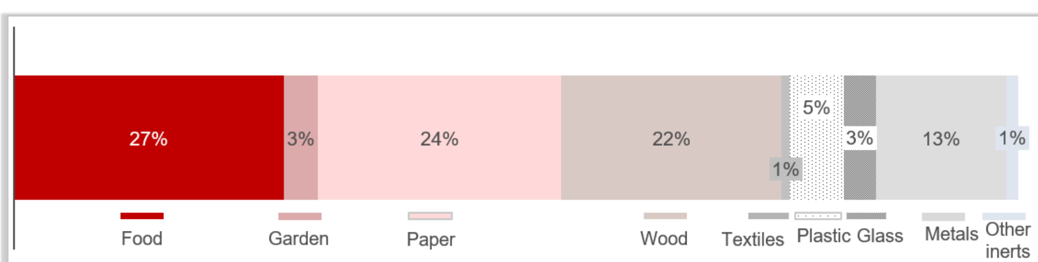

Figure 26 - Average regional C&I mix

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[82] Data from ORDEEC PACA 2020, ORDECO Occitanie 2017, TEO Pays de la Loire, CCI Bretagne.

APPENDIX N°8: Reference scenario of the waste tonnage and mix sent to landfills in 2035

The evolution of the waste mix and volume for the coming years is calculated on the basis of the 2020 mix (see APPENDIX N°7) and on the FNADE voluntarist scenario for 2050.

Evolution of waste volumes sent to landfills:

The objective set by the European Union is to reduce the **share of household waste landfilled** to a **maximum of 10% by 2035**. FNADE proposes a waste reduction scenario in line with these objectives.

In 2020, ~37.5Mt of DMA were generated in France, and the FNADE scenario plans to reduce this quantity to ~36.5Mt by 2035, i.e. a **reduction of 0.2% per year of DMA generated**. Among this waste, ~8Mt would be landfilled in 2020, representing 21% of the household waste generated. To reach the European objectives, this quantity should be reduced to **3.65Mt in 2035**.

To achieve this, FNADE forecasts a **6% annual reduction in waste landfilled**, from ~18Mt in 2020 to ~7Mt in 2035. The share of MSW would thus rise from 44% in 2020 to 51% in 2035 of waste sent to landfill.

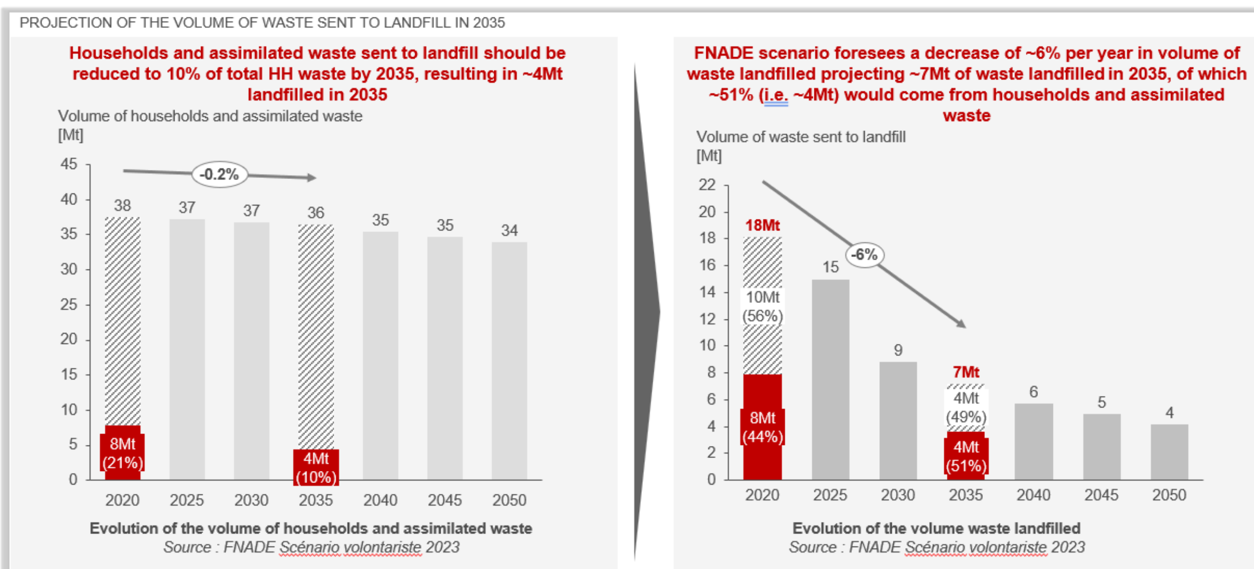


Figure 27 - Projection of the volume of waste sent to landfill in 2035

Evolution of the waste mix sent to landfill:

The waste mix evolution is computed as an evolution between the 2020 mix detailed in APPENDIX N°7, towards FNADE's 2050 voluntarist mix scenario.

<u>FNADE 2050 scenario projects a waste mix evolution as follows:</u>

- In 2050, a reduction of ~95% of the biowaste in residual municipal waste vs 2017, illustrating the efficiency of the separate biowaste collect[83]:
    - ~50% less food waste in 2050 than 2017 due to prevention,
    - ~5% of individual compost projected in 2050,
    - ~70% of organic waste valorisation of residual organic waste projected in 2050.
- From 2017 to 2050, a division by 2 of the residual plastic resulting in ~20% plastic waste.
- From 2017 to 2050, a reduction by 50% of paper, carboard, glass, textiles, metals content.

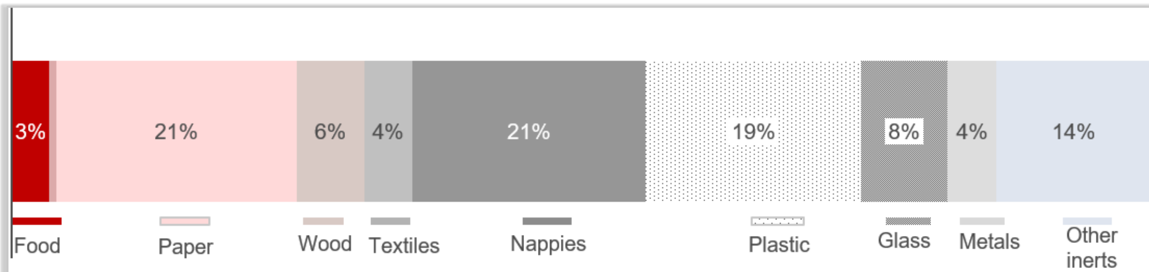


Figure 28 - FNADE waste mix 2050

The **reference scenario** foresees a rapid decline in the share of biowaste in the mix. Therefore, 2035 mix has been calculated computing an exponential decrease from MODECOM 2017 to FNADE 2050.

- <u>Municipal waste</u>: “Food" and "garden" waste would therefore see their share decrease by 10% per year between 2020 and 2035. Other organic waste (wood, paper, textiles, nappies) as well as glass, plastic and metal are supposed to decrease by 2% per year between 2020 and 2035.
- <u>C&I waste:</u> The same reduction rate of 10% per year has been considered for “food” and “garden” wastes. Yet, this decrease of 10% per year has been considered to concern more widely "wood" and "paper" waste. Other waste (textiles, nappies, glass metal and plastics) continues to fall by 2% a year until 2035, compared with 2020 level. (ADEME, 2021)

APPENDIX N°9: Alternative mix scenario – France 2035

Sensitivity analysis has been made on waste composition, to illustrate the variability that could be induced in waste mix evolution. An **“alternative scenario**” has been built to illustrate the case where the organic share does not decrease as much as expected. Therefore, 2035 “alternative mix” has been calculated computing a linear decrease from MODECOM 2017 to FNADE 2050. (ADEME, 2021)

[83] As imposed by the French *Code de l’environnement*

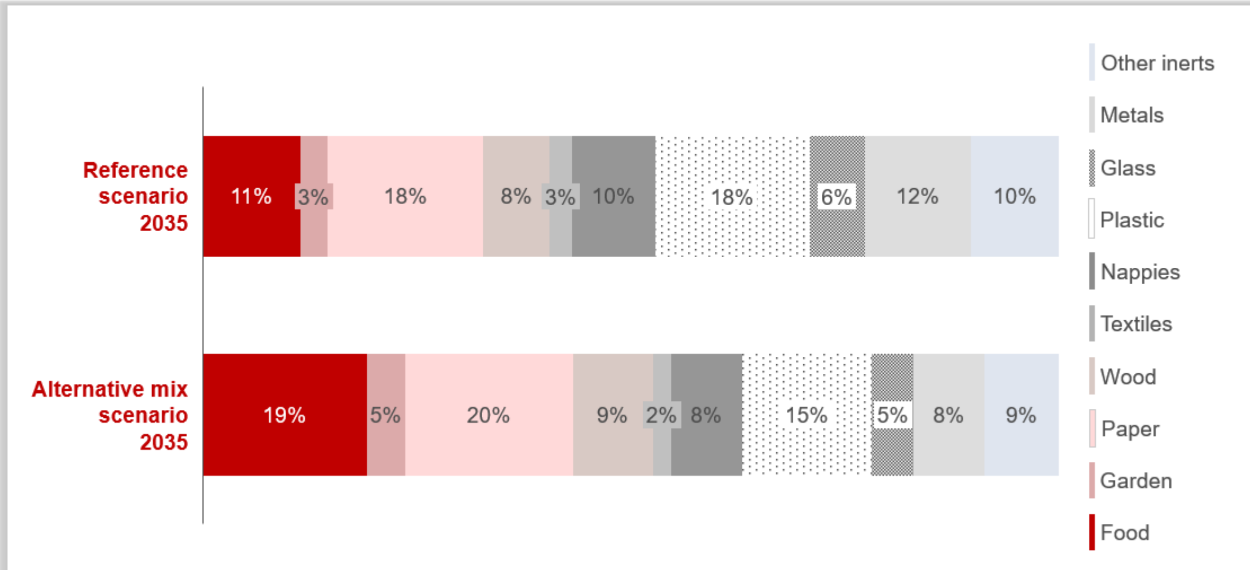


Figure 29 – Reference scenario and alternative scenario mix for 2035

For 2035, this alternative scenario forecasts a more important **organic waste share** in the mix, representing **~54%** compared to **~42%** in the reference scenario mix.

In this scenario, the exact same volume of waste is landfilled from 2023 to 2035 than in the reference scenario, only the mix is affected.

APPENDIX N°10: Alternative volume scenario – France 2035

A scenario providing an alternative waste volume landfilled for 2035 has been constructed, proposing a projection where the EU objective regarding the 10% municipal waste in landfills is not achieved. Like the reference scenario, it was based on the 2020 mix, and on the voluntarist mix scenario FNADE 2050.

The municipal mix considered in this scenario is the same than the reference scenario mix, only the volume landfilled is different.

This alternative scenario foresees a regular decline from the MODECOM 2017 scenario to the FNADE 2050 scenario in terms of tonnage. Therefore, 2035 mix has been calculated computing an linear decrease from MODECOM 2017 to FNADE 2050 for municipal and C&I wastes.

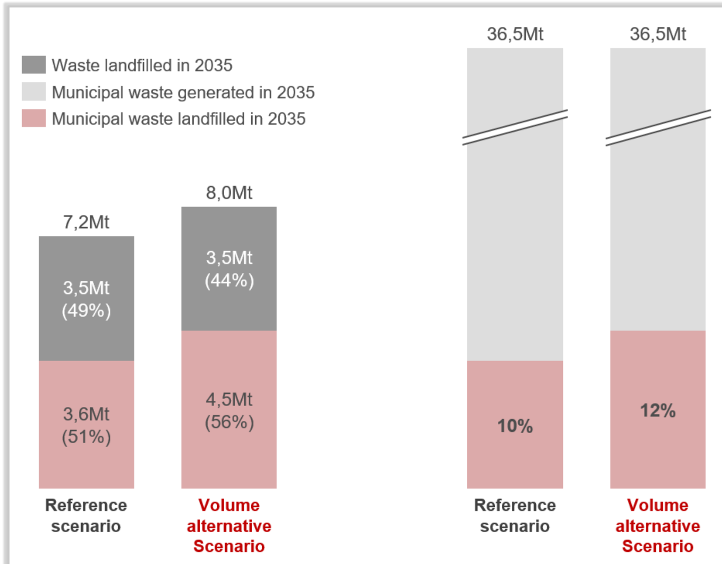


Figure 30 - Volume landfilled in alternative scenario

In this scenario, ~8Mt of waste are landfilled in 2035 vs ~7Mt in the reference scenario, out of which ~4.5Mt are municipal waste, compared to ~3.6Mt in the reference scenario. The EU objective is not achieve, as 12% of municipal waste are still landfilled in 2035.

APPENDIX N°11: Economical modelling of changes in landfill management practices

- The economic analysis of the transition of practices in a landfill was based on the modelling of a typical landfill cell which could receive 100,000 tonnes of waste per year for two years.
- It is assumed that waste is deposited annually from 2024 to 2035 in the quantities projected by the volume scenarios in the study.
- The CAPEX and OPEX necessary for the transformation of practices in SWDS were calculated on the basis of SWDS data managed by Véolia and Suez.
- OPEX associated to the landfill cells are accounted for from 2024 to 2065, 30 years after the last waste is landfilled.
- An actualisation rate of 5%/year is considered for calculation.

APPENDIX N°12: Spanish analysis

As a comparison, the graph below shows the composition of the French reference mix and the Spanish mix landfilled in 2020.

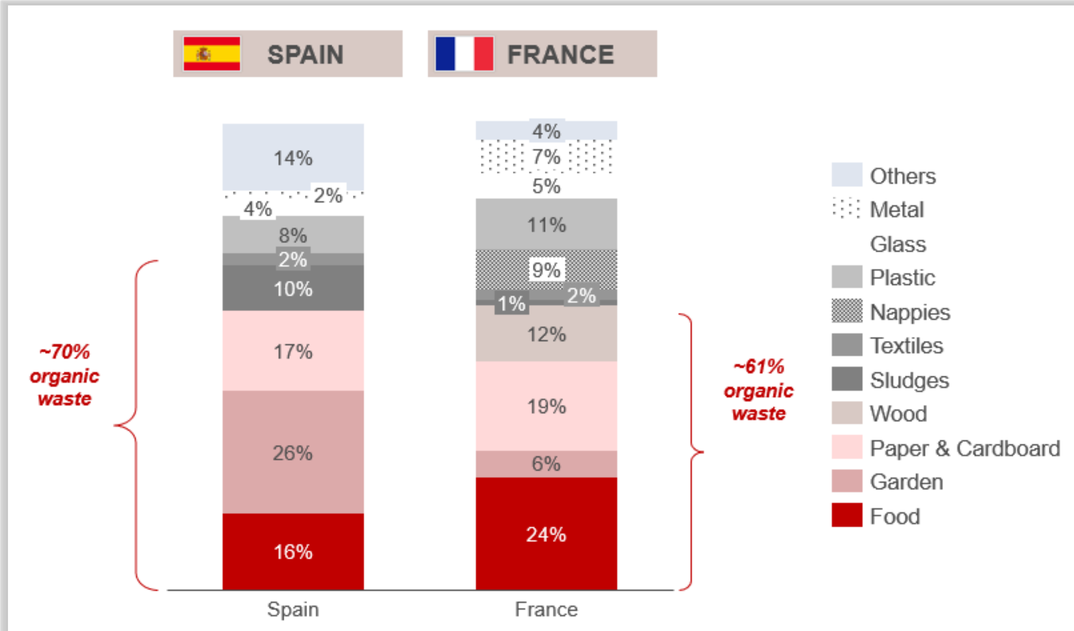
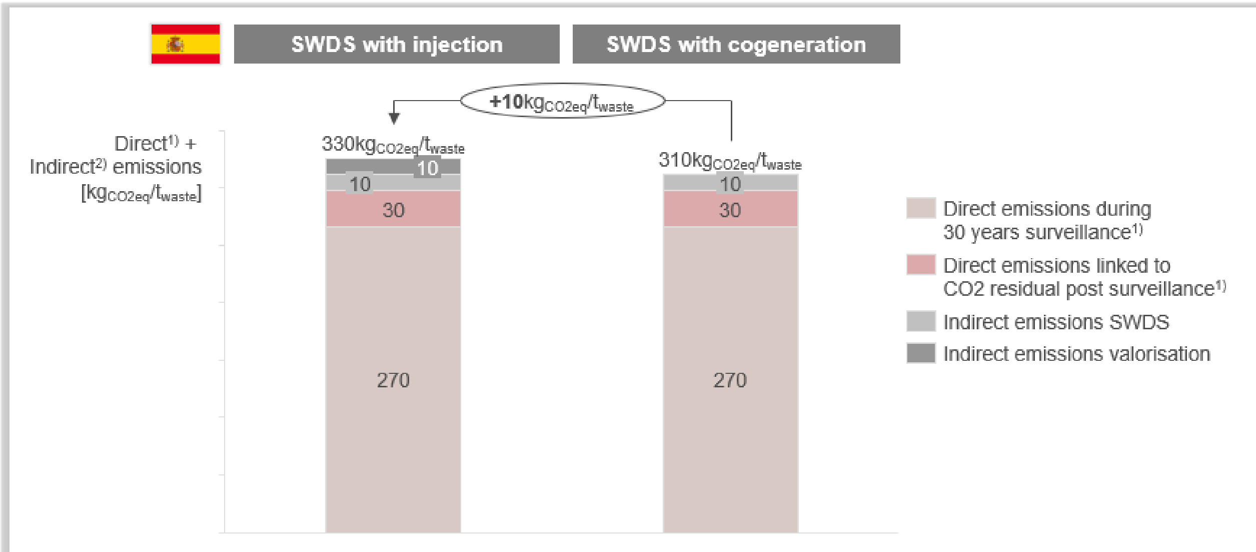


Figure 31 - Comparison of French and Spanish mix landfilled in 2020

The Spanish landfill mix is characterized by a high proportion of organic waste, reaching around 70%. This share is divided into 52% "food"; 13% "garden"; and 4% “paper and cardboard”. The Spanish mix should therefore generate a lot of methane in landfills. However, a closer look reveals that the mix mainly contains “food” and “garden” waste, with very little cardboard and paper. Whereas paper and cardboard waste are among the biggest methane generators, producing almost twice as much methane as food waste during decomposition. So, despite a very organic mix, the presence of only 4% paper and cardboard waste compared with 19% in the French mix makes the Spanish mix less emissive per tonne of waste landfilled. This low proportion of paper waste can be explained by the importance of pretreatment of wastes before being landfilled in Spain. **Still, it is subject to high uncertainties mainly due to the difficulty to assess the methane potential of biowaste that underwent MBT and also due to uncertainties coming from waste classified as “others”.**

Emissions from the Spanish mix, reaching **~330kg$_{CO2eq}$/t$_{waste}$**, are therefore **~5% higher than those from the French reference mix**.



1) Direct emissions generated by lost CH4 for 30 years post-operation and residual CO2 that will be lost in the following 50 years post-surveillance until reaching the total decomposition of waste
2) Indirect emissions linked to the construction and operation of the treatment installation

Figure 32 - Comparison of direct and indirect emissions generated by SWDS in 2020 in Spain

Avoided emissions thanks to cogeneration and injection installations for the Spanish waste mix are similar to the avoided emissions for the French reference mix, reaching respectively **~30kg$_{CO2eq}$/t$_{waste}$** and **~110kg$_{CO2eq}$/t$_{waste}$**

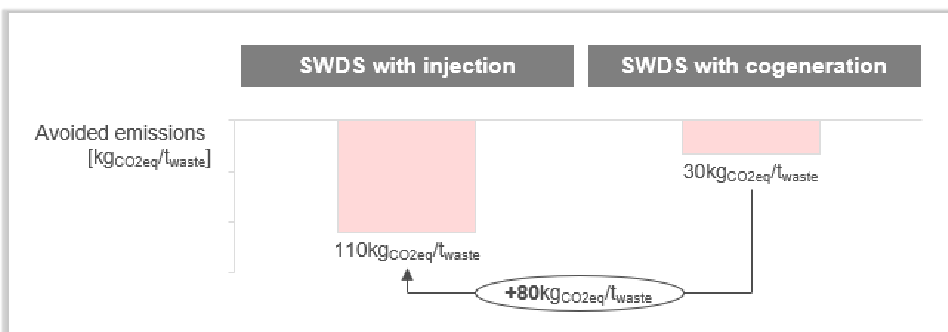


Figure 33 - Comparison of avoided emissions by SWDS in the Spanish mix

- **Reconstitution of waste mix sent to landfills in 2035**

It can be estimated that ~3Mt would be landfilled in Spain in 2035 (vs ~7Mt in France) in order to comply with European legislation limiting municipal waste landfilled to 10% of waste generated (i.e. ~1Mt). Therefore, to respect the regulation limiting at ~10% households and assimilated waste landfilled by 2035, its volume should be reduced from 9.6 Mt in 2020 to ~1.4 Mt in 2035, representing ~51% of the total waste landfilled in 2035.

It is estimated that volume of waste landfill could decrease by ~-8% per year, reaching ~3.4Mt of waste landfilled in 2035, of which ~ 42% (i.e. ~1,4Mt) would come from municipal waste.

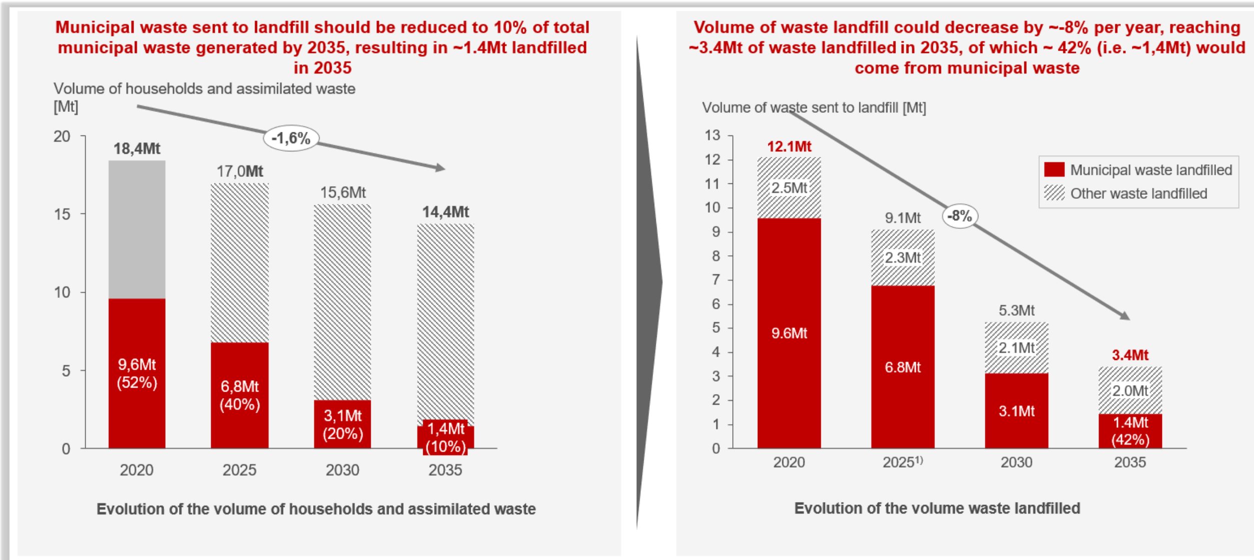


Figure 34 - Projection of the volume of waste sent to landfill in 2035 in Spain

GLOSSARY

C&I: Commercial and industrial

DOC: Degradable organic carbon

DOCf: Fraction of degradable organic carbon which decomposes

E PRTR: European Pollutant Release and Transfer Register

GHG: Greenhouse gas

IPCC: Intergovernmental Panel on Climate Change

MSW: Municipal Solid Waste

SWDS: Solid Waste Disposal Site

WtE: Waste to Energy

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