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Carbon capture from energy-from-waste (EfW): A low-hanging fruit for CCS deployment in the UK?

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Executive Summary

Energy-from-waste (EfW) is a waste treatment process that combusts residual waste after re-use, recycling and composting to produce energy in the form of electricity and/or heat. EfW is considered a more environmentally-friendly method of dealing with residual waste than its alternative – waste dumping or landfilling. In the UK context in particular, the role of the EfW sector is prominent. UK EfW facilities generate around 3.2% of the nation's total power output but also emit around 3.5% (14.4 $MtCO_2$) of net annual territorial GHG emissions (2022 figures). As the UK is moving to expand the scope of its emissions trading scheme (UK-ETS) to include waste combustion and EfW facilities starting from 2028, decarbonising its EfW sector becomes critical. Here, the integration of carbon capture and storage (CCS) can help maintain EfW facilities as a source of sustainable, low-carbon energy while also meaningfully contributing to the UK's emission reduction targets.

In fact, the significance of EfW+CCS in meeting climate objectives cannot be overstated, as the practice can contribute at least three different climate benefits. First, by diverting waste away from landfill, it avoids the generation of methane emissions which would occur otherwise. Second, it directly reduces emissions by capturing CO_2 from the fossil content in waste (around half of waste is fossil-based). Third, and perhaps most critically, EfW coupled with CCS can generate negative emissions (or 'carbon removal') since a substantial portion of the carbon contained in residual waste streams is of biogenic origin, the permanent sequestration of which leads to a negative impact on overall CO_2 stocks in the atmosphere.

This is particularly important as it can contribute towards the UK Government's targets of deploying 5-6 Mtpa in engineered greenhouse gas removals (GGRs) by 2030, 23 Mtpa by 2035 and up to 60 Mtpa by 2050. Meeting these targets will be challenging – especially the near-term ones – as they would require significant scale-up of carbon removal projects, at a time when a pipeline of GGR projects with the necessary scale is still lacking. Moreover, while other nascent GGR solutions such as direct air capture may need to undergo long testing and investment stages, EfW+CCS relies on already-proven technology and can be deployed relatively quickly, further highlighting the strategic role that EfW+CCS can play in meeting those targets.

Not only can CCS help decarbonise EfW facilities, but the EfW sector is also key in ensuring the timely and large-scale deployment of CCS itself as a national decarbonisation solution. For instance, of the 8 projects shortlisted to progress to negotiations through the UK's cluster sequencing approach, two are EfW projects, while Enfinium – a leading UK EfW operator – has also recently announced a proposal for £200m in private investment in carbon capture technology.

In light of these developments, this study has three objectives.

First, it evaluates the business case for CCS in the UK EfW sector, especially as unabated facilities will be subject to carbon pricing for the fossil CO_2 they emit after inclusion in the UK-ETS. The analysis in this study shows that several financial benefits have the potential to outweigh the added costs of CCS retrofit. Namely, in a ETS world, an abated facility avoids carbon compliance costs, and can generate revenue in the form of premium gate fees and sale of zero-carbon energy. In addition, the resulting negative emissions can be monetized in voluntary and/or compliance carbon markets.

Second, this report assesses the technical feasibility of physically installing carbon capture technology at UK EfW facilities, based on minimum capacity requirements and availability of enough on-site space for capture retrofit. The analysis finds that 60-65% of the existing 57 UK EfW facilities meet these criteria – accounting for 74-78% of the total CO_2 emissions from the sector. Most critically, the analysis finds that **negative emissions in the order of 5-8 Mtpa can be captured from the UK EfW fleet (with an average of 6 Mtpa),** depending on the assumed emissions factor of the waste combusted. For reference, this is on par with the aforementioned UK target of 5-6 Mtpa of GGR capacity by 2030 and is equivalent to 21-34% of the 2035 target, and 8-13% of the 60 Mtpa by 2050 target.

Lastly, this study identifies different methods to transport CO_2 from EfW facilities to their nearest storage sites using transportation cost and emissions intensity of different transport options (pipeline, rail, ship, truck) as metrics to evaluate what is economically feasible, and emissions-wise acceptable.

Pipeline transportation of CO_2 provides the lowest cost and lowest CO_2 emissions for EfW facilities in England, Scotland, and Wales, yet some considerations may limit the opportunity for EfW facilities to utilise pipeline transport. For instance, constructing new long-distance pipelines requires significant time to acquire the necessary regulatory approvals and land agreements, and the timeline required for planning and construction may not be consistent with CCS implementation plans. Pipelines also require a significant commitment of upfront capital to construct.

Here, the role of non-pipeline transport (NPT) modes becomes key, especially for dispersed EfW facilities (those not located around industrial clusters). Rail and ship transport are second-best options with site-specific characteristics determining which option is preferable in terms of cost and emissions. Both modes could offer benefits for project proponents by utilising existing infrastructure that reduces the timeline and risks associated with approval and construction of CO_2 transport infrastructure.

Overall, for sites where all transport modes are viable, the typical cost merit order is *pipeline* < *ship* < *rail* < *truck*. The analysis of both pipeline and ship transport options for UK EfW facilities highlights the importance of creating central hubs to achieve economies of scale for key infrastructure to reduce costs associated with CO_2 transportation. While this study only focuses on UK EfW facilities, it is key to note that CO_2 transport infrastructure would need to be shared with emission sources in other industries to achieve the production scale associated with cost forecasts.

It is also noteworthy that there are 17 new EfW plants under construction in the UK (plus one replacement) with a licenced capacity of 5.7 $MtCO_2$/y which were not included in this study but represent further opportunity for CO_2 capture from the sector. Moreover, this work only considered transportation to the four CO_2 sequestration hubs currently being developed under the UK government's initial CCS cluster sequencing; however, other CCS hubs may be developed in the future that would reduce cost/emissions for CO_2 transportation from certain UK EfW facilities.

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1. Introduction

Limiting global warming to 1.5°C above pre-industrial levels is crucial to mitigate the ecological and socio-economic consequences of climate change. The Intergovernmental Panel on Climate Change (IPCC) recognises that achieving this goal will require not only aggressive abatement of greenhouse gas (GHG) emissions, but large-scale deployment of carbon dioxide removal solutions (CDR) – also known as greenhouse gas removals (GGR)[1] and negative emission technologies (NETs) – as soon as possible to remove CO_2 from the system.[2] CDRs reduce the overall stock of CO_2 in the atmosphere and help address historical emissions and offset emission sources which are otherwise difficult or expensive to directly abate.[3]

Some of the most important CDR solutions available today include afforestation and bioenergy production coupled with carbon capture and storage (BECCS).[4] However, despite their high removal potential, both solutions suffer from shortcomings. For instance, while afforestation represents one of the least expensive CDRs and there is significant, potentially-suitable land area available globally, carbon sequestered in forests can be subject to release during disturbances (e.g., insects or wildfires), and complex interactions within the biosphere means that its net climate impact can be uncertain.[5,6] On the other hand, BECCS provides a more permanent, and relatively easier-to-quantify, CO_2 sequestration pathway, yet it is a land-intensive mitigation technique which can conflict with other uses and, unless properly managed, can incentivise deforestation in other jurisdictions – ultimately leading to carbon leakage.[7]

A variant of BECCS which mitigates land use impacts while retaining the benefits of permanent CO_2 sequestration is retrofitting energy-from-waste (EfW) facilities with carbon capture and storage (EfW+CCS). EfW facilities combust residual waste which remains after reuse and recycling, for the purpose of producing electricity and/or heat.[8] Already a mainstream practice in many regions, producing energy from waste avoids the environmental impacts associated with its counterfactual: disposal in landfills, which leads to increased land use, pollution, and methane emissions.[9] However, if left unabated, EfW facilities still generate CO_2 emissions – this is where CCS comes in.

EfW coupled with CCS is especially valuable as, much like BECCS, the practice can lead to 'carbon removal' since a substantial portion of the carbon contained in residual waste streams is of *biogenic* origin (in other words, it belongs to the natural carbon cycle).[10] The permanent sequestration of this biogenic content generates a negative impact on overall CO_2 stocks in the atmosphere.[11] On average, around half of waste is composed of biogenic content, including food, paper, cardboard; and half is fossil content, such as

[1] The terms 'CDR' and 'GGR' are used interchangeably in this paper. 'GGR' is used where in reference to EfW in the UK context as this is the term of choice in UK policy/business models.
[2] IPCC (2018). Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
[3] IPCC (2022a). Energy Systems. In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
[4] IPCC (2022b). Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
[5] Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., ... & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental research letters*, *13*(6), 063002.
[6] Deng, J., Xiao, J., Ouimette, A., Zhang, Y., Sanders-DeMott, R., Frolking, S., & Li, C. (2020). Improving a biogeochemical model to simulate surface energy, greenhouse gas fluxes, and radiative forcing for different land use types in northeastern United States. *Global Biogeochemical Cycles*, *34*(8), e2019GB006520.
[7] ibid
[8] Tolvik (2023). UK Energy from Waste Statistics – 2022. Tolvik Consulting. Available: https://www.tolvik.com/published-reports/view/uk-energy-from-waste-statistics-2022/
[9] CEWEP (2022). Wate-to-Energy Climate Roadmap. Confederation of European Waste-to-Energy Plants. Available: https://www.cewep.eu/wp-content/uploads/2022/06/CEWEP-EfW-Climate-Roadmap-2022.pdf
[10] ibid
[11] ibid

plastics.[12] It follows that if biogenic alongside fossil CO_2 is captured from EfW facilities, EfW+CCS becomes a net negative emissions solution, without creating new land use demands.

In the UK context in particular, the role of the energy-from-waste sector is prominent. In 2022, UK EfW facilities produced 9.4TWh, equivalent to 3.2% of the nation's total power output of 293.7TWh.[13] In similar proportions, these facilities emit around 3.5% (14.4 $MtCO_2e$) of the UK's overall annual territorial GHG emissions, estimated at 406.2 $MtCO_2e$ in 2022.[14] It is unsurprising, then, that the UK has recently (July 2023) moved to expand the scope of its emissions trading scheme (UK-ETS) to include waste combustion and EfW facilities starting from 2028. Integrating CCS into the EfW sector helps maintain EfW facilities as a source of sustainable, low-carbon energy while also meaningfully contributing to the UK's emission reduction targets.

Not only is CCS an important technology to decarbonise UK EfW facilities, but the EfW sector is key in progressing the timely and large-scale deployment of CCS as a decarbonisation solution itself. In March 2023, the UK Government shortlisted 8 industrial projects to proceed to negotiations for support through its established CCS business models, as part of its cluster sequencing approach (Track-1, Phase-2). Two of these projects are energy-from-waste, including the Runcorn Energy Recovery Facility (ERF) and the Protos ERF. In April 2024, Enfinium, one of the UK's largest EfW developers, further announced a proposal for £200m private investment in carbon capture technology, while also publishing a Net Zero Transition Plan[15] which outlines an objective of moving from energy-from-waste operations today to a carbon removals business in the future, with CCS at the heart of this plan.

More broadly, these developments resonate with the UK Government's 'CCUS Vision' (published in December 2023) which delineates a long-term vision for moving from government-backed to self-sustaining, merchant business models for CCS from 2035. These also come at a time when the UK, in its 2021 Net Zero Strategy[16], had committed to negative emissions targets of 5-6 Mtpa of greenhouse gas removals (GGRs) deployment by 2030, 23 Mtpa by 2035 and up to 60 Mtpa by 2050, a significant proportion of which could come from capturing CO_2 from EfW.

In light of the above, the objectives of this study are threefold. First, we qualitatively evaluate the business case for CCS in the UK EfW sector, comparing costs of abated and unabated facilities, following the future inclusion of EfW facilities into UK-ETS. Second, we assess the technical feasibility of physically installing carbon capture technology at UK EfW facilities, on a facility-by-facility basis, taking the entire UK EfW fleet into account. Here, CCS integration may be constrained by location-specific attributes such as availability of on-site space for retrofit, or economic attributes if the processing capacity of the facility itself is not large enough to economically justify capturing CO_2. Third, we identify different methods to transport CO_2 from EfW facilities to their nearest storage sites – again on a facility-by-facility basis – using transportation cost and emissions intensity of different transport options as metrics to evaluate what is economically-feasible, and emissions-wise acceptable.

It is worth noting that this study and the methodology adopted here is largely based on previous research published by the Oxford Institute for Energy Studies (Muslemani et al., 2023)[17] where a similar assessment was conducted on the European EfW fleet.

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[12] GCCSI (2019). Waste-to-energy with CCS: A pathway to carbon-negative power generation. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2019/10/Waste-to-Energy-Perspective_October-2019-5.pdf
[13] ibid
[14] UK DESNZ (2023). 2022 UK Provisional Greenhouse Gas Emissions. UK Department for Energy Security and Net Zero. Available: https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2022
[15] Enfinium (2024). Our journey to carbon removals – Net Zero Transition Plan 2024. Available at: https://enfinium.co.uk/wp-content/uploads/2024/04/201029.04_Enfinium_Net-Zero-Report-AWK_SCREEN_AWK_4.pdf
[16] HM Government (2021). Net Zero Strategy: Build back greener. Available at: https://assets.publishing.service.gov.uk/media/6194dfa4d3bf7f0555071b1b/net-zero-strategy-beis.pdf
[17] Muslemani, H., Struthers, I., Herraiz, L., Thomson, C., & Lucquiaud, M. (2023). *Waste not, want not: Europe's untapped potential to generate valuable negative emissions from waste-to-energy (WtE) using carbon capture technology* (No. 01). OIES Paper: CM01, Oxford.

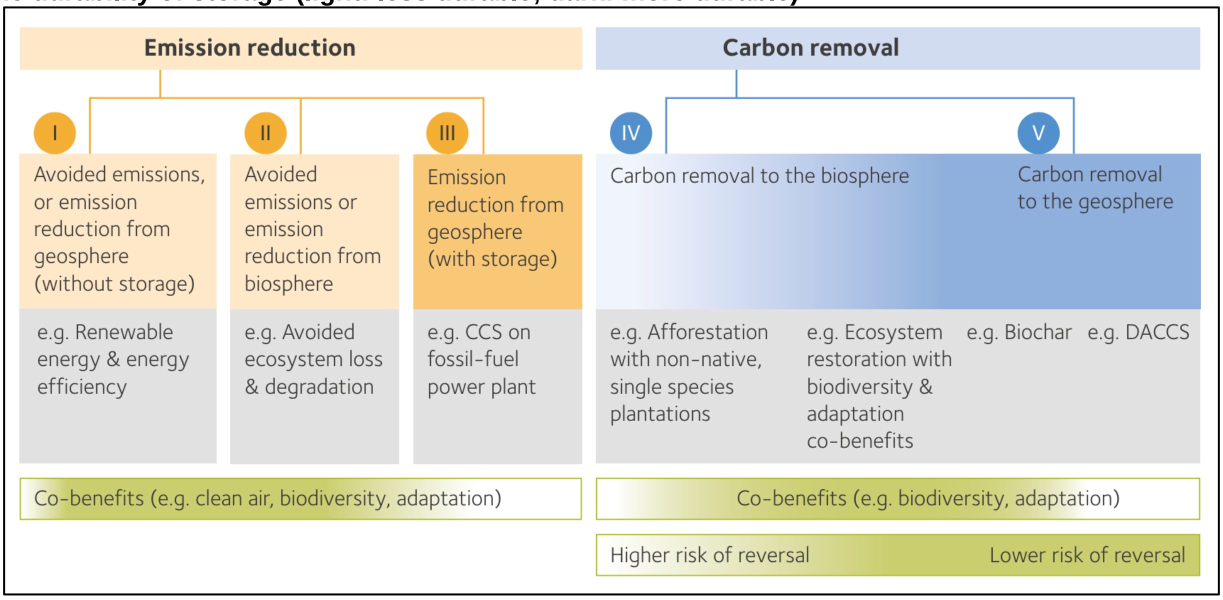
2. The case for CCS in the EfW sector

The case for deploying CCS in the EfW sector depends on a number of factors, including the possibility of capturing CO_2 at source (as will be demonstrated later) and the availability of adequate CO_2 transport and storage (T&S) infrastructure for its eventual disposal. In addition, CO_2 capture from EfW will necessitate other non-technical factors, namely a robust and reliable accounting framework to measure the captured and sequestered CO_2, including methods to quantify, monitor and verify the amounts of emissions captured/avoided, and viable business models that facilitate the technology's deployment and economically support its operation throughout the project's lifetime.

On the former, a sound carbon accounting framework is necessary for several reasons. First, waste is a dynamic resource whose quantities and composition vary over time, influenced by existing policies such as recycling rates and incentives (or lack thereof) for waste treatment, as well as other macro factors such as population and economic growth. Second, under an EfW+CCS scenario, while both fossil and biogenic CO_2 emissions are captured from the same facility, the application creates two value chains: one leading to *emission reductions* (from the capture of fossil CO_2) and another to *negative emissions* (from the capture of biogenic CO_2 as outlined earlier), and so the overall economic and environmental value brought about by deploying CCS in the sector should be appraised accordingly. For instance, negative emissions help capturing *historical* emissions which are already in the atmosphere, while emission reductions (e.g., through 'conventional' CCS as in fossil power plants) help lower existing emissions and avoid *future* emissions. Because of this, in a carbon-constrained world, the former may often be regarded as more 'valuable'.[18]

More specifically, both from an accounting and a value-added perspective, retrofitting an EfW facility with CCS is unique in that it is an application that would simultaneously contribute to three different types of climate mitigation activities, as categorised in the recently-revised Oxford Offsetting Principles (Figure 1).[19]

Figure 1: Taxonomy of climate mitigation activities. Shading of colours from light to dark pertain to the durability of storage (light: less durable; dark: more durable)



Source: Oxford Offsetting Principles (2024)

First, waste combustion – whether with or without CCS – leads to ***avoided emissions*** (Category II in Figure 1) as its counterfactual is waste diverted into landfill, which would have in time generated methane emissions that, from a global warming potential perspective, are significantly more potent than the CO_2 emitted under an EfW scenario. Despite this, it is here worth noting that accurately measuring the environmental benefits associated with these avoided emissions remains a challenge (i.e., methane emissions which would

[18] Zickfeld, K., Azevedo, D., Mathesius, S., & Matthews, H. D. (2021). Asymmetry in the climate–carbon cycle response to positive and negative CO_2 emissions. *Nature Climate Change*, *11*(7), 613-617.
[19] See revised 2024 version of Oxford Offsetting Principles here: https://www.smithschool.ox.ac.uk/sites/default/files/2024-02/Oxford-Principles-for-Net-Zero-Aligned-Carbon-Offsetting-revised-2024.pdf

otherwise have occurred cannot be physically quantified). This contrasts with some CDR solutions such as Direct Air Capture (DAC) where the baseline scenario is zero additional emissions i.e., no additional emissions would be generated in absence of the project.

Second, EfW+CCS leads to ***emission reduction*** (Category III) due to the capture and storage of *fossil* CO_2 and, third, to ***carbon removal*** (Category V) from the capture and geological storage of *biogenic* CO_2. Alongside these climate contributions, waste combustion also has the added benefit of ***producing energy*** as a by-product, which can be economically monetized. Again, it is important to highlight that this added benefit may increase the complexity of emissions accounting at the project level, as the generated electricity/heat would displace grid electricity and/or a heat source with a different emission factor.

The treatment of the various benefits of EfW+CCS has not only accounting but also policy and economic dimensions. As noted earlier, negative emissions may be viewed as more valuable since they can address potential future temperature overshoots. This is perhaps one of the reasons why participants in carbon markets today are increasingly procuring carbon removal over avoidance/reduction solutions, despite their higher cost on average, as they are widely regarded as higher quality, more future-proof, and are much less contested.[20] It is key to note here that this assertion assumes that removal solutions are not used to substitute the need to reduce emissions in hard-to-abate applications where the removal solution may have a lower cost of abatement, something that corporate net-zero guidance frameworks such as the Science-Based Targets Initiative (SBTi) makes explicit.[21]

Most relevant to this study, the stated benefits of EfW+CCS (avoided emissions, emissions reduction, carbon removal, and energy generation) directly impact the business models which may support the deployment of CCS in the sector.

For context, the revenue stream of a typical EfW facility consists predominately of gate fees charged to consumers for treatment of residual waste, after recycling of waste collected through local authorities, in addition to the sale of electricity produced in the process. In the UK, the baseline scenario is that, from 2028, the EfW sector will enter the UK-ETS where *unabated* EfW facilities will become exposed to carbon pricing on the fossil portion of the CO_2 they emit (e.g., around 50%).[22] This added cost could ultimately translate to increased gate fees to be passed up the supply chain, as responsibility for emissions does not arguably lie with the EfW developer but with end-consumers who produce the waste in the first place.

On the contrary, biogenic emissions emitted by that facility are exempt from carbon pricing under the current UK-ETS proposal, although the UK Government has signalled its intention to include GGRs within the scope of the UK-ETS (without a firm timeline for its inclusion at the time of writing).[23] Here again, if GGRs can monetised, EfW operators would be expected to pass on additional profits to end-consumers in the form of gate fees reduction. Put simply, a fraction of the *value* and *responsibility* of procuring the biogenic carbon belongs to the end-consumer who produces the waste.

Under this same compliance market, an *abated* facility would incur significant costs for CCS deployment and maintenance over the project's lifetime, in addition to revenue loss from heat and power consumption associated with CCS (Figure 2). However, assuming capture rates close to 100% (Su et al., 2023), CCS retrofit means the facility will no longer be subject to carbon pricing for its fossil-based emissions, and an economic benefit in the form of cost avoidance is reaped in an ETS world. From an EfW facility's and its local authority's perspective, if the carbon cost savings due to CCS outweigh the needed increase in gate fees without CCS, revenue can be generated and potentially shared amongst both in a gainsharing mechanism.

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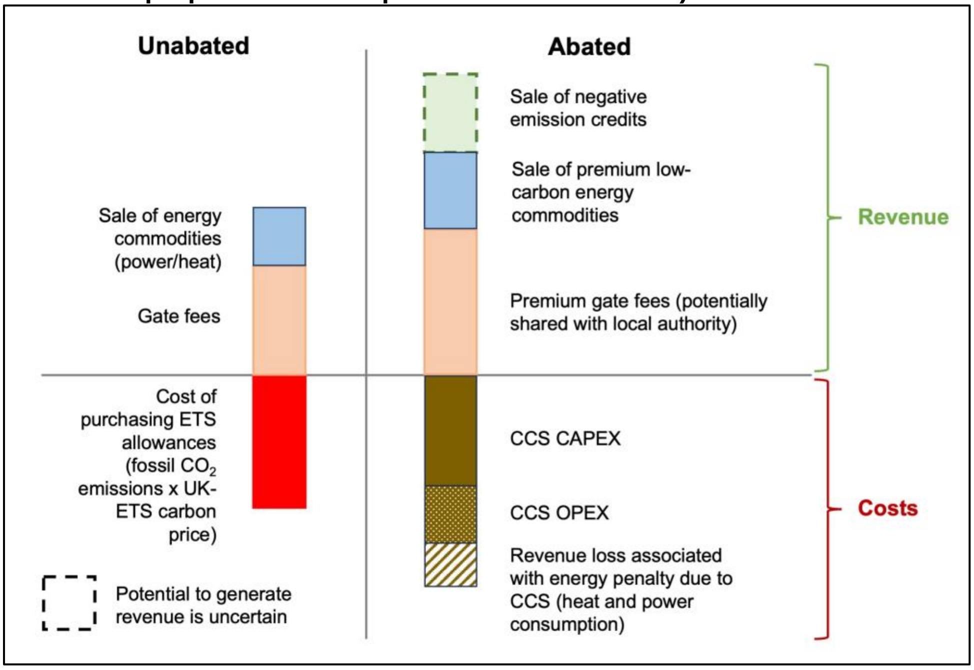
[20] Walsh, V. R. & Toffel, M.W. (2023). What every leader needs to know about carbon offsets. Available at: https://hbr.org/2023/12/what-every-leader-needs-to-know-about-carbon-offsets

[21] University of Oxford (2023). CO_2 removal is essential, along with emissions cuts, to limit global warming. https://www.ox.ac.uk/news/2023-01-19-co2-removal-essential-along-emissions-cuts-limit-global-warming-report#:~:text=Carbon%20Dioxide%20Removal%20is%20no,up%20to%20achieve%20net%20zero.

[22] https://www.nortonrosefulbright.com/en-gb/knowledge/publications/6c69a0cb/energy-from-waste-efw-facilities#:~:text=Timing%3A%20EfW%20and%20waste%20incineration,is%20subject%20to%20further%20consultation

[23] UK DESNZ (2023). Engineered greenhouse gas removals – Government response to the consultation on a GGR Business Model. Available at: https://assets.publishing.service.gov.uk/media/64955096831311000c296222/engineered-ggrs-government-response.pdf

Figure 2: Costs and revenue streams of unabated (left) vs abated (right) EfW facilities under an ETS (bar sizes are not proportional to respective cost or revenue)



In addition to a premium gate fee and cost avoidance under the ETS, other monetary benefits can be generated due to carbon removal, as noted earlier, for instance through the sale of negative emission credits in the voluntary carbon market (VCM), or later in a compliance carbon market. This assumes revenue from sale of negative emissions credits can be stacked with other government support mechanisms (for instance, the support provided under the UK's waste industrial carbon capture [waste ICC] contracts). Even then, it remains difficult to estimate the price that negative emission credits could command in the VCM as cost estimates vary widely across different CDR solutions (e.g., biochar, DACCS, BECCS, enhanced rock weathering, etc.) and across different regions for the same solution, where some solutions are still in early stages of development. The bilateral nature of trading in the market may also make this difficult to estimate since details of purchase agreements are not always disclosed.

Lastly, a fourth financial benefit for an EfW+CCS operator is generated in the form of zero-emission energy, which can sell at a premium especially as electricity typically generated by an EfW facility is highly carbon intensive (around 500-600 gCO_2/kWh)[24]. However, it is important to ensure that no double counting occurs if negative emission credits are also monetized.

Under current market conditions (low UK-ETS price of around £38/tCO_2, and high CCS costs estimated at around 150 £/tCO_2 for EfW)[25,26], an abated facility would expectedly incur higher costs than an unabated one. However, with additional revenue in the form of premium gate fees and sale of premium low-carbon energy commodities, in addition to potential sales of (high-value) negative emission credits, an abated facility is likely to be profitable if the additional benefits outweigh the costs of CCS (Figure 2).

In what follows, we assess the technical feasibility of retrofitting carbon capture technology on UK EfW facilities.

[24] Energy Systems Catapult (n.d.). Can Energy from Waste drive the deployment of Carbon Capture & Storage?. Available at: https://es.catapult.org.uk/insight/can-energy-from-waste-drive-the-deployment-of-carbon-capture-storage/#:~:text=Energy%20from%20waste%20plants%20%E2%80%93%20large%20carbon%20emitters&text=These%20plants%20produce%20electricity%20with,intensity%20of%20around%20600g%2FkWh.

[25] UK-ETS price accurate as of May 15, 2024 (source: carboncredits.com)

[26] Cost of capture of around £150/tCO_2 estimated in a techno-economic analysis study conducted by the authorship team as part of the NEWEST CCUS project, funded by the ERA-NET Accelerating CCS Technologies (ACT2) initiative.

3. Technical feasibility of carbon capture from UK EfW facilities

Post-combustion CCS can be applied to EfW facilities to capture CO_2 emissions from the facility exhaust stream.[27] Industrial-scale, post-combustion CCS has been implemented at several locations worldwide including the SaskPower coal power plant in Canada (1 $MtCO_2$/y) and the Petra Nova coal power plant in USA (1.7 $MtCO_2$/y).[28] Within the EfW sector, post-combustion carbon capture has been installed at the AVR Netherlands EfW plant (105 $ktCO_2$/y), where the captured CO_2 is supplied to nearby greenhouse horticulture[29] and the Hafslund Oslo Celsio EfW facility (400 $ktCO_2$/y) in Norway is currently being retrofitted with CCS to sequester CO_2 as part of the Northern Lights project.[30]

CEWEP (2022) evaluated the GHG mitigation potential of applying CO_2 capture to the European EfW sector for a range of assumed CO_2 capture rates (50-90%) and market shares (50-90%). They found potential net negative GHG emission rates ranging from -20 to -75 $MtCO_2$e/y, including credits for reduced landfill emissions and energy substitution. However, they did not consider any limitations on ability of facilities to implement CCS.

Muslemani et al. (2023) screened European EfW facilities to assess the feasibility of retrofitting CCS based on three criteria: less than 300 km from a central CCS cluster or hub, available space on-site to physically install CCS equipment, and sufficient plant capacity to economically justify CCS (>100 $ktCO_2$/y). For European EfW facilities meeting those three criteria, they determined potential net negative direct CO_2 emissions of -20 to -28 $MtCO_2$/y based on 1 tCO_2 per tonne of waste and 100% CO_2 capture. Due to the large geographic area of their study, the analysis of transportation options was limited in scope (i.e., considered straight-line pipelines).

This study performs a detailed investigation of potential to apply CCS to EfW facilities in the UK. We follow the general screening framework of Muslemani et al. (2023), but apply a greater level of detail to the analysis to assess the feasibility, cost, and emissions associated with multiple CO_2 transportation options (pipeline, shipping, rail, and truck) for each facility meeting the suitability criteria.

3.1. Minimum capacity requirements

To do this, we used the inventory of 57 operating UK EfW facilities as basis (Table 1). EfW facilities with annual CO_2 emissions greater than 100 $ktCO_2$/y were selected for analysis. The minimum capacity criteria was selected based on the typical scale of CCS facilities in operation and in planning globally (Muslemani et al., 2023). Tolvik (2023) reports the licenced waste capacity of each UK EfW facility and an average CO_2 emission factor of 0.94 tCO_2 per tonne of waste. Here, we considered a range of CO_2 emission factors: 0.7, 0.94, and 1.18 tCO_2 per tonne of waste based on the range of values reported by UK EfW facilities excluding outliers.[31] The proportion of exhaust CO_2 captured at a particular facility would depend on the process and equipment design.

Eventually, we quantify the potential size of the CCS market for UK EfW facilities with the assumption that all net CO_2 produced by each facility could be captured based on recent studies and pilot tests which have shown that post-combustion capture rates near 100% are achievable and economically viable.[32,33,34,35] Here, negative emissions potential was estimated based on the average biogenic content of UK residual waste (52.5%).[36]

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[27] ibid

[28] IEA (2023). CCUS Projects Database. International Energy Agency. Available at: https://www.iea.org/data-and-statistics/data-product/ccus-projects-database.

[29] ibid

[30] ibid

[31] ibid

[32] Feron, P., Cousins, A., Jiang, K., Zhai, R., Thiruvenkatachari, R., & Burnard, K. (2019). Towards zero emissions from fossil fuel power stations. *International Journal of Greenhouse Gas Control*, *87*, 188-202.

[33] Gao, T., Selinger, J. L., & Rochelle, G. T. (2019). Demonstration of 99% CO2 removal from coal flue gas by amine scrubbing. *International Journal of Greenhouse Gas Control*, *83*, 236-244.

[34] Danaci, D., Bui, M., Petit, C., & Mac Dowell, N. (2021). En route to zero emissions for power and industry with amine-based post-combustion capture. *Environmental Science & Technology*, *55*(15), 10619-10632.

[35] Su, D., Herraiz, L., Lucquiaud, M., Thomson, C., & Chalmers, H. (2023). Thermal integration of waste to energy plants with Post-combustion CO2 capture. *Fuel*, *332*, 126004.

[36] ibid

Table 1: Statistics for EfW facilities in the UK

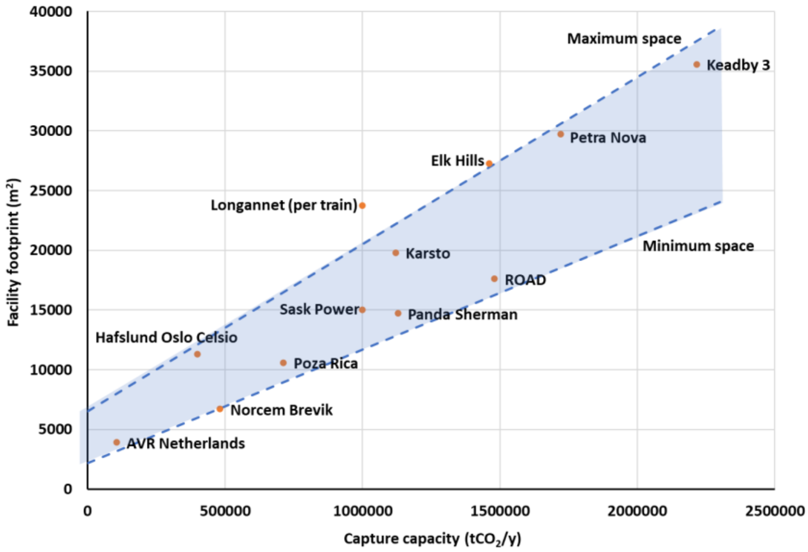
Facilities	Quantity	Permitted waste capacity	Waste processed in 2022
Operating	57	17.5 Mt/y	15.3 Mt
In construction	18	5.7 Mt/y	-

Source: Tolvik (2023)

3.2. On-site space availability for CCS

Each facility meeting the minimum capacity criteria was screened for physical on-site space availability for CCS equipment using satellite imagery (Google Earth). Note that physical space requirements for a particular CCS facility will vary significantly based on the CO_2 capture capacity and site-specific factors such as facility design philosophy and the extent to which existing utility systems can be utilised. Minimum and maximum correlations for space required for the CCS equipment as a function of capacity were developed using existing CCS facilities and detailed front-end engineering design studies for upcoming CCS facilities, as shown in Figure 3.

Figure 3: CCS facility footprint versus capacity



Note: Dashed lines show the minimum and maximum space requirement assumed in this study for given CO_2 capture capacity. Based on existing CCS facilities and detailed front-end engineering design studies for proposed CCS facilities.

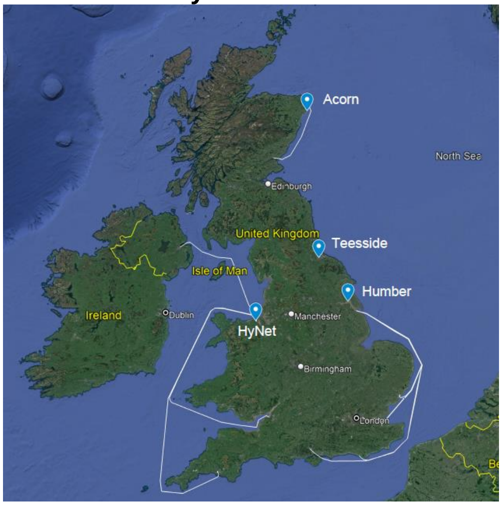
- If available space at an EfW facility exceeded the maximum space requirement, we consider that space would be unlikely to constrain CCS installation at that facility;
- If available space at an EfW facility exceeded the minimum space requirement but was less than the maximum space requirement, we consider that there may be sufficient space available, but site-specific investigation would be required to confirm. *Facilities in either of the first two categories were included in the following transportation analysis;*
- If available space for an EfW facility was less than the minimum space requirement, we assume that space is likely inadequate to support CCS installation with current commercially available amine-based technology and thus the facility was not considered further in the analysis. The spatial analysis was considered independently for each CO_2 emission factor.

3.3. CO_2 transport options

As far as CO_2 transport options are concerned, it is important to note that the UK's current CCS cluster sequencing approach assumes pipeline-only transport away from the clusters. Yet, in this analysis, we consider other non-pipeline modes of CO_2 transport especially as the UK CCUS Vision recognises the strategic significance of these solutions to mitigate emissions from 'dispersed emitters'.

As such, four CO_2 transport modes were considered for each facility meeting the above capacity and space requirement criteria: pipelines, ship, rail, and truck. CO_2 was assumed to be transported from each facility to the closest of the four announced CO_2 sequestration hubs within the UK: Teesside, and Viking (Humber), HyNet (Liverpool Bay), and Acorn (Firth of Forth/Peterhead). CO_2 transport for EfW facilities linked to Acorn was based on delivery to Firth of Forth with pipeline transport to Peterhead for EfW facilities located south of Firth of Forth, or directly to Peterhead for EfW facilities located north of Firth of Forth. Pipelines and truck transport were considered for all EfW facilities in England, Scotland, and Wales. Ship transport was considered for Northern Ireland and facilities in England, Scotland, and Wales where the nearest deep-water port was closer than the nearest CO_2 sequestration hub (Figure 4). Rail transport was considered where there is reasonable access to the UK rail network at the EfW facility. Pipeline, rail, and truck transport were assumed to originate at the EfW facility. Ship transport scenarios included either truck or low-capacity pipeline to the nearest deep-water port.

Figure 4: Ship routes considered in this study



Source: Authors' depiction. Note: Originating at deep-water ports located near UK EfW facilities and terminating at deep-water ports within the nearest UK CO_2 sequestration hub (blue markers).

Table 2: CO_2 transport costs assumed in this study

Mode	Cost basis
Low-capacity pipeline	0.028 £/km-tCO_2
High-capacity pipeline	0.0065 £/km-tCO_2
Low-capacity ship	6.6 £/tCO_2 fixed plus 0.0045 £/km-tCO_2 travel
High-capacity ship	4.0 £/tCO_2 fixed plus 0.0036 £/km-tCO_2 travel
Rail	0.043 £/km-tCO_2
Truck	1.0 £/h-tCO_2 plus 0.015 £/km-tCO_2

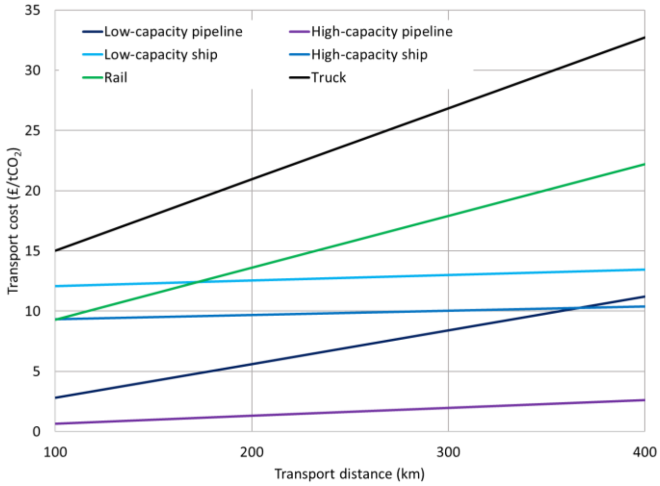
Note: Pipeline and ship estimates based on ZEP (2019) with currency conversion based on purchasing power parity (OECD, 2022). Rail estimate based on revenue and net freight volume for DB Cargo (UK)[37,38] Truck estimate based on MDS Transmodal (2019)[39].

[37] DB Cargo (2023a). DB Cargo (UK) Limited Annual Report for the year ended 31 December 2019. Available at: https://find-and-update.company-information.service.gov.uk/company/02938988/filing-history

[38] DB Cargo (2023b). Our company in numbers. DB Cargo (UK) Limited. Available at: https://uk.dbcargo.com/rail-uk-en/Our-Company/facts-and-figures

[39] MDS Transmodal (2019). 2019. Understanding the UK Freight Transport System. Report commissioned by UK Goverment Office for Science. Available: https://assets.publishing.service.gov.uk/media/5c614f7340f0b676c66a2620/fom_understanding_freight_transport_system.pdf

Figure 5: CO_2 transport cost versus distance



Note: Based on cost assumptions in Table 1 with 5 £/tCO_2 for additional processing to liquify the CO_2 (rail, ship, and truck). Truck transport assumes average speed of 70 km/h, one hour at each end to load/unload, and empty return from the CO_2 sequestration hub to the EfW plant.

CO_2 emission factors for each transport mode were based on distance traveled and empty returns for rail, ship, and truck (Table 2).

Table 3: CO_2 emission factors for transport modes assumed in this study

Mode	CO_2 Transport	Empty return	Total
Pipeline	0.005	N/A	0.005
Ship	0.018	0.002	0.020
Rail	0.021	0.003	0.024
Truck	0.058	0.009	0.067

Note: All values in kgCO_2/km-tCO_2 based on distance from the EfW plant to the CO_2 sequestration hub. Based on Freer et al. (2021)[40].

3.4. Results of technical assessment

In this analysis, 60-65% of the 57 UK EfW facilities were found to meet the minimum capacity and available space criteria in this study for installation of CCS depending on the assumed CO_2 emission factor (Table). These facilities represent 74-78% of the total CO_2 emissions from all UK EfW facilities (Table 4).

Table 4: Number of UK EfW facilities meeting the minimum capacity and available space criteria for inclusion in this study

	Minimum	Average	Maximum
Facilities meeting criteria	23	24	25
Detailed spatial analysis required	10	10	14
Total facilities included	**34**	**35**	**37**
Facilities not meeting criteria	23	22	20

Note: Breakdown of screening results for the three CO_2 emission factor scenarios: minimum (0.70 tCO_2/t waste), average (0.94 tCO_2/t waste), and maximum (1.18 tCO_2/t waste).

[40] Freer, M., Gough, C., Welfle, A., & Lea-Langton, A. (2021). Carbon optimal bioenergy with carbon capture and storage supply chain modelling: How far is too far?. *Sustainable Energy Technologies and Assessments*, *47*, 101406.

Table 5: CO_2 emissions (megaton) from UK EfW facilities meeting the minimum capacity and available space criteria for inclusion in this study

	Minimum	**Average**	**Maximum**
Emissions from facilities meeting criteria	5.98	7.82	8.65
Detailed spatial analysis required	3.58	4.21	6.70
Total emissions included (Mtpa)	**9.56**	**12.03**	**15.35**
Negative CO_2 potential (Mtpa)	**5.02**	**6.32**	**8.06**
Facilities not meeting criteria	2.70	4.44	5.33

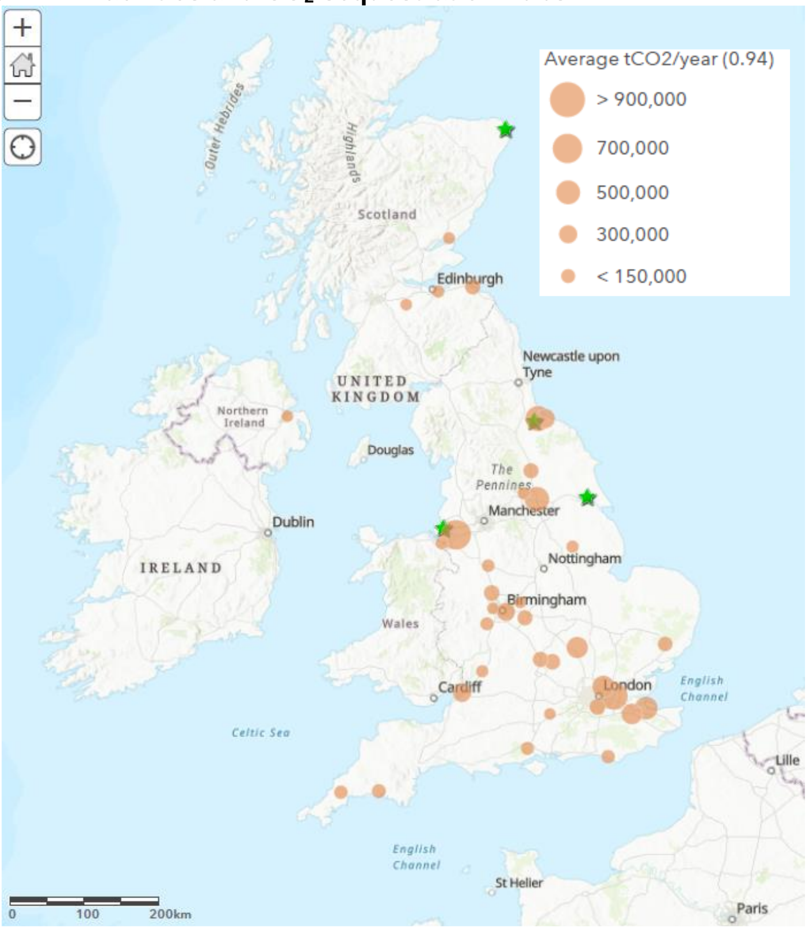
Note: Breakdown of screening results for the three CO_2 emission factor scenarios: minimum (0.70 tCO_2/t waste), average (0.94 tCO_2/t waste), and maximum (1.18 tCO_2/t waste). All values in $MtCO_2$/y.

CO_2 transport distances for UK EfW facilities vary widely – from 7 to 665 km – depending on the transport mode and proximity of the nearest sequestration hub (Figure 6). **High-capacity pipelines are the most economical CO_2 transport mode for all UK EfW facilities outside Northern Ireland** – less than 3.6 £/tCO_2 to the nearest CO_2 sequestration hub (Figure 7).

Ship transport costs are less affected by distance than pipeline, truck, or rail. The variability in CO_2 transport via ship is primarily due to distance from EfW facilities to the nearest deep-water port. Using low-capacity pipelines to transport CO_2 from EfW facilities to deep-water ports reduces the overall transport cost by an average of 5.4 £/tCO_2 compared to trucking. It is noteworthy that, when comparing costs for ship transport with other modes, the average distance for cases where ship transport is viable is significantly larger than land-based modes (484 km v. 239-267 km for truck, pipeline, and rail) because those facilities are generally further away from sequestration hubs (Figures 8-11).

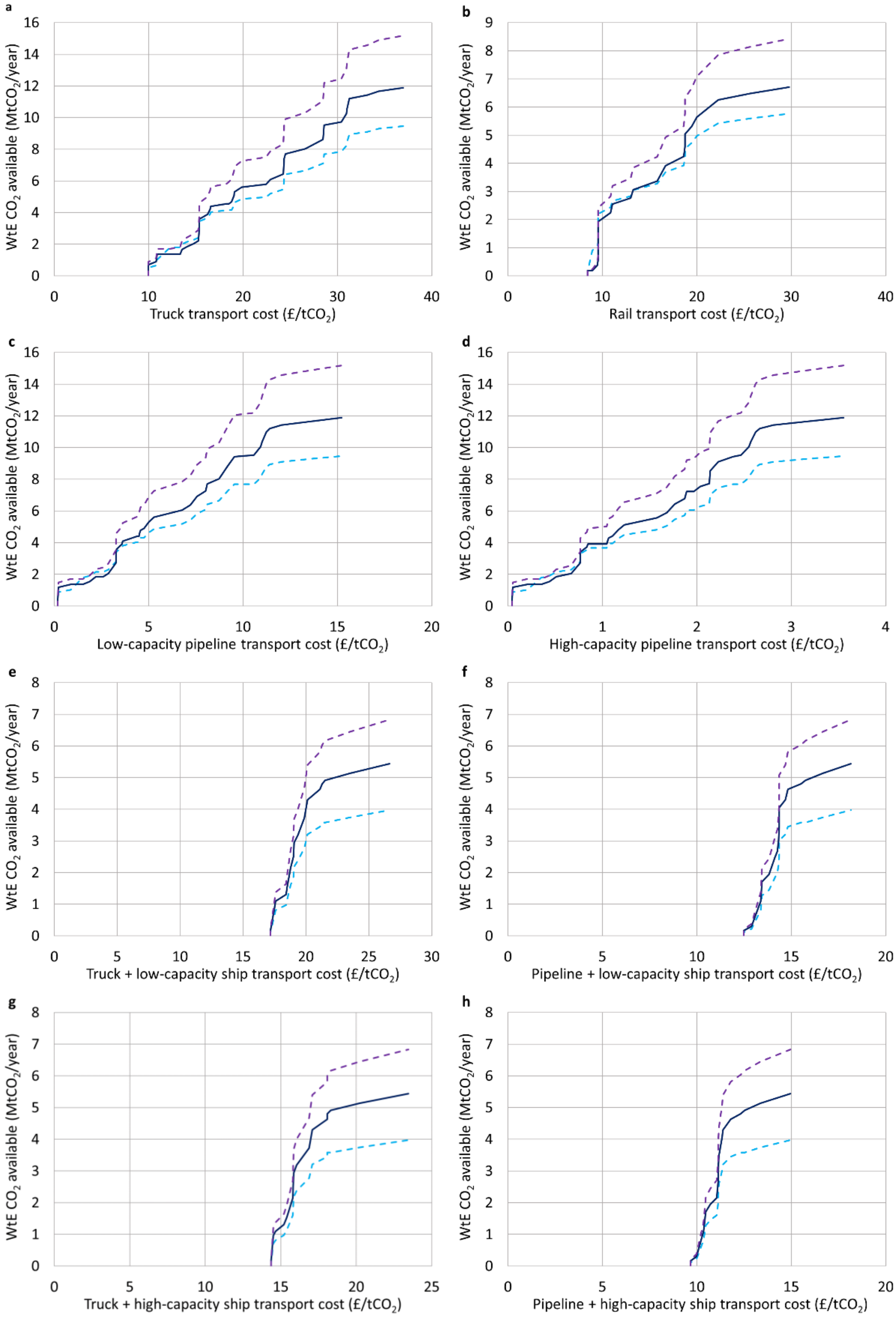
Logistical constraints limit the opportunity to use rail and ships to transport CO_2 from UK EfW facilities to approximately 55% and 53% of the total CO_2 available respectively. Among sites where all modes are viable, the typical cost merit order is ***pipeline < ship < rail < truck***. However, for 9 out of the 38 EfW facilities considered in the transportation analysis (19% of permitted waste capacity) the only viable options identified in this study are pipeline or truck.

Figure 6: Map of UK EfW facilities and CO_2 sequestration hubs



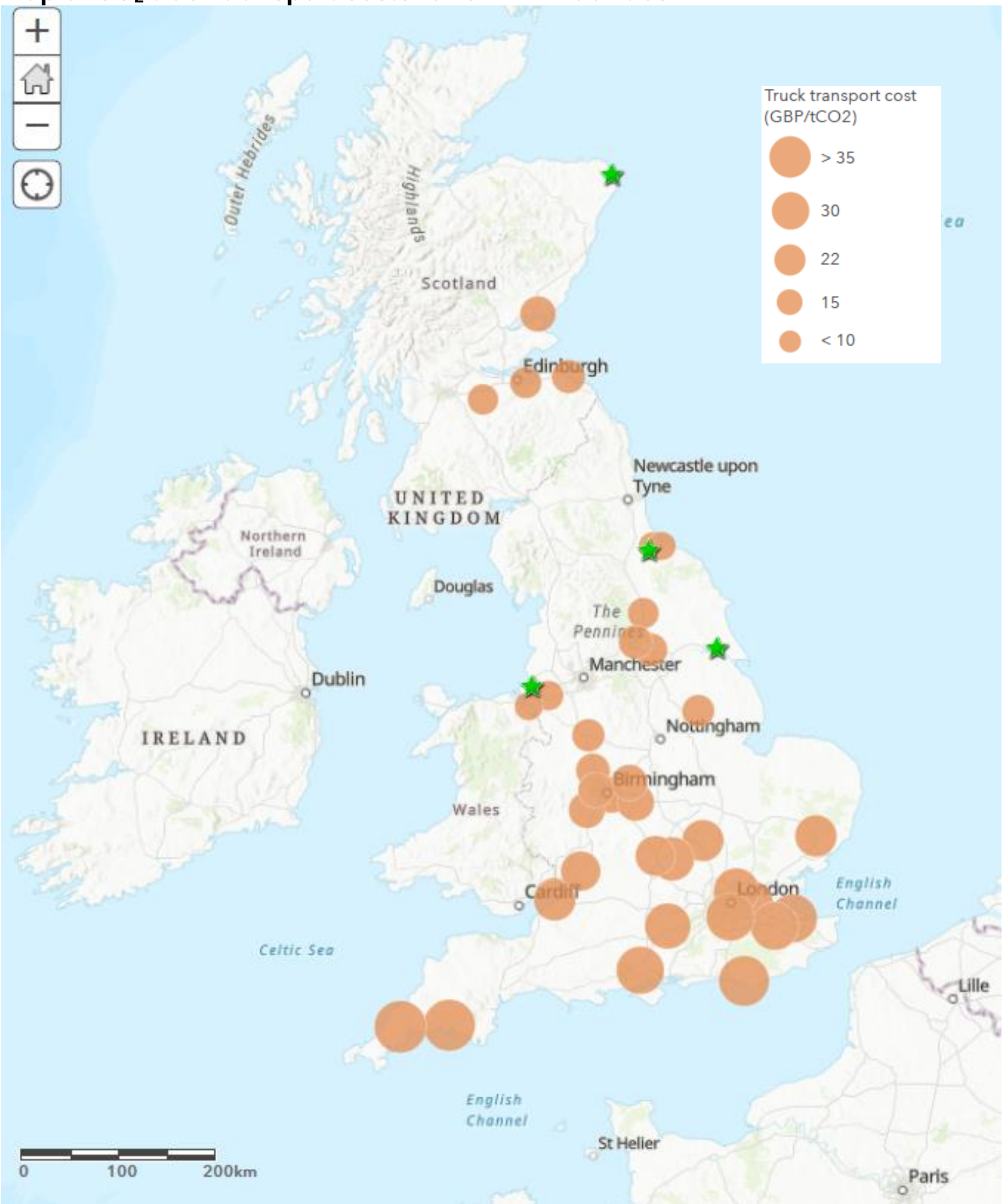
Note: Location of UK EfW facilities meeting the capacity and available space criteria for inclusion in this study (brown circles) relative to CO_2 sequestration hubs (green stars). Size of EfW facility symbols based on CO_2 emissions (tCO_2/y) using permitted waste capacity and 0.94 tCO_2 per tonne of waste.

Figure 7: Cumulative UK EfW CO_2 emissions available versus CO_2 transport cost for each mode



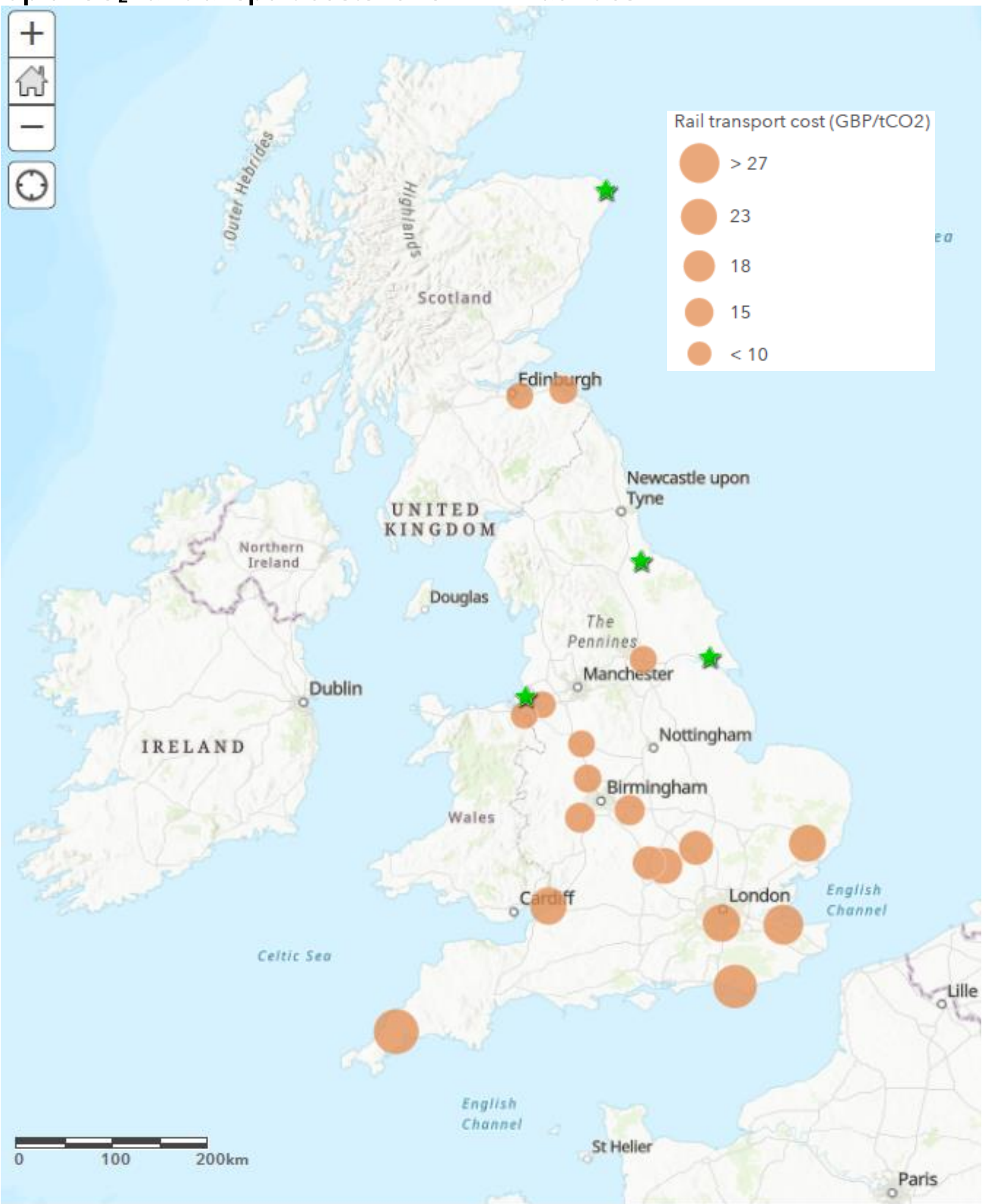
CO_2 emissions based on facility licenced capacity and three CO_2 emission factors: average (0.94 tCO_2 per tonne waste, solid dark blue line), maximum (1.18 tCO_2 per tonne waste, dashed purple line), and minimum (0.7 tCO_2 per tonne waste, dashed light blue line). **a**, truck. **b**, rail. **c**, low-capacity pipeline. **d**, high-capacity pipeline. **e**, low-capacity ship with truck transport to port. **f**, low-capacity ship with pipeline transport to port. **g**, high-capacity ship with truck transport to port. **h**, high-capacity ship with pipeline transport to port.

Figure 8: Map of CO_2 truck transport costs for UK EfW facilities



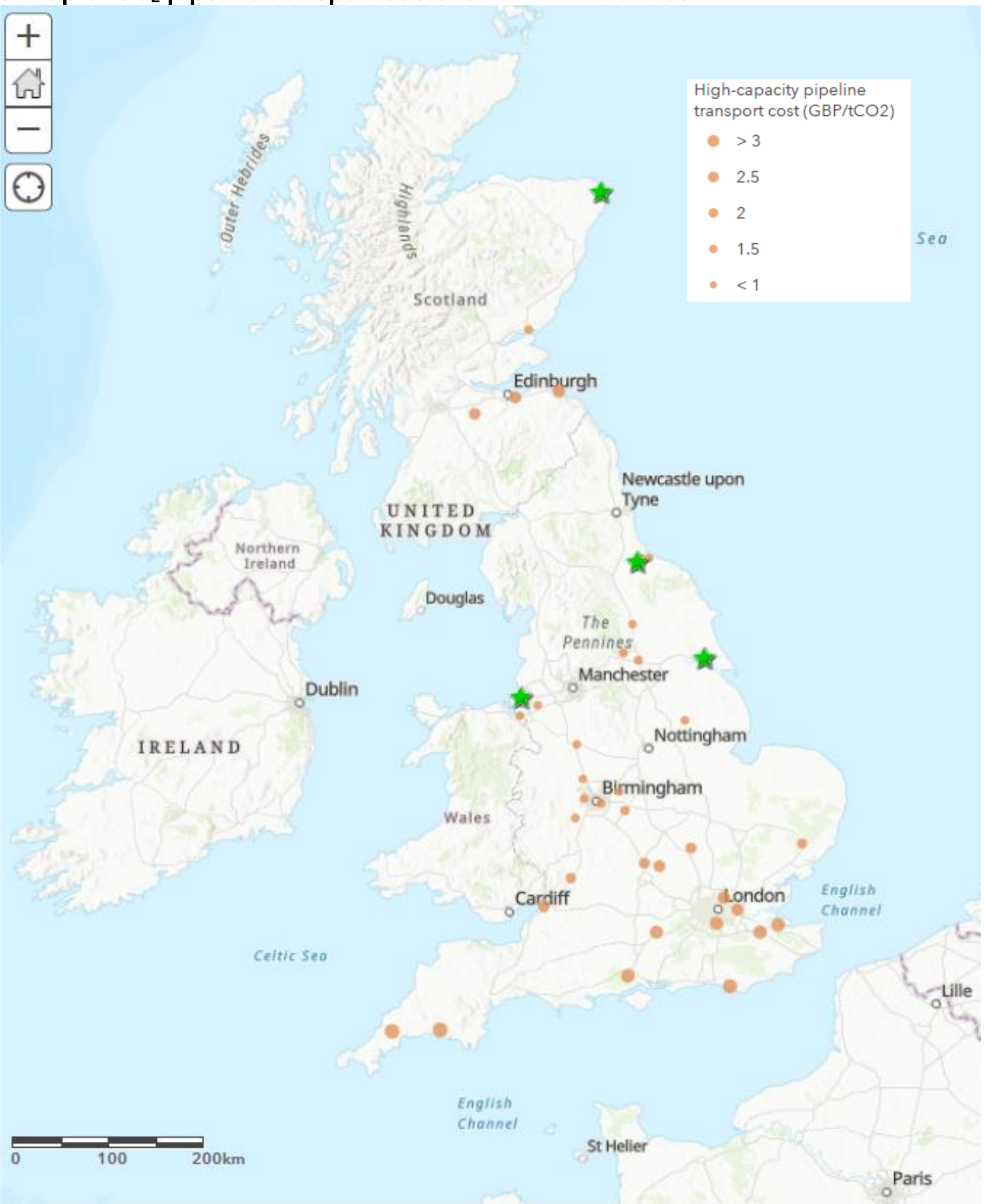
Note: Location markers for UK EfW facilities (brown circles) scaled by cost to transport CO_2 by truck to nearest CO_2 sequestration hub (green stars).

Figure 9: Map of CO_2 rail transport costs for UK EfW facilities



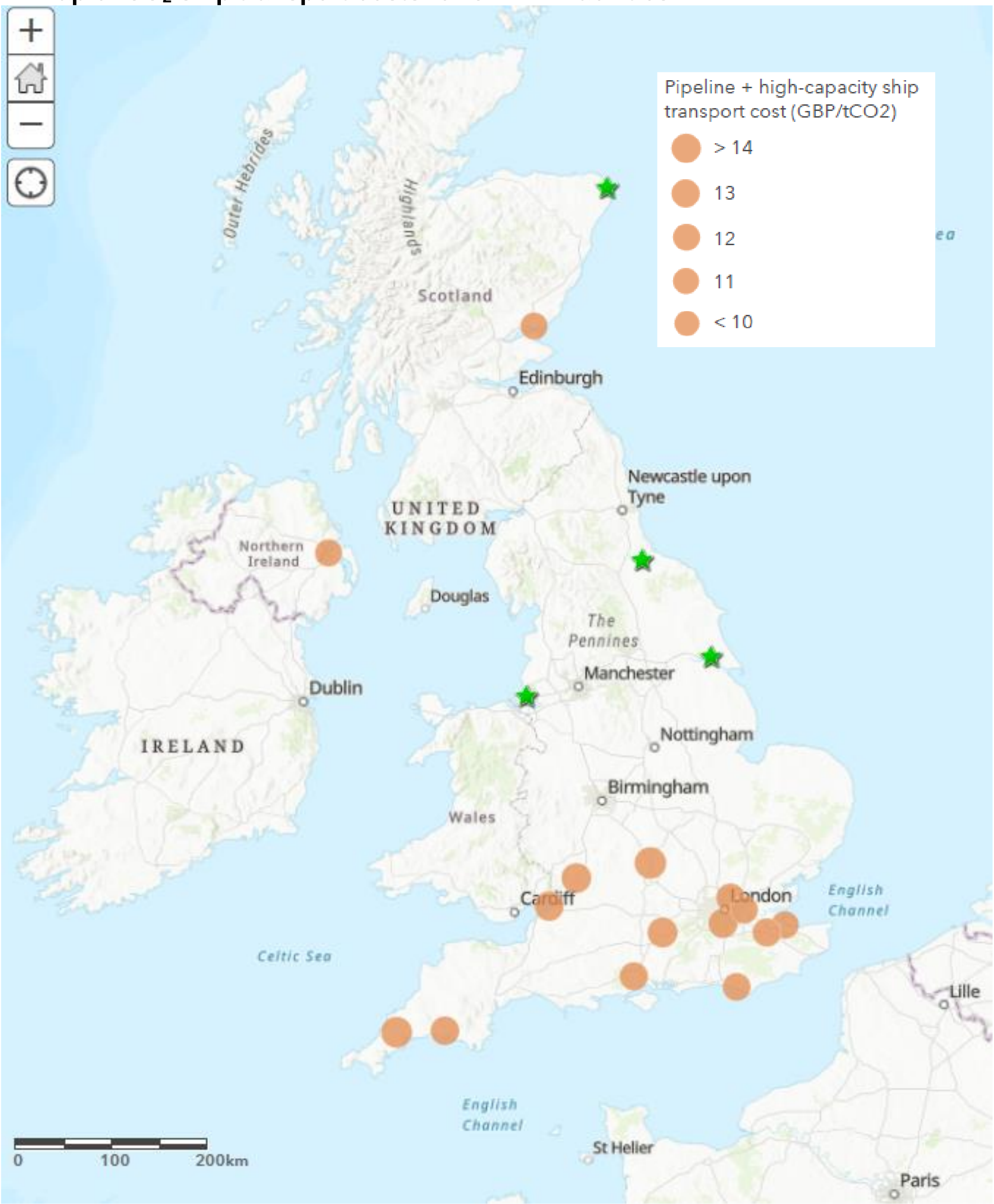
Note: Location markers for UK EfW facilities (brown circles) scaled by cost to transport CO_2 by rail to nearest CO_2 sequestration hub (green stars).

Figure 10: Map of CO_2 pipeline transport costs for UK EfW facilities



Note: Location markers for UK EfW facilities (brown circles) scaled by cost to transport CO_2 by high-capacity pipeline to nearest CO_2 sequestration hub (green stars).

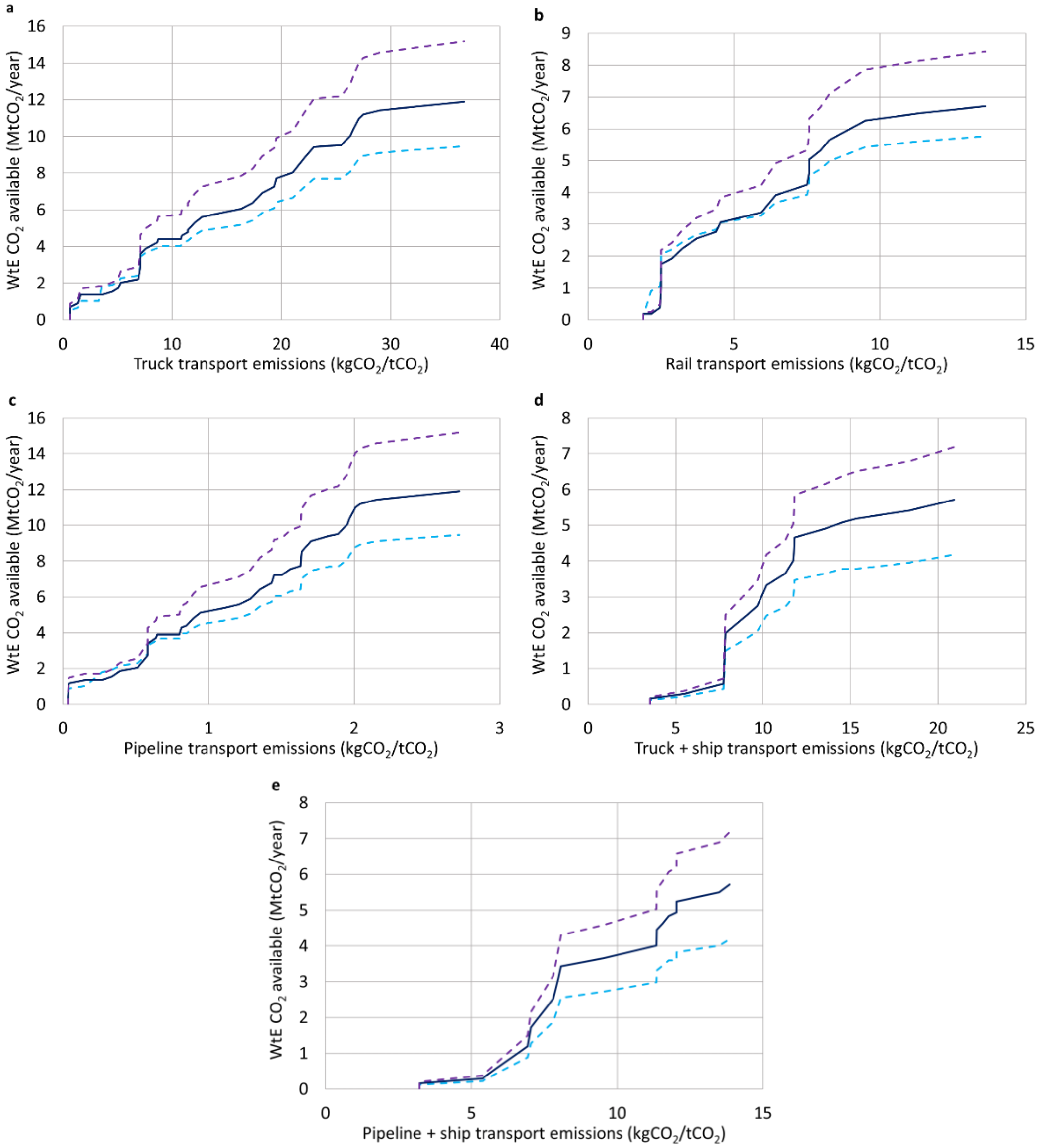
Figure 11: Map of CO_2 ship transport costs for UK EfW facilities



Note: Location markers for UK EfW facilities (brown circles) scaled by cost to transport CO_2 by pipeline to nearest deep-water port and high-capacity ship to nearest CO_2 sequestration hub (green stars).

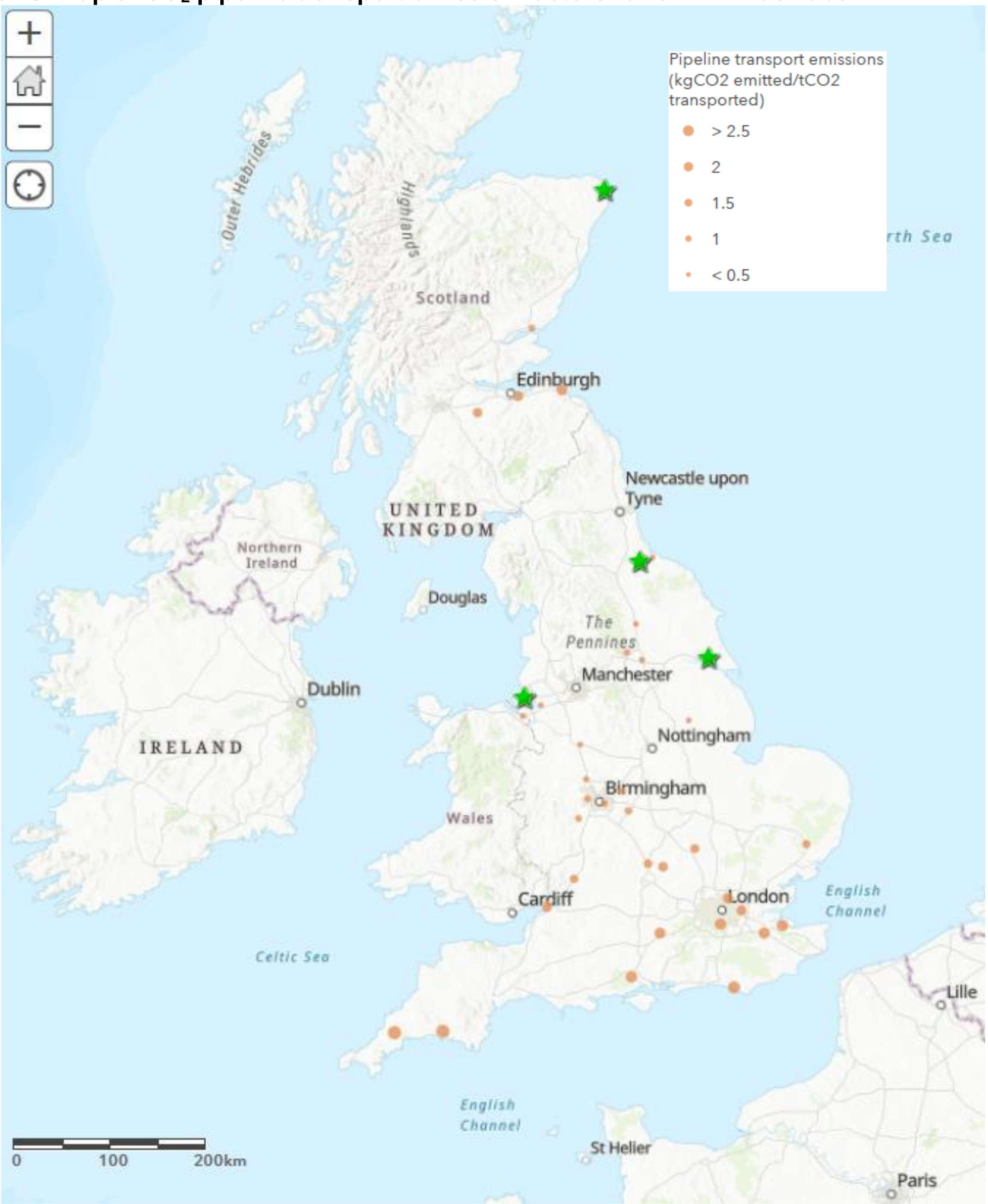
Pipeline transportation also has the lowest carbon footprint of the four CO_2 transportation modes by a significant margin – an average of 1.2 $kgCO_2/tCO_2$ transported versus 5.8-14.7 $kgCO_2/tCO_2$ for the other modes (Figure 12). Direct CO_2 emissions associated the pipeline transportation are less than 2.7 $kgCO_2/tCO_2$ transported from all EfW facilities in England, Scotland, and Wales to the nearest CO_2 sequestration hub (Figure 13). Truck transportation is the most carbon-intensive mode (Figure 14) and increases the carbon footprint of ship transport up to 74% compared to using pipelines to transport CO_2 to the nearest deep-water port. However, transportation emissions with trucking to the nearest sequestration hub are less than 4% of captured CO_2 for all UK EfW facilities. CO_2 emissions for rail and ship transport (Figures 15 and 16, respectively) lie between pipelines and trucks, but the relative merit order is site-specific because the transport distance can be quite different for the two modes depending on geographical features between the EfW facility and the nearest CO_2 sequestration hub.

Figure 12: Cumulative UK EfW CO_2 emissions available versus CO_2 transport emissions ($kgCO_2$ emitted per tCO_2 transported) for each mode



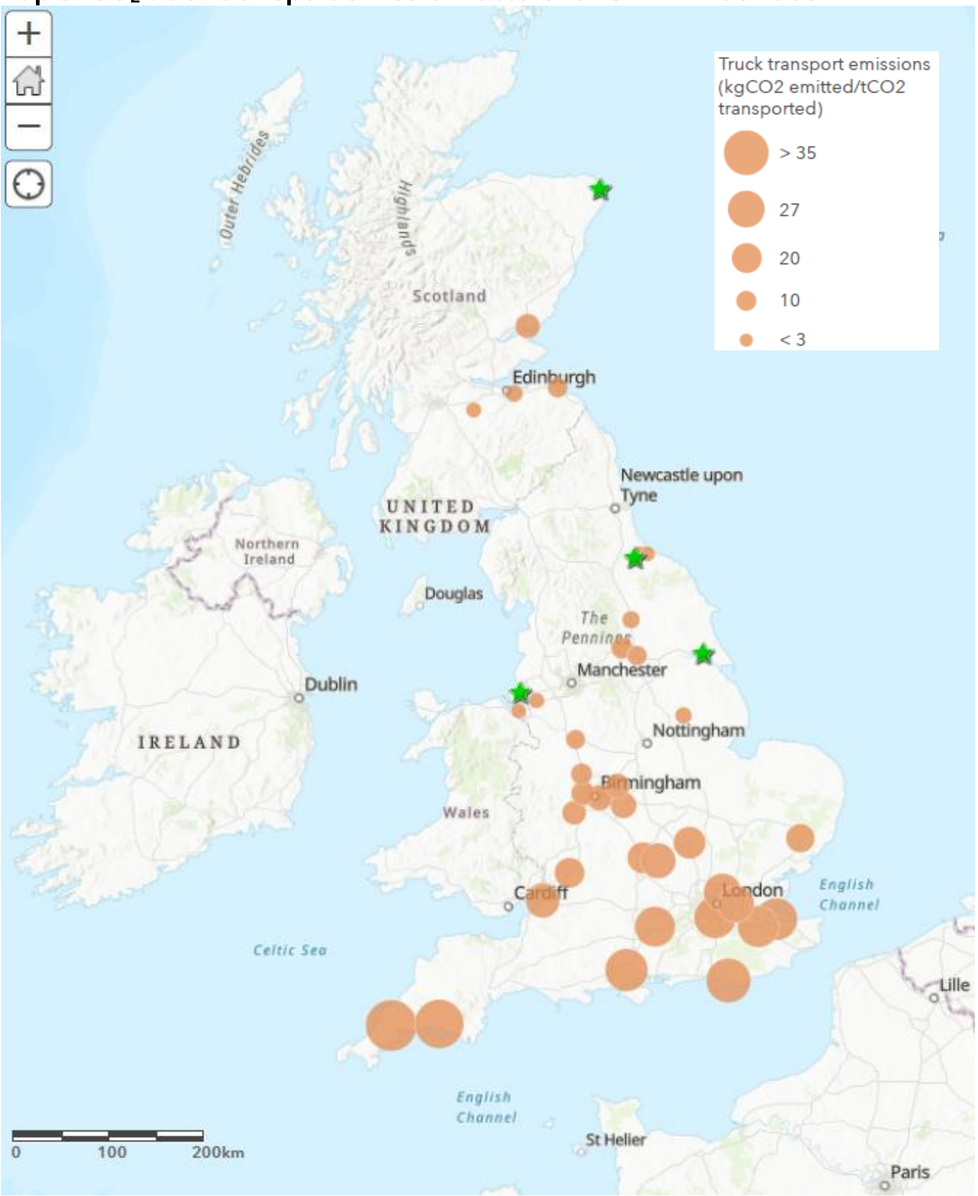
Note: Cumulative CO_2 emissions ($MtCO_2$/year) based on facility licenced capacity and three emission factors: average (0.94 tCO_2 per tonne waste, solid dark blue line), maximum (1.18 tCO_2 per tonne waste, dashed purple line), and minimum (0.7 tCO_2 per tonne waste, dashed light blue line). a, truck. b, rail. c, pipeline. d, ship with truck transport to port. e, ship with pipeline transport to port.

Figure 13: Map of CO_2 pipeline transport emission factors for UK EfW facilities



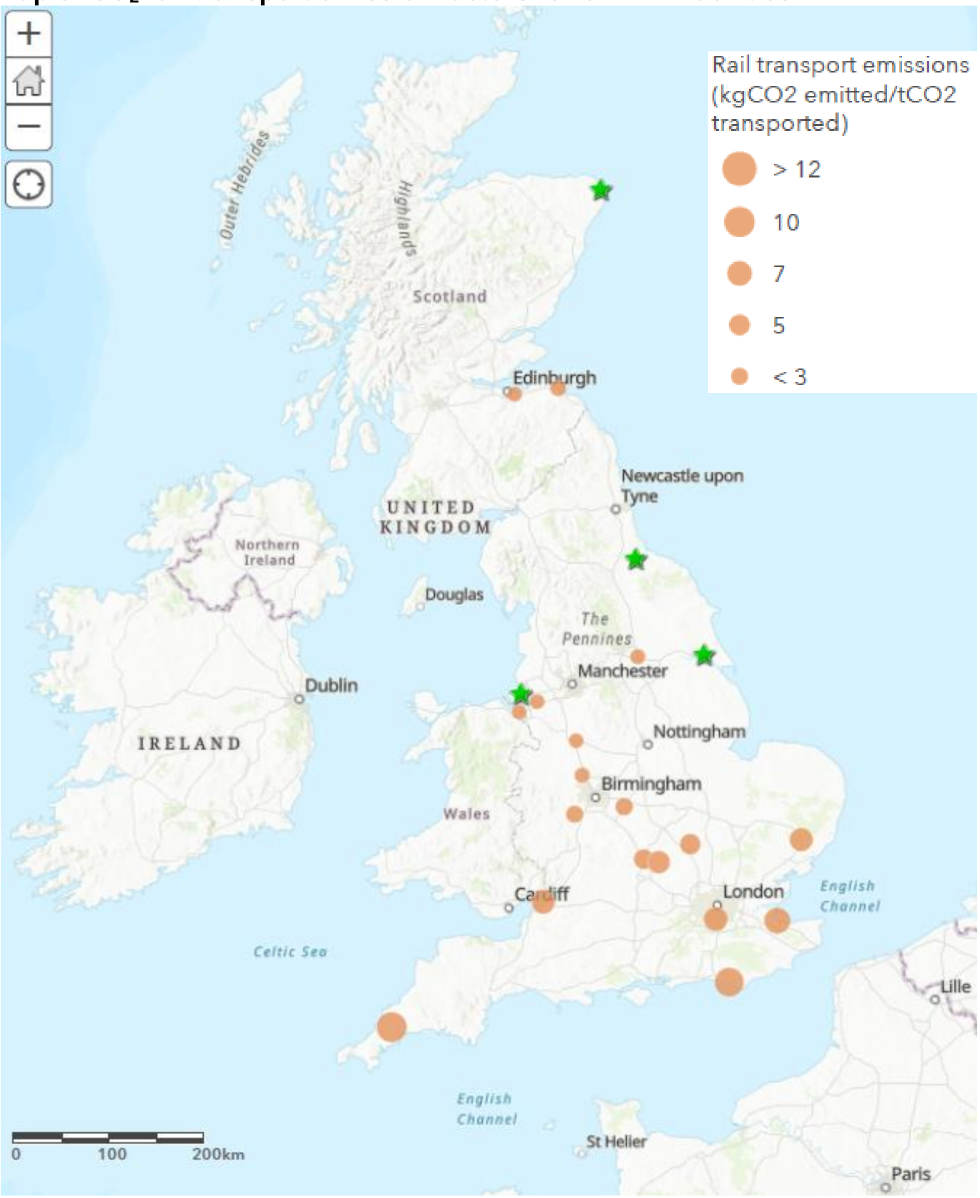
Note: Location markers for UK EfW facilities (brown circles) scaled by emissions to transport CO_2 by pipeline ($kgCO_2$ emitted/tCO_2 transported) to nearest CO_2 sequestration hub (green stars).

Figure 14: Map of CO_2 truck transport emission factors for UK EfW facilities



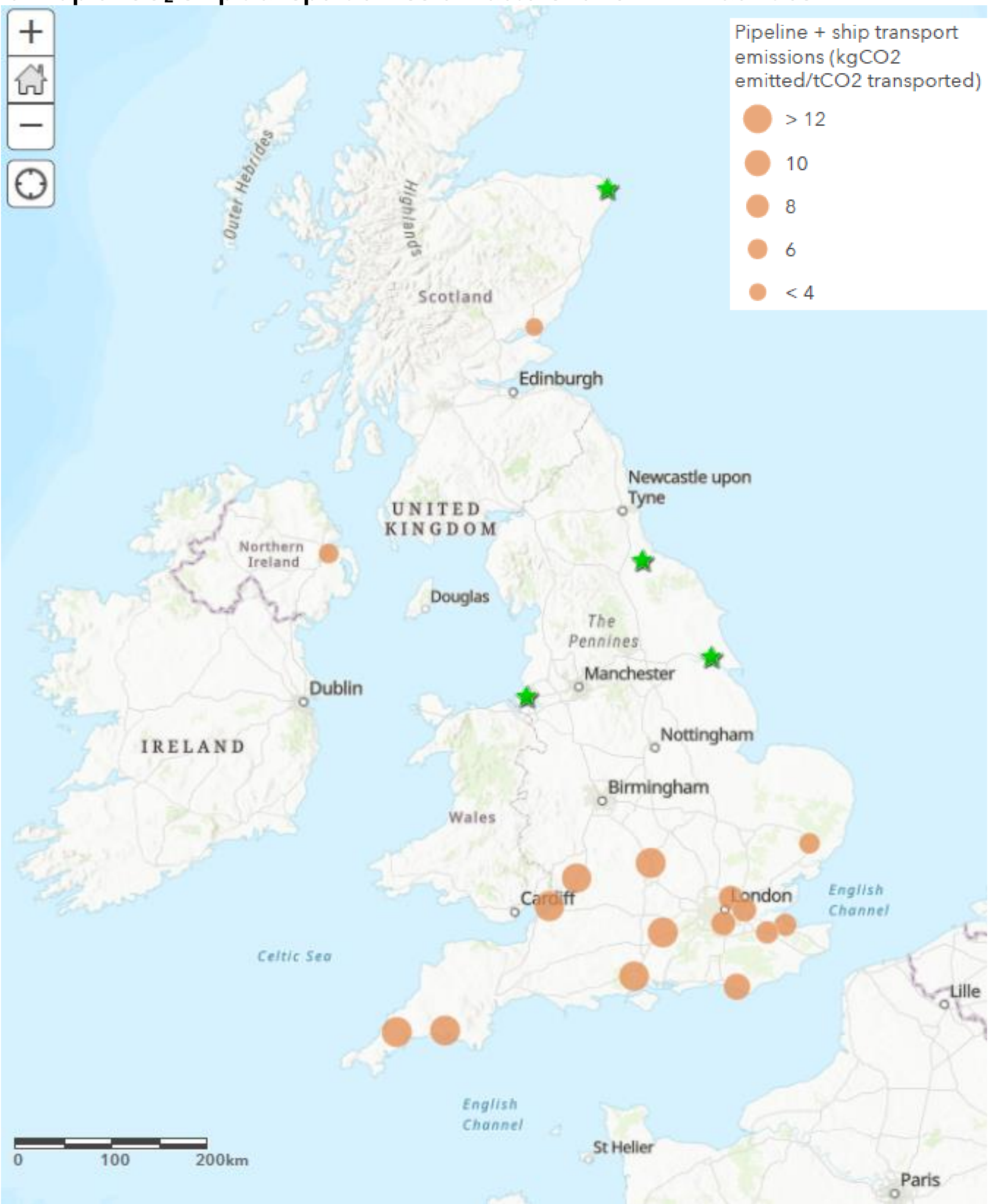
Note: Location markers for UK EfW facilities (brown circles) scaled by emissions to transport CO_2 by truck ($kgCO_2$ emitted/tCO_2 transported) to nearest CO_2 sequestration hub (green stars).

Figure 15: Map of CO_2 rail transport emission factors for UK EfW facilities



Note: Location markers for UK EfW facilities (brown circles) scaled by emissions to transport CO_2 by rail (kgCO_2 emitted/tCO_2 transported) to nearest CO_2 sequestration hub (green stars).

Figure 16: Map of CO_2 ship transport emission factors for UK EfW facilities



Note: Location markers for UK EfW facilities (brown circles) scaled by emissions to transport CO_2 by pipeline to the nearest deep-water port and ship (kgCO_2 emitted/tCO_2 transported) to nearest CO_2 sequestration hub (green stars).

3.5. Study limitations and other considerations for CO_2 transport

While pipeline transportation of CO_2 provides the lowest cost and lowest CO_2 emissions for EfW facilities in England, Scotland, and Wales, other considerations may limit the opportunity for EfW facilities to utilise pipeline transport. Constructing new long-distance pipelines requires significant time to acquire the necessary regulatory approvals and land agreements and the timeline required for planning and construction may not be consistent with CCS implementation plans. Furthermore, addressing community concerns along proposed rights-of-way could be challenging and delay construction.[41]

Pipelines also require a significant commitment of upfront capital to construct; therefore, certainty in government policy related to CCS and CO_2 emissions is important to mitigate risk and encourage investment

[41] Gough, C., & Mander, S. (2014). Public perceptions of CO_2 transportation in pipelines. *Energy Policy*, *70*, 106-114.

in these long-lived assets. Construction of long-distance CO_2 pipelines would need to be part of a larger strategy for CO_2 transportation (e.g., national) as the scope of these projects is beyond the means of any individual emitter.

Although pipelines were considered for all EfW facilities in this study, they may not be feasible at all locations due to existing development and infrastructure in the surrounding area. Determining feasibility would be particularly important for 24% of EfW facilities which do not appear to have reasonable access to rail or ship transportation. Pipeline transport distances in this study were based on rights-of-way following existing transportation corridors, but this may not be possible in practice and alternative routes may need to be chosen. Nonetheless, there are significant benefits for UK society in reduced cost and emissions for CO_2 transport that would support development of long-distance CO_2 pipeline infrastructure.

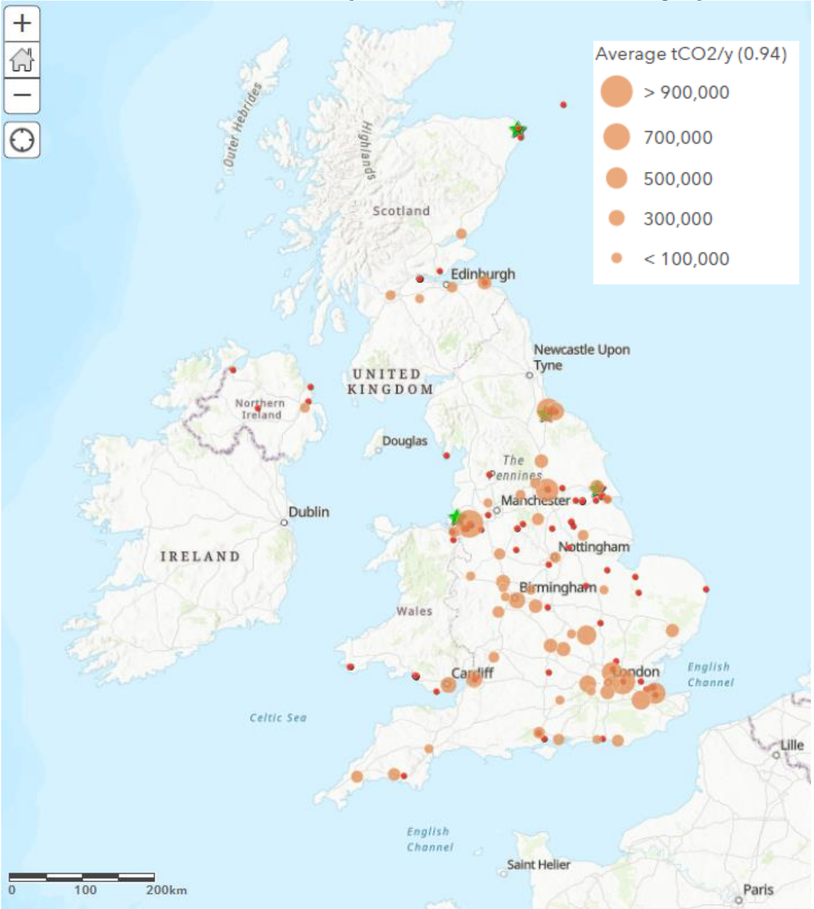
Rail and ship transport are the second-best options for CO_2 transport with site-specific characteristics determining which option is preferable in terms of cost and emissions. Rail and ship transport could offer benefits for project proponents by utilising existing infrastructure to reduce the timeline and risks associated with approval and construction of CO_2 transportation infrastructure. It is economically favourable for EfW facilities located in southern England near deep-water ports to utilise ship transport; however, many facilities are located inland away from ports. Rail is more economical than ship transport for facilities which are located within 100km of a central CO_2 sequestration hub. This study assumed available capacity at existing ports and on existing rail lines, but this may be a limiting factor for specific sites in practice. Site-specific feasibility would need to consider capacity of existing rail and port facilities. Furthermore, alternative combinations of transport options may be preferred based on site-specific circumstances (e.g., pipeline to a rail terminal or rail to a deep-water port).

The analysis of both pipeline and ship transport options for UK EfW facilities highlights the importance of creating central hubs to achieve economies of scale for key infrastructure to reduce costs associated with CO_2 transportation. This study focuses on UK EfW facilities, but CO_2 transportation infrastructure would need to be shared with emission sources in other industries (Figure 17) to achieve the production scale associated with cost forecasts in this study associated with either the “high-capacity” or “low-capacity” scenarios for pipeline and ship transport (25 and 2.5 $MtCO_2$/year respectively).

Note that this study assumed a cut-off of 100 $ktCO_2$/y for minimum facility size for CCS to be feasible, but it may be economic in practice to install CCS at smaller facilities if they are located near large-scale CO_2 transportation and/or sequestration infrastructure (Figure 17). However, this is not expected to materially affect the results of this overall analysis as the facilities excluded based on capacity represent approximately 2% of the overall sector’s CO_2 emissions. Similarly, facilities which were excluded in this study based on space constraints may be viable for CCS using future processes with footprints smaller than conventional amine-based post-combustion CO_2 capture, albeit likely at higher abatement costs.

It is also imperative to highlight that there are 17 new EfW plants under construction in the UK (plus one replacement) with a licenced capacity of 5.7 $MtCO_2$/y which were not included in this study but represent further opportunity for CO_2 capture from the sector. Moreover, this work only considered transportation to the four CO_2 sequestration hubs currently being developed under the UK government’s initial CCS cluster sequencing; however, other CCS hubs may be developed in the future that would reduce cost/emissions for CO_2 transportation from certain UK EfW facilities. This study assumed capacity would be available for CO_2 delivery to the CO_2 sequestration hub nearest each EfW facility, but constraints on sequestration infrastructure capacity would need to be considered in the planning for any specific EfW facility.

Figure 17: Map of UK EfW facilities, CO_2 sequestration hubs, and large point source emitters



Note: Location of all UK EfW facilities (brown circles), excluding Shetland Islands, relative to CO_2 sequestration hubs (green stars) and UK point sources of CO_2 emissions greater than 250 $ktCO_2/y$ in 2021 (red dots). Size of EfW facility symbols based on CO_2 emissions (tCO_2/y) using permitted waste capacity and 0.94 tCO_2 per tonne of waste. Point source emission data from UK NAEI (2023)[42].

4. Concluding remarks

This analysis makes evident that the potential to generate negative emissions from the UK EfW sector is substantial. Under the most conservative scenario in this study, which assumes a low emissions intensity factor of 0.7 tCO_2 emitted per tonne of waste combusted, and only considering facilities where there is high certainty of available on-site space for CCS retrofit, we estimate that around 5 Mtpa of negative emissions can be captured from the entire UK fleet. If a higher emissions intensity factor of 1.18 tCO_2/t is assumed, this estimate increases up to 8 Mtpa; that is while excluding facilities where further analysis on space availability is needed, which may increase this estimate even further.

For perspective, this range (5-8 Mtpa, with a median average of 6.3 Mtpa) is on par with the UK's target of 5-6 Mtpa of deployed engineered greenhouse gas removals (GGRs) by 2030 and translates to 21-34% of the UK's target of 23 Mtpa by 2035, and 8-13% of the 60 Mtpa in GGR capacity by 2050. Meeting those targets will be challenging, especially the near-term ones, as they would require significant scale-up of carbon removal projects, at a time when a pipeline of GGR projects with the necessary scale to meet those targets is still lacking. Moreover, while other nascent GGR solutions may need to undergo long testing and investment stages, EfW+CCS relies on mature, already-proven technology and can be deployed relatively quickly, which speaks to the strategic role that EfW+CCS can play in meeting those targets.

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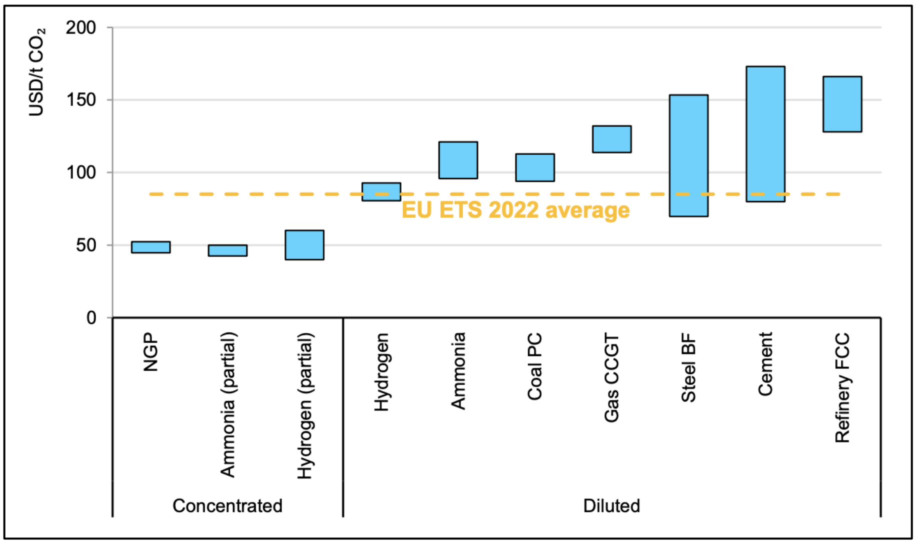
[42] UK NAEI (2023). Emissions from NAEI large point sources. UK National Atmospheric Emissions Inventory. Available: https://naei.beis.gov.uk/data/map-large-source

From an economic standpoint, previous analysis shows that costs of CCS retrofit in EfW can be around £150/t which is comparable to its costs in other industrial sectors (Figure 18),[43] yet it is with the potential to generate negative emissions that the business case for EfW+CCS becomes clear. Negative emissions have become a sought-after asset due to their widely regarded role in climate mitigation and their increasing importance in meeting national and corporate net-zero goals. At the project level, sale of negative emission credits has been at the core of the business case of some existing and in-planning GGR projects such as DACCS where, coupled with government subsidy, it can be the only other revenue stream to support their deployment. In contrast, alternative GGR solutions such as BECCS can rely on other revenue streams such as the sale of energy commodities, while secondary revenue from negative emissions sales is a welcome by-product.

Figure 18: Levelized cost of CCS across different sectors



Source: Figure extracted from International Energy Agency (2023), CCUS Policies and Business Models: Building a Commercial Market. Notes: Notes: BF = blast furnace; CCGT = combined cycle gas turbine; FCC = fluid catalytic cracker; NGP = natural gas processing; PC = pulverised combustion.

To that extent, the business case of BECCS perhaps represents the closest proxy to that of EfW+CCS, where multiple revenue streams exist. However, as noted earlier, if not properly managed BECCS may lead to increased pressure on land use and, depending on the incentives in place to support it, the practice may suffer from public perception issues.[44] Similarly, the role of DACCS as a legitimate climate mitigation solution has been criticized due to its high energy intensity and significantly higher costs than CCS (whether deployed in EfW or other sectors). Compared with both solutions, EfW+CCS alleviates the need for additional land space while also addressing an existing problem (landfilling), and instead of requiring high amounts of energy to operate, it (cleanly) produces it.

In the UK context specifically, at a time when the UK Government has committed to adopting CCS as a main pathway for national decarbonisation – evident by its now-established CCS business models including the Waste ICC contracts framework – this study makes clear that the EfW sector may well be the low-hanging fruit for CCS deployment and the well-needed generation of negative emissions nationally.

[43] As noted earlier, cost of capture of around £150/tCO_2 estimated in a techno-economic analysis study conducted by the authorship team as part of the NEWEST CCUS project, funded by the ERA-NET Accelerating CCS Technologies (ACT2) initiative.

[44] Bellamy, R., Lezaun, J., & Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nature communications*, *10*(1), 743.