# Life-Cycle Assessment of Sustainable Aviation Fuel and Electricity from Municipal Solid Waste

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ICF SH&E Limited, LLC

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# I. Executive Summary

Aviation represents approximately 2-3% of global emissions, and this proportion is likely to increase relative to other emissions as low carbon alternatives are deployed in other easier-to-abate sectors. Therefore, it is essential that approaches to decarbonise aviation are developed to ensure the economic and social benefits of the industry are retained through the transition to a net-zero society.

The UK government has made considerable progress to drive the decarbonisation of aviation. A Net Zero target by 2050 has been established, and the Jet Zero Strategy[1] provides a framework to achieve it. The UK Sustainable Aviation Fuel (SAF) Mandate is proposed as a keystone to the strategy and will obligate increasing use of sustainable fuel by the aviation sector. However, SAF production is a nascent industry and several economic and technological challenges must be overcome for it to be commercially scaled, with strict sustainability criteria necessary to ensure the SAF meaningfully contributes to emission reductions. The UK Government has proposed two broad mechanisms to ensure sustainability, including (1) constraining the allowable feedstocks to only the most sustainable wastes, residues, and additional energy, and (2) better incentivising SAF that offers higher emissions reductions by allowing them to count more towards the mandate obligations.

These approaches are essential to ensure the decarbonisation is robust. However, they greatly constrain the usable feedstock, and make the allocation of scarce resources between industries of critical importance. A key feedstock for the UK SAF industry is expected to be municipal solid waste (MSW), which includes waste from households and similar sources. This can be converted from a low-value waste to a high value jet fuel, reducing lifecycle emissions, creating jobs, and improving national energy security. In 2018[2], the UK produced 222.2 million tonnes of waste, including 27.3 million tonnes from households and 39.8 million tonnes from commercial and industry[3]. Of this, 8.5 million tonnes was incinerated with energy recovery, and 7.3 million tonnes incinerated with no energy recovery. 21.3 million tonnes (non-soil waste) was sent to landfill, including 7.2 million tonnes of biodegradable wastes. The UK waste hierarchy[4] dictates the UK government objectives to prioritise waste reduction, re-use, and recycling. However, not all waste will be technically feasible for these approaches, and a residual will remain. This should be recovered where possible (to produce energy), and if no alternative is possible, cleanly disposed of.

Guidance is clear that the 21.3 million tonnes of waste that the UK sent to landfill and 7.3 million tonnes incineration without energy recovery should be minimised. However, the waste hierarchy does not currently differentiate between approaches to recover energy from waste – including incineration with energy recovery and production of SAF. This presents a challenge for the aviation industry as currently, SAF production is a more complex process with several technical challenges to overcome, resulting in uncertainty across commissioning timelines. This puts SAF

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[1] https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050

[2] 2018 is the latest year the whole dataset is available for. ICF notes that some progress has been made to advance recycling and reduce landfill since then.

[3] https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste

[4] https://assets.publishing.service.gov.uk/media/5a795abde5274a2acd18c223/pb13530-waste-hierarchy-guidance.pdf

producers at a disadvantage as authorities responsible for waste management generally prefer greater certainty that is provided by the comparative incineration with energy recovery. This approach means that the UK is not maximising associated opportunities, including:

1. **Improved emissions reductions** from SAF production compared to energy from waste.
2. **Energy security benefits** from domestic production of jet fuel. While energy from waste (EfW) can be used to produce domestic electricity, this provides a smaller marginal contribution to national security as (1) most UK electricity consumption is already served from domestic generators, and (2) alternative clean and affordable technologies for domestic electrical production (e.g. wind and solar) exist. By comparison, the UK imports 64% of net jet fuel[5], with this portion expected to increase if the Grangemouth refinery closes in 2025[6].
3. **The opportunity to link decarbonisation and industrial strategies,** with the UK poised to become a hub for SAF expertise. The UK has greater MSW to SAF capacity planned than any other country[7], and seizing this opportunity could allow the UK to become a global leader and exporter of the technologies and expertise.

This analysis is focused on emissions reductions only by conducting a like-for-like comparison of the emissions reduction achieved when MSW is used to produce SAF compared to using MSW to generate electricity in an energy from waste process. These comparisons were completed

**Results from this analysis show that the use of MSW for SAF drives an emission reduction at least 5x greater than the equivalent use for electricity production.**

- The GHG reduction for SAF is greatest, with a reduction of 453 kg CO2e/ metric tonne (“MT”) MSW achieved, equivalent to an 89% emissions reduction.
- In some cases, EfW can increase emissions compared to the grid baseline.
- For EfW technology where the heat produced is utilised in district heating, the EfW+CHP S1 can offer a reduction of 89 and 48 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively) and the EfW+CHP S2 can offer an emissions reduction of 79 and 38 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively).
- When the heat is not utilised, the EfW S1 reduces emissions by 66 and increases by 200 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively) and the EfW S2 reduces emissions by 0.1 and increases by 266 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively).

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[5] https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/Sustainable-Aviation-SAF-Roadmap-Final.pdf
[6] https://www.argusmedia.com/en/news/2511962-uks-grangemouth-refinery-to-close-in-2025
[7] https://www.gov.uk/government/publications/developing-a-uk-sustainable-aviation-fuel-industry#:~:text=In%20October%202022%2C%20the%20Department,SAF%20)%20industry%20in%20the%20UK%20.

using a lifecycle assessment approach, and three LCAs were developed (1) SAF production using MSW as feedstock and (2,3) electricity generation from incineration of waste using two different air pollution control (APC) systems. The UK's Renewable Transportation Fuel Obligation ("RTFO") methodology was used to calculate the GHG emissions.

The emissions reduction achieved strongly depends on the technology stack and sorting of the waste, which in turn depend on policies driving the industry. SAF production is heavily incentivised to achieve meaningful emissions reductions through the proposed mandate sustainability criteria and increasing carbon pricing imposed on the aviation industry. Comparitively, waste incineration is more variable, with three categories of facility in the UK, (1) incineration with no energy recovery *(78 of 115 facilities in the UK[8])*, (2) incineration with electricity generation *(29 of 115)*, and (3) incineration with electricity and heat recovery *(8 of 115)*. As the first category provides no benefit besides waste disposal, only the latter two categories were considered in this analysis. To show the full range of emissions from EfW facilities, the emissions were calculated along three dimensions; with and without heat recovery (in addition to energy generation), two types of technology, which this analysis has categorised as S1 and S2, and for MSW sorted to 4% and 20% non-biogenic component. The results for each category are given below.

| | | Without heat recovery | | With heat recovery | | SAF |
|---|---|---|---|---|---|---|
| | | S1 | S2 | S1 | S2 | |
| 20% NBC | gCO2e/MJ | 119.7 | 140.1 | 31.9 | 37.3 | |
| 4% NBC | gCO2e/MJ | 37.0 | 57.5 | 9.9 | 15.3 | 9.5 |
| UK Baseline | gCO2e/MJ | 57.52 | | | | 89 |
| 20% NBC | % | 108% | 144% | -45% | -35% | |
| 4% NBC | % | -36% | -0.1% | -83% | -73% | -89% |

*NBC = Non-biogenic component, Negative percent difference values show emissions reduction from baseline case.*

The comparatively greater emission reduction through SAF production is expected to grow as the UK works towards the goal of complete grid decarbonisation by 2035. As this is achieved, the GHG reduction for electricity from EfW will decrease and eventually the EfW GHG emissions will exceed those of the grid. The carbon intensity of fossil-based jet fuel will not reduce over time, so the GHG reduction for SAF from MSW will remain. Both options (SAF production and EfW) can further reduce emissions with the use of carbon capture on the production facilities. The potential coverage of EfW facilities with the UK ETS may incentivise this for EfW facilities, although the proposed reward for lower CI SAF in the UK SAF Mandate consultation would provide a similar (and likely greater) incentive for SAF facilities to use carbon capture.

These combined advantages suggest a considerable advantage for the use of MSW for SAF production rather than incineration with energy recover, and a substantially greater benefit compared to incineration without energy recovery and landfill. Recognising this within the waste

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[8] https://researchbriefings.files.parliament.uk/documents/CDP-2020-0029/CDP-2020-0029.pdf

hierarchy and wider policy framework would ensure the UK makes best use of limited resources to accelerate efforts to decarbonise, bolster the economy, and reinforce national energy security.

## II. Methodology and Emission Factors

The LCAs were conducted using emissions factors published by the UK's RTFO, which obligates producers of transportation fuels used in the UK to blend a portion of renewable fuels. While aviation is not an obligated fuel, the emission reduction from SAF can be sold into the Renewable Transportation Fuel Credit ("RTFC") market. Once the UK SAF mandate is implemented (from 2025), the SAF emissions reduction compliance credits can be traded separately, although the RTFO will be used as a reference for several logistical and sustainability requirements.

SAF production is assumed to take place in the UK and the RTFO's standard emission factors were used to calculate emissions when available[9]. However, the RTFO's standard set of emissions factors do not include a UK grid mix emission factor, so these were calculated based on the UK Government's 2023 conversion factors[10] instead. A list of emissions factors used in this analysis can be found in the table below. The RTFO emissions are calculated using the IPCC's 5th annual report global warming potentials ("GWP")[11]. The life cycle assessment ("LCA") results include the emissions for combustion of non-biogenic feedstock to calculate the overall impact of using MSW feedstock.

**Exhibit 1. Emissions Factors from RTFO Standard**

| Item | Units | Emissions Factor |
|---|---|---|
| **Energy inputs** | | |
| UK grid mix (UK Government Emissions Factors for 2023) | gCO2e/MJ | 57.52 |
| Fuel oil | gCO2e/MJ | 94.20 |
| Diesel | gCO2e/MJ | 95.10 |
| **Transportation** | | |
| Truck (40 ton[12]) for biowaste (Diesel) | gCO2e/t*km | 80.65 |
| Inland ship for oil transport, 1.2 kt (diesel) | gCO2e/t*km | 48.68 |
| Local (10 km) pipeline | gCO2e/t*km | 0.00 |
| Rail (Electric, MV) | gCO2e/t*km | 29.63 |
| Truck (40 ton) for chips (and similar size dry product) (Diesel) | gCO2e/t*km | 80.65 |
| **Material inputs** | | |
| Pure Calcium Oxide for processes | gCO2e/kg | 1,193.23 |
| Ammonia | gCO2e/kg | 2,351.34 |

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[9] rtfo-standard-data.xlsx (live.com)

[10] Greenhouse gas reporting: conversion factors 2023 - GOV.UK (www.gov.uk)

[11] Draft RTFO guidance: greenhouse gas emissions methodology and default values for biofuels (publishing.service.gov.uk)

[12] Imperial ton, as this value is from ICAO-GREET (which gives all values in lb and ton)

| | | |
|---|---|---|
| Sodium hydroxide | gCO2e/kg | 529.73 |
| Urea | gCO2e/kg | 1,846.65 |
| **Global Warming Potentials** | | |
| CH4 | gCO2e/g | 25 |
| N2O | gCO2e/g | 298 |
| CO2 | gCO2e/g | 1 |

The RTFO methodology uses an energy-based allocation method to allocate the GHG emissions among co-products. The LCA boundary includes emissions for cultivation/collection of feedstock, feedstock transport, fuel production, fuel transport, and product combustion (wake emissions). MSW is a waste feedstock, so there are no cultivation/ collection emissions or land use change emissions considered. For consistency across different pathways, it is assumed that the MSW at the landfill contains 20%[13] non-biogenic carbon feedstock and that it is then sorted with non-biogenic carbon reduced to ~4% based on internal modelling.

Per Transport & Environment's briefing paper[14], the UK is internationally committed to ending plastic pollution before 2040 and will be legally bound to the forthcoming UNEP plastic pollution treaty which is due by the end of 2024. This ambitious goal advocates for the promotion of plastic recycling, as well as the systematic separation and reduction of the non-biogenic content of MSW. This implies that MSW with significantly lower non-biogenic carbon content (i.e. ~4%) is more likely to be utilised as feedstock for renewable fuel production.

Regulatory value for SAF (e.g. use to comply with the mandate) is contingent upon the GHG emission reduction, which is calculated with a heavy weighting on the biogenic fraction of waste. This incentivises producers to remove recyclable and non-biogenic carbon to maximize the renewable portion of feedstock and produce SAF. Comparatively, electricity generation from EfW does not currently have similar incentives. Considering this, it is less likely that an EfW facility would invest in sorting the waste to 4% non-biogenic carbon content compared to a SAF facility. However, this assumption is used for both pathways for consistency.

# III. Data Sources, Assumptions and Results

## 1. MSW to SAF

MSW feedstock is converted to SAF, renewable diesel, and naphtha via a gasification and Fischer Tropsch ("FT") process. While the major methods and emission factors follows RTFO guidance, the material and energy inputs used in the GHG emissions calculation for this process are based on ICF modelling. It is assumed that no natural gas is required for SAF production as the fuel gas is recycled back into the process for heating. Oxygen is assumed to be produced onsite using an air separation unit ("ASU"), and the additional electricity requirement is also considered. Transportation distances are based on International Civil Aviation Organization's ("ICAO") Carbon

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[13] 40_IEAPositionPaperMSW.pdf (ieabioenergy.com)
[14] 2306 - SAF mandate 2 consultation response (transportenvironment.org)

Offsetting Reduction Scheme for International Aviation (“CORSIA”) default values. The inputs and co-product split can be found in the table below.

**Exhibit 2. Inputs for MSW to SAF Pathway**

| Item | Unit | Value |
|---|---|---|
| **Feedstock** | | |
| Feedstock input | MT / MJ SAF | 0.0019 |
| **Feedstock transport** | | |
| Feedstock transported | MT / MJ SAF | 0.00022 |
| Truck, heavy-heavy duty truck (“HHDT”) | km | 32 |
| **Feedstock Pretreatment** | | |
| Electricity for sorting | MJ/MJ SAF | 0.0234 |
| **SAF Production** | | |
| Natural Gas (at plant), use of fuel gas | MJ/MJ SAF | 0 |
| Natural Gas (at plant) | MJ/MJ SAF | 0.109 |
| Oxygen production electricity requirement | MJ electricity / MJ SAF | 0.025 |
| **Product and Co-product split** | | |
| SAF | by energy | 70% |
| Renewable Diesel (RD) | by energy | 15% |
| Naphtha | by energy | 15% |
| **Jet fuel transport** | | |
| Barge | km | 837 |
| Pipeline | km | 644 |
| Rail | km | 1,288 |
| Barge | % contribution | 33% |
| Pipeline | % contribution | 60% |
| Rail | % contribution | 7% |
| Truck (distribution) | km | 48 |

An energy-based allocation method was used to allocate emissions among coproducts producing SAF from MSW. A breakdown of the results can be found in the table below. RTFO guidance lists the CI of the fossil fuel comparator for transport as 94 gCO2e/MJ fuel, which can subsequently be used to calculate GHG savings[15]. The ICAO CORSIA model CI score for Jet fuel A is 89 gCO2e/MJ of jet fuel[16]. Since RTFO does not have a specific jet fuel A CI score, the ICAO CORSIA CI score was used.

**SAF from MSW has a 89% GHG emission reduction compared to jet fuel A.**

**Exhibit 3. MSW to SAF Results**

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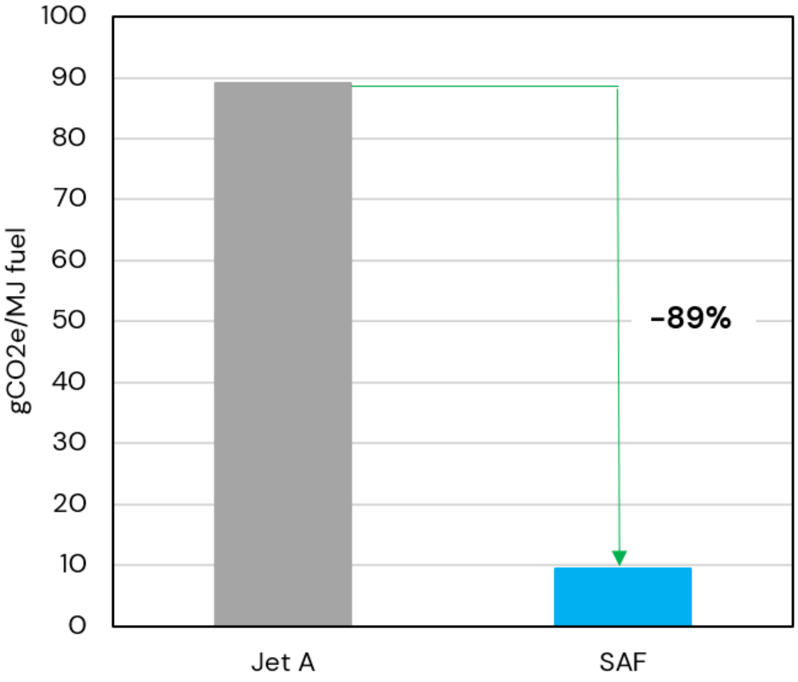
[15] Draft RTFO guidance: greenhouse gas emissions methodology and default values for biofuels (publishing.service.gov.uk)
[16] CORSIA Supporting Document "CORSIA Eligible Fuels_LCA_Methodology" (icao.int)

| Stage | SAF LCA Results (gCO2e/MJ SAF) |
|---|---|
| Cultivation/Collection | 0.00 |
| Feedstock Transportation | 0.54 |
| Feedstock Sorting | 1.27 |
| SAF Production | 1.37 |
| Fuel Transportation | 0.45 |
| Fuel Combustion | 5.89 |
| **Total** | 9.53 |

**Exhibit 4. MSW to SAF GHG Reduction**



## 2. MSW to Electricity (EfW)

MSW is incinerated to produce heat which heats water to produce steam which is used to power a turbine to produce electricity. There are different systems available for EfW facilities. For this analysis, two scenarios were modeled with different operating inputs using mechanical grate incineration: EfW scenario 1 (“EfW S1”) which the inputs align more with a dry air pollution control system[17] and EfW scenario 2 (“EfW S2”) with inputs that align more with a wet air pollution control system[18]. Both wet and dry air pollution control systems are used in EfW facilities, so both were considered in this analysis. Electricity yield rate is assumed to be similar to generations with primarily biogenic feedstock[19]. Some EfW utilize the heat in district heating. Two scenarios were developed using the EfW S1 and EfW S2 inputs, but electricity and heat yield based on a EfW with combined heat and power unit (CHP) (“EfW+CHP S1” and “EfW+CHP S2”)[20]. It is also assumed that the EfW is co-located with the landfill and no feedstock transportation was considered. Inputs and yield information can be found in the table below.

**Exhibit 5. Inputs for EfW Pathways**

| Item | Unit | EfW S1 | EfW S2 | EfW+CHP S1 | EfW+CHP S2 |
|---|---|---|---|---|---|
| **Feedstock** | | | | | |
| Feedstock input | MT MSW / MJ electricity | 0.00059 | 0.00059 | 0.00034 | 0.00034 |
| **Feedstock pretreatment** | | | | | |
| Electricity for sorting | MJ grid electricity / MJ electricity produced | 0.08 | 0.08 | 0.05 | 0.05 |
| **Electricity production** | | | | | |
| Slaked lime | kg / MJ electricity | 0.0098 | 0.006 | 0.0057 | 0.0035 |
| Ammonia | kg / MJ electricity | 0.0003 | - | 0.0002 | - |
| Activated Carbon | kg / MJ electricity | 0.0003 | 0.001 | 0.0002 | 0.0003 |
| Sodium hydroxide | kg / MJ electricity | - | 0.001 | - | 0.0007 |
| Urea | kg / MJ electricity | - | 0.002 | - | 0.0010 |
| Fuel Oil | MJ/MJ electricity | - | 0.111 | - | 0.0641 |
| Electricity | MJ/MJ electricity | - | 0.003 | - | 0.0016 |
| Diesel | MJ/MJ electricity | - | 0.119 | - | 0.0690 |
| **Products** | | | | | |
| Electricity | MJ/MT feed | 1,692 | 1,692 | 2,921 | 2,921 |
| Heat | MJ/MT feed | - | - | 3,432 | 3,432 |

There are no fuel transportation emissions for electricity production. EfW S1 and EfW S2, no heat is captured or utilized in the process, so there are no co-products. For the EfW+CHP S1 and EfW+CHP S2 scenarios, the heat is utilized in district heating. An energy-based allocation of 46% is applied between the electricity and heat generated. These four scenarios provide a range of EfW technologies available. The results can be found in the table below. The U.K.’s grid mix

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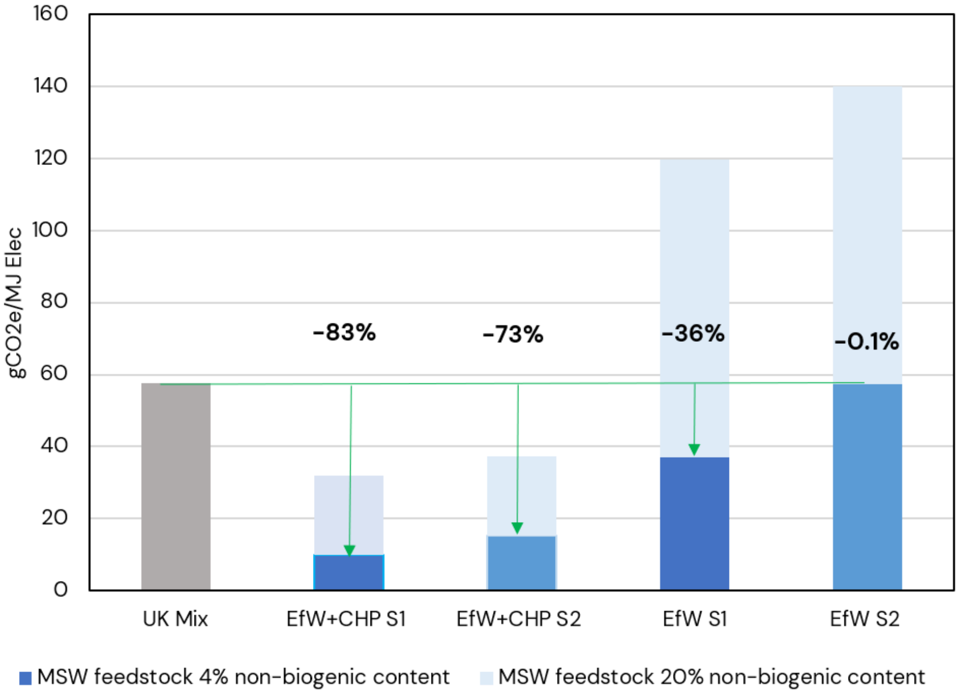
[17] https://doi.org/10.1016/j.enconman.2019.06.016
[18] https://doi.org/10.1016/j.jclepro.2018.08.139
[19] es802395e (acs.org)
[20] Review of BEIS assumptions underlying estimates of power generation costs for ACT and EfW with CHP (publishing.service.gov.uk)

electricity has a score of 57.52 gCO2e/MJ electricity (as shown in Exhibit 1). The two EfW scenarios modeled have GHG emissions reduction of 36% and 0.1%, respectively when compared to the U.K. grid mix. The two EfW+CHP scenarios have emissions reductions of 83% and 73%, respectively. For all EfW and EfW+CHP cases, the CI was also calculated without feedstock sorting, so the feedstock is assumed to have a non-biogenic carbon content of 20%. When the non-biogenic carbon content is 20%, the CI is greater for both EfW S1 and EfW S2 than the current U.K. grid mix. EfW+CHP S1 and EfW+CHP S2 have GHG emissions reduction of 45% and 35% from U.K. grid mix, respectively when using feedstock with 20% non-biogenic content. The CI can also be seen in Exhibit 6 below.

**Exhibit 6. Results for EfW Pathways**

| Stage | EfW S1 (gCO2e/MJ Electricity) | EfW S2 (gCO2e/MJ Electricity) | EfW+CHP S1 (gCO2e/MJ Electricity) | EfW+CHP S2 (gCO2e/MJ Electricity) |
|---|---|---|---|---|
| Cultivation/Collection | 0.00 | 0.00 | 0.00 | 0.00 |
| Feedstock Transportation | 0.00 | 0.00 | 0.00 | 0.00 |
| Feedstock Sorting | 4.72 | 4.72 | 1.26 | 1.26 |
| Electricity Production | 12.45 | 32.90 | 3.32 | 8.76 |
| Fuel Transportation | N/A | N/A | N/A | N/A |
| Fuel Combustion (4% non-biogenic content) | 19.84 | 19.84 | 5.28 | 5.28 |
| Fuel Combustion (20% non-biogenic content) | 107.23 | 107.23 | 28.56 | 28.56 |
| **Total (4% non-biogenic content)** | 37.01 | 57.46 | 9.86 | 15.30 |
| **Total (20% non-biogenic content)** | 119.68 | 140.13 | 31.88 | 37.32 |

**Exhibit 7. EfW Pathway GHG emission reductions from U.K. grid electricity utilizing 4% and 20% non-biogenic carbon content MSW feedstock**

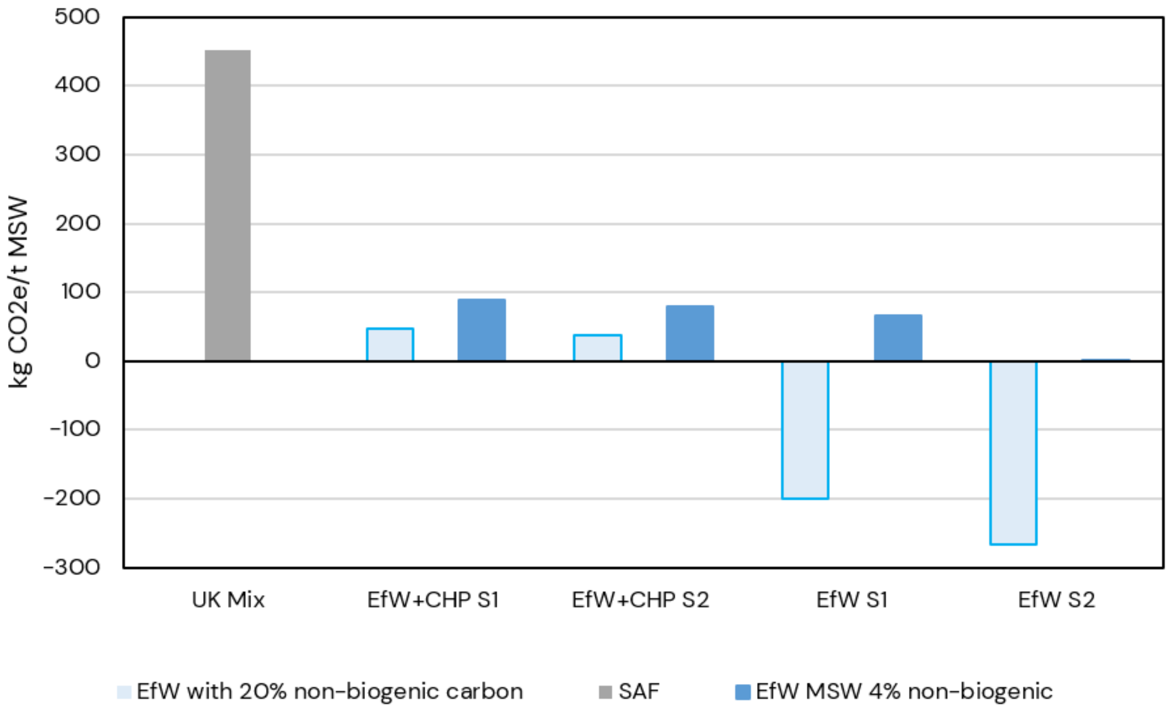


# IV. GHG Emission Reduction Comparison

The GHG emissions reduction comparisons can be made when converting one MT of MSW to produce electricity and the same to produce SAF. When comparing the two, the GHG reduction for SAF is greatest at 453 kg CO2e/ MT MSW. For EfW technology where the heat produced is utilised in district heating, the EfW+CHP S1 has a reduction of 89 and 48 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively). The EfW+CHP S2 has a reduction of emissions of 79 and 38 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively). In situations where the heat is not utilised, the EfW S1 reduces emissions by 66 and increases by 200 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively) and the EfW S2 reduces emissions by 0.1 and increases by 266 kg CO2e / MT MSW (for MSW feedstock with 4% and 20% non-biogenic content, respectively). **The conversion of MSW to SAF therefore results in a carbon reduction of at least 5 times the alternative pathway of generating electricity.**

It is important to note that the UK has a goal to decarbonise the grid by 2035, thus the GHG reduction from EfW will become less significant over time as the grid decarbonises. The GHG reduction from SAF would remain.

**Exhibit 8. Emission Reduction from Waste to Renewable Fuel / Energy**



500
400
300
200
100
0
-100
-200
-300
kg CO2e/t MSW
UK Mix
EfW+CHP S1
EfW+CHP S2
EfW S1
EfW S2
EfW with 20% non-biogenic carbon
SAF
EfW MSW 4% non-biogenic