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Breeding for reduced methane emissions in livestock

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1 Executive summary

The agriculture policies outlined in the Update to the Climate Change Plan (CCP) provide a route map for agricultural transformation, to reduce greenhouse gas emissions. They take a co-development approach and work with stakeholders and farmer-led groups to secure increased uptake of low-emission farming measures through new schemes and approaches.

This project examined the potential reductions in livestock methane emissions through breeding, and the policy levers that could motivate these changes.

We began by exploring the technologies that detect and measure methane, manage data and are used in the breeding process. This included considering the availability of these technologies in Scotland in 2030 and 2045, with practical considerations for a Scottish context, and identifying the breeding traits that can lead to lower methane emissions.

We then identified the relevant policy levers and behaviour changes and considered what Government, the post-farm market, pre-farm gate actors and farmers can do differently to encourage methane reductions through breeding.

1.1 Key findings

- By 2045, **breeding could reduce methane emissions from the digestive process in livestock, known as enteric methane, by up to 9.5%** (382.2 kt CO_2 equivalent). This is under the "Policy changes" scenario, where legislation will require farmers to introduce methane reducing breeding techniques to their herds (with uptake rates of 100% in dairy, 80% in beef, and 60% in sheep).

  - This includes a 6.8% reduction in emissions from beef, 6% from dairy and 17.5% from sheep.
  - This reduction is achieved by selecting traits for methane efficiency (methane production, intensity and yield), feed efficiency, offspring carcass weight, milk yield and milk fat and protein when choosing breeding stock.
  - Our research highlighted selective breeding for feed efficiency as a promising option. This is because, despite its lower methane reduction potential, it builds on a practice that is already well understood by farmers.
- To achieve emission reductions, **actions and behaviour changes will be required** of Government policymakers, pre- and post-farm gate actors and farmers. We found key barriers were lack of knowledge and perceived cost.
- **Scotland has a well-developed research base** around breeding livestock for reduced emissions, placing it in good stead to develop further work in this area. Funding could be targeted towards building on this research, with more data points to support innovation and enhance the robustness of results. Further research could include the potential for a specific methane reduction target to increase clarity and focus action. Funding would be useful if targeted to **better communication** of the research findings to inform farm advisers, pre- and post-farm actors and supporting farmer peer-to-peer learning. Collaboration between stakeholder groups will achieve greater progress.
- Relevant **technologies** include methods to detect and measure enteric methane in animals, data management, reproductive technologies and genomics. Those that could be mainstream in Scotland by 2030 include a national breeding programme, sexed semen and the breeding potential of an animal for a specific trait, known as estimated breeding values. The interaction between technologies is key to success. For instance, the wide use of data management tools will depend on the wide use of genomics to collect data.
- We found very few instances of methane detection methods being used on farm in the UK. We therefore believe it is unlikely these will be used beyond research and innovators by 2045. As such, we recommend encouraging the use of proxies such as mid-infrared (MIR) spectra in milk to determine methane emissions.
- Many reproductive technologies are already in use, particularly in the dairy industry, so we estimate these to be mainstream across the cattle sector by 2045. We estimate lower uptake in the sheep sector due to artificial insemination being a complex procedure. However, as sheep start breeding at an early age and often have multiple births per animal, there is greater potential for emission reductions if low-emitting traits are introduced into the herd such as through a ram.

On this basis, we think there is **a strong foundation for breeding for reduced methane emissions** to contribute to Scottish Government’s methane and climate commitments and to support Scottish livestock farmers’ future resilience.

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2 Glossary / Abbreviations

AI	Artificial insemination
DNA	Deoxyribonucleic acid is an organic chemical that contains genetic information and instructions for protein synthesis
EBVs	Estimated breeding values
DMI	Dry Matter Intake
FAO	Food and Agriculture Organisation
Gene	A genetic sequence that contains information on specific traits.
Genetic modification	Any process by which genes are changed or deleted in order to adjust a certain characteristic of an organism. It is the manipulation of traits at the cellular level.
Genetic selection	Selecting for specific genes that carry desirable traits.
Genetics	The study of how genes are passed down from one generation to the next.
GHG	Greenhouse gas
CO_2	Carbon dioxide
ICBF	Irish Cattle Breeding Federation
Methane	A powerful greenhouse gas, a chemical compound with the chemical formula CH_4.
Microbes	Microscopic organisms
Microbiome	A collection of microbes (e.g. bacteria) that occur in the rumen.
NERC	Natural Environment Research Council
PAC	Portable Accumulation Chambers
Precision breeding	Amends sections of DNA by adding or moving genetic material
Proxy	An object/thing that is being used in the place of something else
REA	Rapid evidence assessment
Rumen	The specialised stomach of a ruminant (e.g. cow) that digests feed by microbial fermentation.
Ruminant	Animals, including cattle and sheep, that have more than one stomach and have the ability to bring food up from their stomach and chew it again.
Selective breeding	Choosing animals that carry desirable traits to be bred so that the traits are passed on to their offspring.
Traits	Specific characteristics that are genetically determined.

3 Introduction

Methane is a powerful greenhouse gas (GHG), 28 times more potent than CO_2, produced as a by-product of the ruminant digestive process called enteric fermentation. During enteric fermentation, microbes digest feed in a specialised stomach, known as the rumen, subsequently releasing enteric methane. In 2021, enteric fermentation from ruminant livestock, such as cattle and sheep, was responsible for 48% of GHG emissions from agriculture in Scotland.

The UK signed the Paris Agreement, committing to limit global warming to 1.5°C and is a signatory of the Global Methane Pledge, aiming to reduce global methane emissions by at least 30% from 2020 levels by 2030. The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 outlines a net zero target for Scotland by 2045, with a 75% reduction in emissions by 2030. The strategy to meet these targets is laid out in Scotland's Climate Change Plan (CCP) 2018-2032 and Climate Change Plan Update (CCPU).

One potential way to reduce emissions from the livestock sector is to select breeding traits in livestock that lead to lower methane emissions.

Traditional breeding programmes select cows or ewes producing offspring with desirable characteristics to either produce meat, milk or fibre, or to continue in the breeding herd. This method relies on waiting for the offspring to mature before the desired traits can be identified. The use of genetic technologies allows desired traits to be chosen at the point of breeding, giving a more assured outcome at an earlier stage.

Genetics are already used to facilitate precision breeding to improve livestock performance. As genetic changes are permanent and cumulative, it is an attractive option for targeting and reducing GHG emissions from ruminants (González-Recio et al., 2020; Manzanilla-Pech et al., 2021; Rowe et al., 2021).

Scottish research is at the forefront in breeding livestock for reduced methane. A recent project by the Roslin Institute highlighted the strong relationship between the rumen microbiome and methane emissions; SRUC has several relevant research studies (published and ongoing), with research facilities such as GreenCow measuring GHG emissions, and Moredun has researched the impact of livestock health and welfare on methane emissions. In 2023, Defra awarded £2.9 million to the sheep sector to launch 'Breed for Ch4nge' which aims to measure methane from 13,500 sheep to improve the efficiency of the UK flock; some of the research is taking place on Scottish farms.

The issue is of interest internationally. New Zealand research has shown that breeding for reduced emissions in sheep does not impact productivity and health; Canadian traders are marketing dairy semen with methane efficiency traits, and beef farmers in Ireland are being paid to take part in genomic programmes.

Please note, reducing methane through dietary amendments (such as feed additives) is out of scope for this project.

3.1 Project aims

This research project has two key aims:

1. **To understand the methane emission reductions that could be achieved in Scotland through breeding**. We do this by identifying technologies that detect and measure methane, manage data and are involved in the breeding process. We look at the likely availability of these technologies in Scotland in 2030 and 2045, with practical considerations. Finally, we identify the breeding traits that can lead to lower methane emissions and quantify these.
2. **To identify what is needed to support this through policy levers and behaviour change**. Using the findings of our literature review and stakeholder consultation, we suggest behaviour changes and discuss their impacts.

4 Identifying the evidence

To better understand where and how methane emissions could be reduced for project aim 1, we performed a Rapid Evidence Assessment (REA) and a series of stakeholder interviews[1] (now on referred to as our review) to understand:

- The technologies involved in reduced emission breeding;
- The important traits to select for reduced emissions;
- Emission reduction values;
- The benefits and challenges of breeding for reduced emissions;

The review also sought evidence on what is needed to support further uptake of these technologies in Scotland, for project aim 2.

4.1 The technologies involved in breeding for reduced emissions

We grouped the technologies used to identify livestock with low methane emissions into four categories: detection methods, data management, reproductive technologies and animal genomics.

We found little information regarding the timeline of availability for the technologies on farms in Scotland. In the stakeholder interviews, many were not aware of specific technologies being used unless they were directly involved in research. Our research did find international evidence, for example, portable accumulation chambers (PAC) in New Zealand support The Cool Sheep™ Programme. Due to this limited data on timing, we categorised the availability of the technology in Scotland in 2030 and 2045 under the following headings:

Experimental (E): used in research only, with no use on Scottish farms.
Innovative (I): used in trials on Scottish farms by a few innovators.
Mainstream (M): considered mainstream and being used on Scottish farms.

[1] See methodology in Appendix A, section 9.1

Future possibility (FP): unlikely the technology will be used by 2030 or 2045, however not ruling out its availability in the future.
Not applicable (NA): not relevant to the sector.

The rate of technology uptake will differ between and within sectors. For instance, dairy cattle are milked multiple times a day, providing an opportunity to closely assess individuals interacting with the technology. For the same assessment in the beef and sheep sectors, the grazing nature of the system may require cultural and habitual change for widespread uptake (Jones and Haresign, 2020). Farmers also have different interests, business structures, cash flow etc which impacts their decisions on changing farm practices.

Cost was excluded from our review due to the complexities in estimation. The cost of a technology is likely to depend on the individual farm situation, for example, the number of livestock or proximity to infrastructure or manufacturers. Technologies requiring installation may vary depending on whether adjustments are required to an existing building.

We understand the technologies presented below have the potential to be used in Scotland. The full list of technologies discovered in our research can be found in Appendix A, section 9.1.

4.1.1. Detection methods

Detection methods are used to detect and measure enteric methane to identify which animals emit less. Examples include a **respiration chamber** which measures the difference in methane emissions with and without the animal, while **spot sampling** uses head chamber systems or hand-held lasers to take short-term measurements from the animal's breath (Tedeschi et al., 2022). Further examples can be seen in Table 1.

We found very few instances of detection methods being used in UK research, but we estimate that some will be available in 2030 and more by 2045 (see Table 1). However, as detection methods are primarily a research tool, it is unlikely they will be used beyond innovators by 2045. Practical constraints such as large technological components and measuring a few animals at a time make it challenging to introduce respiration chambers (which are considered the 'gold standard' of measurements) on a large scale (Manzanilla-Pech et al., 2021; Rowe et al., 2020). As such, we recommend encouraging use of proxies such as mid-infrared (MIR) spectra in milk to determine methane emissions.

Portable Accumulation Chambers (PACs) have been launched recently by scientists at Scotland's Rural College (SRUC) for use across the UK. The two units (of 12 trailers) are currently only being used for research purposes. Each trailer holds 12 chambers and is capable of measuring between 60 – 80 sheep per day providing breeding values for methane emissions for representative samples of sheep within a breeding programme (Duthie et al., 2024)

New Zealand currently incorporates the use of PACs in breeding programmes through The Cool Sheep™ Programme, where breeders use PACs to measure and select for low-emitting rams available for breeding. Research trials are underway in countries such as Australia, Norway and Uruguay and now the UK. This technology provides a promising option for Scotland as it is transportable between farms and has a short measurement period which limits stress in livestock. However, current research trials on UK sheep systems need to be completed before PACs can be used widely (Duthie et al., 2024).

4.1.2. Data management

Data management technologies are essential to store, share and analyse data, while also tracking individuals and breeding lines with desired traits to improve target outcomes (including emissions reductions).

The dairy sector is advanced in this area compared to beef and sheep sectors, with established tools for monitoring and measuring production characteristics. Stakeholders discussed the possibility to enhance or repackage these tools and platforms, such as ScotEID, to incorporate methane traits. Using a tool that is familiar for farmers might reduce resistance for adoption.

Case study: New Zealand

N-Prove is a free website tool for New Zealand farmers to find the best rams for breeding. Using a series of buttons and slider scales, farmers can customise what traits they are looking for in a ram. NProve then generates a list of breeders with rams that best fit. Farmers can select terminal or maternal traits, as well as breeders based on location, breed and exclude certain flocks from results. Methane production is an option to select from the maternal traits. The tool is free to use and registration is not required. The tools anonymity means farmers can gather their options for the best breeder for their farm. NProve sources data from a central database and genetic evaluation service (SIL database) that holds information for more than 600 flocks, making it one of the largest genetic evaluations of sheep in the world. This tool could be used in a similar fashion for other species in other geographies as long as an appropriate database was available or was developed to source information.

Data technologies rely on wider infrastructure, such as website portals or cross-country collaboration, making it challenging to estimate the availability for 2030 and 2045. However, there is high potential. Stakeholders discussed that a risk for these technologies is the lack of interest and uptake from farmers, so it is important to inform and engage the industry regarding their benefits.

These technologies offer benefits for farmers by improving the understanding of the genetic qualities of their livestock and having a head-start on understanding the genetics and traits being brought into the herd. See Table 2 for the relevant data management technologies.

Table 1. Examples of the detection methods involved in breeding livestock for reduced methane emissions. Please see Appendix A, section 9.1 for the full list of the technologies found in our review.

	Description	Livestock Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations in Scotland
						Beef	Dairy	Sheep	
Automated head chamber system (e.g. GreenFeed)	A head chamber unit that can be positioned in housing or pasture. Feed is used to attract livestock to the unit (van Breukelen, 2023; Zaman et al., 2021).	All	Methane and CO_2 concentrations	Non-invasive. Can be set up in grazing fields or in housing. Portable	High purchase and running costs. A spot measurement, not a true reflection of emissions per day. Feed to attract livestock increases costs.	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	No evidence was found for use in the UK. It could be a feasible option for Scotland due to the benefits of transportability and ability to measure grazing livestock.
Mid-Infrared (MIR) data	MIR spectroscopy is used to predict the fat and protein content of milk. As methane is linked to milk composition, the latter can be used as a proxy to predict methane emissions (Dehareng et al., 2012; Semex, 2023).	Dairy	Milk components such as lactose, protein and fat	MIR technology is already used routinely in milk recording. Therefore providing an existing infrastructure to integrate methane reporting to.	Because it is a proxy, validation of results (for example with a respiration chamber) is required (Denninger et al., 2020).	NA	2030: I 2045: I	NA	No evidence found of MIR in the UK to estimate methane, but European examples were found. The data could become available through existing milk recording schemes, so it could be introduced by innovators by 2030. If the need for verifying results via detection methods is removed, this could be mainstream by 2045.
Portable accumulation chambers (PAC)	A portable respiration chamber which takes measurements over a short period of time (e.g. 1 hour) (Cummins et al., 2022).	All	Methane and CO_2 concentrations	Quick measurement period reduces animal stress (Cummins et al., 2022). Transportable (NZHerald, 2023).	Feeding and management protocols must be followed prior to measurements (Duthie et al., 2024). Not suitable for long-term measurements (Cummins et al., 2022).	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	A promising option for Scotland as it is transportable between farms. SRUC recently acquired a PAC for sheep. However, current research needs to be completed before they can be used widely (Duthie et al., 2024).
Handheld lasers	A handheld device originally developed to detect gas leaks can measure concentrations of methane in livestock breath (Sorg, 2021).	All	Methane concentration	Non-invasive and portable. Can take measurements from grazing livestock. Can take measurements from several animals in one day. Results can be sent to a smart phone (Sorg, 2021).	Has a lower accuracy, measurements are highly affected by environmental conditions (de Haas et al., 2021; Sorg, 2021).	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	No evidence found for use in UK research. However, the benefit of taking measurements from several animals in the same day may make it an attractive option for Scotland. Its widespread use may depend on supporting infrastructure such as reporting systems.

Table 2. Examples of data management tools involved in the process of breeding livestock for reduced methane emissions. Please see Appendix A, section 9.1 for the full list of the technologies found in our review.

	Description	Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations in Scotland
						Beef	Dairy	Sheep	
nProve	A free tool for New Zealand farmers to use to choose rams for breeding. They can choose the terminal or maternal traits that fit their breeding goals. When choosing maternal traits, methane production is an option.	Sheep	Reproduction, lamb growth, size, meat, wool, health indices, methane production.	User friendly. Farmers can choose rams based on location, breed and exclude certain flocks from results.		NA	NA	2030: FP 2045: I	Success requires genetic evaluation and measuring methane (via PAC) to be common practice. Existing tools such as ScotEID (records births, deaths, and movements), and RamCompare (presents performance recorded ram data), could be repackaged to incorporate methane production.
National breeding programme	A programme which plans and identifies breeding objectives, traits and information on selection criteria	All	Methane emissions	UK wide	To be successful at a national scale, significant data, cooperation and initial funding is required.	2030: M 2045: M	2030: M 2045: M	2030: M 2045: M	In 2023, The National Sheep Association began a 3-year initiative to measure methane from 13,500 sheep to incorporate production traits into breeding programmes. With progress like this, it is possible that national breeding programmes will be mainstream by 2030.
Multi-country database	An international database that contains data from many livestock (Manzanilla-Pech et al., 2021).	All	performance/ production (trait-related) records	A larger dataset improves robustness (Manzanilla-Pech et al., 2021).	Combining data from different countries can be challenging due to differences in reporting, recording, technology, favoured breeds and management style (Van Staaveren e al., 2023). Sharing genetic information between countries requires compliance with the Nagoya Protocol.	2030: FP 2045: FP	2030: E 2045: I	2030: FP 2045: FP	Due to data sharing challenges, it is unlikely this will be available by 2045 in this context. There may be progress in the dairy sector due to the use of methane indexes, e.g. in Canada and the international scope of many dairy processors.
Bull catalogues (e.g. Genus Bull search)	This index allows farmers to see the scores of certain traits in bulls.	Dairy, beef	One of these traits is called Feed Advantage which can identify bulls with the greatest feed conversion (ABS, 2023).	Farmers can choose bulls with the desired characteristics to use in breeding.		2030: M 2024: M	2030: M 2024: M	NA	These are already available for farmers to use, so we would estimate them to be mainstream by 2030.

4.1.3. Reproductive technologies

Reproductive technologies are directly used for breeding. With many already in use on Scottish dairy farms, we estimate that it is likely most will be mainstream in the cattle sectors by 2045. We estimate lower progress in the sheep sector reflecting the current low uptake. Stakeholders discussed the reasons for low uptake in the sheep sector are due to the extensive nature of sheep farming in Scotland and less infrastructure for sheep in this area, such as semen collection and storage, the availability of which determines uptake. In addition to this, artificial insemination (AI) in sheep requires a vet to perform a surgical procedure (in cattle it can be done by a qualified farmer), adding a practical and financial hurdle.

Table 3. Examples of reproductive technologies involved in the process of breeding livestock for reduced methane emissions. Please see Appendix A, section 9.1 for the full list of the technologies found in our review.

	Description	Sector	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M),Future possibility (FP), Not applicable (NA)			Practical considerations in Scotland
					Beef	Dairy	Sheep	
Artificial insemination (AI)	A technique to inseminate females, using fresh or frozen semen.	All	High success rate for cattle. No requirement for a bull to be on the farm. Better guarantee of uniform calving.	AI in sheep is often done by laparoscopic artificial insemination which is a surgical procedure done by a vet. Due to the scale and extensive nature of sheep farming, this brings practical challenges. Relies on sufficient infrastructure to collect and store semen (Stakeholder comment, 2023).	2030: M 2045: M	2030: M 2045: M	2030: I 2045: I	AI is common practice in the dairy sector, with some use in the beef sector. It's likely this will be mainstream by 2030 for cattle. Due to the practical challenges in sheep, it may still only apply to innovators.
Sexed semen	A method which allows control over the sex of the offspring by separating sperm cells based on their X or Y chromosome content. By focusing on females for example, there is the potential to reduce methane emissions by reducing the number of unwanted males (Duthie et al., 2024).	All	Increasing selection of females in the dairy sector improves productivity.	Success relies on the uptake of AI.	2030: M 2045: M	2030: M 2045: M	2030: I 2045: I	This is widely done in the dairy sector. Use in the beef sector is currently lower, however by 2030 there is the potential for this to be mainstream. Progress is determined by the uptake of AI in the sector. Due to the practical challenges associated with AI, it will likely remain an innovative practice in the sheep sector.
Conventional breeding	The use of bull/ram to cow/ewe breeding. Selecting cows or ewes producing offspring with desirable characteristics to remain in the breeding herd.	All	Minimal technical input. Familiar practice for farmers.	Little control over selecting desirable traits. Time intensive as it requires offspring maturity before seeing if they have the desired traits.	2030: M 2045: M	2030: M 2045: M	2030: M 2045: M	Already common practice for general breeding, so breeding for methane reduction could be mainstream by 2030.

4.1.4. Animal Genomics

Genomics is the study of the genome, a complete set of an organism's DNA[2]. Genomics provides the opportunity to better understand how well an animal will perform based on its DNA profile. DNA and management both determine performance qualities, such as milk yield. Precision breeding (which is not genetic modification) amends sections of DNA by adding or moving genetic material. This has been used in the cropping sector to improve yields and/or disease resistance. In the livestock sector, research focusses on increased resilience to bovine tuberculosis and mastitis. In 2023, England introduced The Precision Breeding Act, outlining classifications for using precision breeding on crops and livestock, including how the products from them should be regulated, "Neither the Scottish nor Welsh Parliaments have granted legislative consent to the Bill.".

[2] DNA contains the information required to create the entire organism, a unit of DNA containing specific information to create a protein or set of proteins is referred to as a gene. It is these proteins which make up the body and control chemical reactions between cells. the study of genes is referred to as genetics.

Table 4. Examples of animal genomic technologies involved in the process of breeding livestock for reduced methane emissions. Please see Appendix A, section 9.1 for the full list of the technologies found in our review.

	Description	**Sector**	**Data collected**	**Benefits**	**Risks**	**Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)**			**Practical considerations in Scotland**
						Beef	**Dairy**	**Sheep**	
Microbiome -driven breeding	Emphasis is on selecting livestock with a rumen microbiome composition which is more efficient at fermenting feed so producing less methane.	All	Rumen fluid samples - sequencing of microbial DNA.	Potential method for improving animal health and reducing environmental impact.	This is a relatively new field and much is unknown about how the gut microbiome develops and is maintained over time. It is unclear how much influence the animal may have over those processes.	2030: E 2045: E	2030: E 2045: E	2030: E 2045: E	Good early signs but still at research stage.
Genomic breeding values (GEBVs)	Values that are based on information from livestock DNA and measured performance. Can be used with EBVs to improve accuracy of breeding programmes. (Meat Promotion Wales. 2013).	All	DNA and performance records.	Can be used to identify traits that are difficult to record. Beneficial for traits measured in only one sex. Useful for accurately measuring traits that occur later in life (Scholtens et al., 2020).	Accuracy of the estimate is dependent on the number of animals included in the reference population (Scholtens et al., 2020).	2030: I 2045: M	2030: M 2045: M	2030: I 2045: M	GEBVs are currently available for a number of carcass traits in Limousin cattle in the UK (Business Wales, 2016) and offered by the genetic company Genus.
Estimated Breeding values (EBVs)	Calculated from the performance data of recorded animals. Environmental factors (e.g. feeding) are filtered out to provide a genetic value for each trait (Stout, D. 2021).	All	Performance records – parentage and traits of interest (e.g. weight traits).	Provides a more objective (data driven approach) towards selection. Genetic selection based on EBVs leads to faster rates of genetic gain and flock improvement (compared to selection based on raw data or basic observation).	Allows comparisons within breeds, not between breeds.	2030: M 2045: M	2030: M 2045: M	2030: M 2045: M	Use as a tool to aid in the selection of healthy and structurally sound animals.

4.2 Traits

Traits are specific characteristics of an individual (physical or behavioural) that are influenced by genes and environmental factors. Understanding the traits that lead to lower methane emissions is key to a successful breeding programme for methane emissions reduction.

It should be noted that the breeding focus, and therefore traits selected, depends on the farmer's goals. For example, breeding for breeding stock would focus on selecting offspring traits, such as calving or lambing ease, while farms producing fat or store stock would focus on product traits, such as increased liveweight gain (Stakeholder comment, 2023). Currently, most traits are associated with productivity, such as increasing milk yield in the dairy sector. Progress in the beef and sheep sectors has been much slower, with fewer examples found of genetics used in breeding programmes.

The traits in Table 5 are used for breeding in global research to reduce methane emissions directly and indirectly. We have categorised these traits into the following groups:

Production – offspring: Traits associated with reproduction.
Production – product: Traits associated with products from the animal.
Functional: Traits that underpin the function of the animal and are not specific to production or emissions improvements.
Climate: Traits directly linked to reducing methane emissions.

Stakeholders and the literature emphasised that selection for methane reduction traits should ensure production traits, such as health, are not compromised (Stakeholder comment, 2023; Llonch et al., 2017). To look into this further, we examined performance and methane efficiency data from SEMEX. For their Holstein bulls with above average methane efficiency scores, we could not identify any clear relationship between this trait and the other traits. However, this is only for one breed of cattle from one company.

Case study: New Zealand

Research in New Zealand genotyped low emitting sheep which identified traits that lead to reduced methane emission. The research found no negative impacts on physiology, productivity and health when selecting for reduced emissions.

Our research highlighted the importance of selecting for feed efficiency. Despite this trait having a lower methane reduction potential than others, it will benefit farmers through more efficient use of feed through better feed conversion (Stakeholder comment, 2023).

Table 6 presents the traits that were selected for further analysis, including quantification and the technologies used to detect or select them. Only a few of the traits found in our review were taken forward because some of the traits did not have robust emission reduction values, so were therefore excluded from our calculations.

Table 5. Traits included in breeding indexes around the world, split by sector and type.

Production - offspring

	Calving ease	Carcass conformation	Carcass weight (kg)	Cow calving interval	Fertility	Longevity (years)[3]	Maternal weaning weight	Offspring carcass conformation	Offspring carcass fat	Offspring carcass weight	Offspring feed intake	Offspring survival	Energy corrected milk	Lambing percentage[4]	Maternal instinct
Beef	x	x	x	x	x	x	x	x	x	x	x	x			
Dairy	x	x	x	x	x	x	x	x	x	x	x	x	x		
Sheep						x						x		x	x

Production - product

	Mature weight	Feed efficiency[5]	Growth rate[6]	Heifer live weight	Body condition score	Heat tolerance	Milk fat + protein	Milk yield	Production efficiency[7]	Residual feed intake	Fleece weight
Beef	x	x	x	x							
Dairy		x			x	x	x	x	x	x	
Sheep	x	x	x		x						x

Functional

	Cow health	Disease resistance	Microbiome
Beef	x	x	x
Dairy	x	x	x
Sheep			

Climate

	Methane efficiency Error! Bookmark not defined., 8	Methane intensity[9]	Methane production
Beef			
Dairy	x	x	x
Sheep		x	x

[3] The productive lifespan of livestock. For beef and dairy – a longer productive lifetime would reduce the number of replacement heifers needed to maintain a constant herd size. For sheep - the longer ewes can produce lambs, production efficiency improves.
[4] The number of lambs born per number of ewes mated, expressed as a percentage.
[5] For beef and dairy - less feed is used for the same output of product and less loss of energy to methane (kg CO_2e/kg product). For sheep - this is CO_2e but as far as can be told it is only methane in this value. Less feed is used for the same output of product and less loss of energy to methane (kg CO_2e/kg product).
[6] The number of kilograms gained by the animal per day, measured in kg/day.
[7] Overall production of the animal (including feed efficiency), supporting the animal to reach its full genetic potential and ensuring it reaches the highest possible level of performance.
[8] ME is expressed as a Relative Breeding Value (RBV) with a mean score of 100 and a standard deviation (how much a point differs from the average), of five. A score below 100 indicates below average and a score above 100 indicates above average. A higher RBV indicates a higher methane reduction potential.
[9] The amount of methane produced per unit of milk or sheepmeat produced (kg CH4/kg milk/sheepmeat).

Table 6. The quantifiable traits in each sector, with the technologies which can be used to detect or select them.

Technologies used to detect or select traits		**Quantifiable traits in each sector**								
		Beef			**Dairy**				**Sheep**	
		Feed efficiency	**Offspring carcass weight**	**Methane production**	**Feed efficiency**	**Milk fat and protein**	**Milk yield**	**Methane intensity**	**Feed efficiency**	**Methane yield**
Detection methods	Respiration chambers			X				X		X
	Sniffers			X				X		X
	SF6 tracer gas			X				X		X
	Automated head chamber system			X				X		X
	Mid-Infrared (MIR) data (proxy)			X		X		X		X
	PAC			X				X		X
	Handheld lasers			X				X		X
	Rumen microbial composition			X				X		X
	Feed efficiency index	X			X				X	
Data management	Selection index theory	X	X	X	X	X	X	X	X	X
	National breeding programmes	X	X	X	X	X	X	X	X	X
	Multi-country database	X	X	X	X	X	X	X	X	X
	Efficient Dairy Genome Project				X	X	X	X		
	Ram Compare								X	X
	Bull catalogues	X	X	X	X	X	X	X		
Reproductive technologies	Artificial Insemination (AI)	X	X	X	X	X	X	X		
	Conventional breeding		X			X	X			
Animal genomics	Microbiome-driven breeding	X		X	X			X	X	X
	Genomic breeding values (GEBVs)	X	X	X	X	X	X	X	X	X
	Estimated Breeding values (EBVs)	X	X	X	X	X	X	X	X	X
	Genotyping	X	X	X	X	X	X	X	X	X
	Genetic markers	X	X	X	X	X	X	X	X	X

5 Quantifying the potential emission savings

We calculated the potential methane emission reductions under different traits for dairy, beef and sheep. Further information can be found in Appendix E.

The traits identified in our review (see Section 4.2) were further evaluated to assess their applicability to emission reduction calculations, based on requirements for defined quantification of methane emission values (either absolute or relative) and values to have a comparative emission baseline. A summary of the applicable traits used in the quantification calculations are presented in Table 7 below, with further information presented in Appendix E, Section 10.6.4.

Table 7. Traits used in the calculations of emissions savings

Sector	Trait Category	Trait Name	Unit of baseline	Value of methane reduction from baseline
Beef	Production	Feed efficiency	kg CO_2e/kg product	7%
		Offspring carcass weight	kgCO_2e/per kg meat per breeding cow per year	1.3%
	Climate	Methane yield	gCH4/kgDMI per generation	12%
Dairy	Production	Feed efficiency	kg CO_2e/kg product	5%
		Milk fat + protein	MJ CH4/kg milk	12%
		Milk yield	kg CH4/kg milk	15%
	Climate	Methane intensity	kg CH4/kg milk	24%
Sheep	Production	Feed efficiency	kg CO_2e/kg product	7%
	Climate	Methane yield	g CH4/kg DMI	35%

The current uptake of genetic traits focused on methane emissions is estimated based on our review and discussions with Scottish Government. This was based on an understanding on the currently uptake of AI and breeding technologies used within the sector from expert knowledge and limited research able to be found online. This rate provides a baseline for the quantification of additional uptake in 2030 and 2045 under four scenarios (further described in Appendix E, Section 10.6.4). The scenarios include: no additional intervention, voluntary uptake, supplier demand and policy changes. Scenario uptake percentages are presented with the current baselines in Table 8 below. These values were developed based on technical expertise and discussion with both stakeholders and Scottish Government, as well as published research. The impact of other traits (such as functional, health related traits) could not be estimated in this work as relevant values for methane reduction potential could not be identified in the literature. Further information in the calculation methodology, including additional detail on the selected scenarios, traits selected and limitations to the data is presented in Appendix E, Section 10.6.

Table 8. Scenario implementation values for dairy, beef and sheep

Type	Scenario	Current baseline	2030 uptake	2045 uptake
Dairy	1. No intervention	75%	80%	80%
	2. Voluntary uptake	75%	80%	85%
	3. Supplier demand	75%	82.5%	92.5%
	4. Policy changes	75%	85%	100%
Beef	1. No intervention	40%	45%	45%
	2. Voluntary uptake	40%	45%	50%
	3. Supplier demand	40%	47.5%	65%
	4. Policy changes	40%	50%	80%
Sheep	1. No intervention	10%	15%	15%
	2. Voluntary uptake	10%	15%	20%
	3. Supplier demand	10%	17.5%	40%
	4. Policy changes	10%	20%	60%

Baseline enteric fermentation methane emissions for beef, dairy cattle and sheep in Scotland in 2021 (totalling 4,020 kt CO2e), show beef cattle emitted the most at 59% (2,370 kt CO2e), sheep emitted 26% (1,061 kt CO2e), and dairy cattle 15% of (590 kt CO2e).

Our calculations found that methane focused traits (methane production/intensity/yield) presented the highest emission reductions for all livestock categories. As the impact of the interaction between traits are unknown, reductions from traits focused on feed efficiency, offspring carcass weight (beef specific) and milk yield, milk fat and protein (dairy specific) are not presented in the maximum reduction potential. However, we acknowledge that reductions for these traits were found within the three livestock categories. Results are presented in Figure 1, Figure 2 and Figure 3 below. These figures show that in each sector, up to 2030, the reductions are relatively steady, but there is a greater reduction at 2045, influenced by the proposed increase in uptake. Due to the proposed uptake percentages the policy change scenario presents the greatest reduction under all traits, with the no intervention scenario showing the smallest reduction due to a 5% increase in uptake in 2030 and no further uptake in 2045.

In the policy change scenario, choosing climate traits, we estimate that emissions would reduce in 2045 up to 382.2 kt CO_2e or 9.5% of enteric methane emissions. This includes a 6.8% reduction from beef cattle (161.1 kt CO_2e), 6% in dairy cattle (35.4 kt CO_2e) and 17.5% in sheep (185.6 kt CO_2e). Smaller reductions are feasible from traits focused on feed efficiency, offspring carcass weight (beef specific) and milk yield, milk fat and protein (dairy specific). Further details presented in Appendix E.

Figure 1. Methane emissions for beef cattle traits against the 2021 baseline enteric methane emissions of beef cattle in Scotland. Please note the y-axes do not start at zero to allow for greater visibility of results.

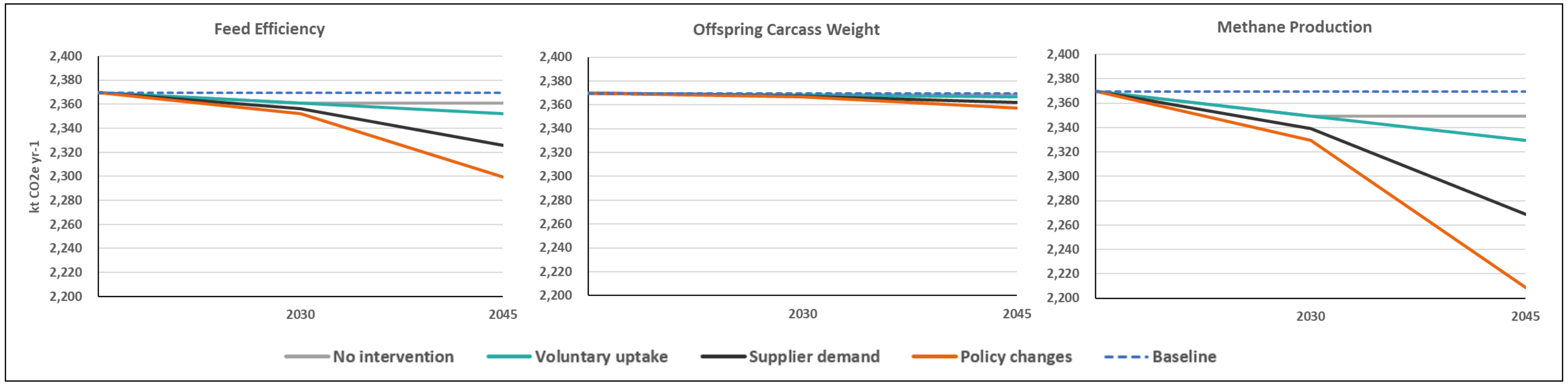


Figure 2. Methane emissions for dairy traits against the 2021 baseline enteric emissions of dairy cattle in Scotland. Please note the y-axes do not start at zero to allow for greater visibility of results.

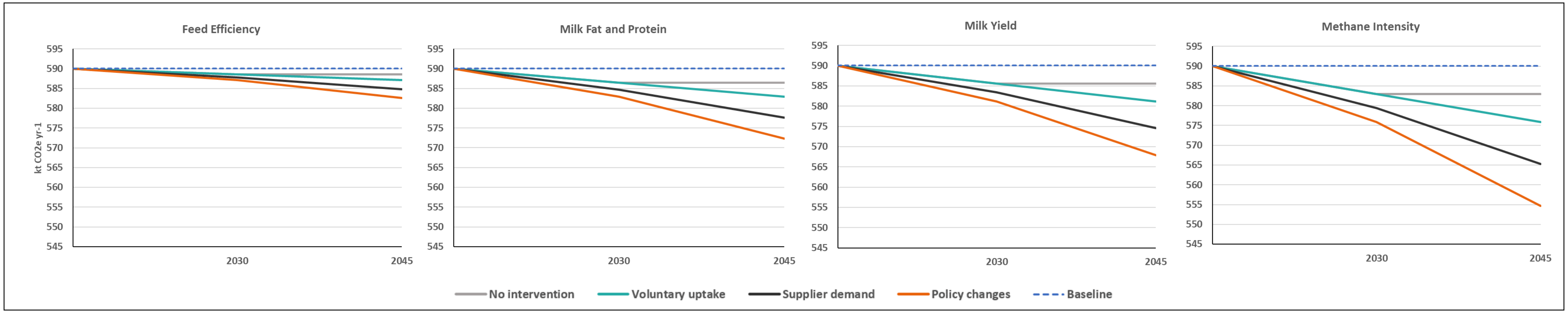
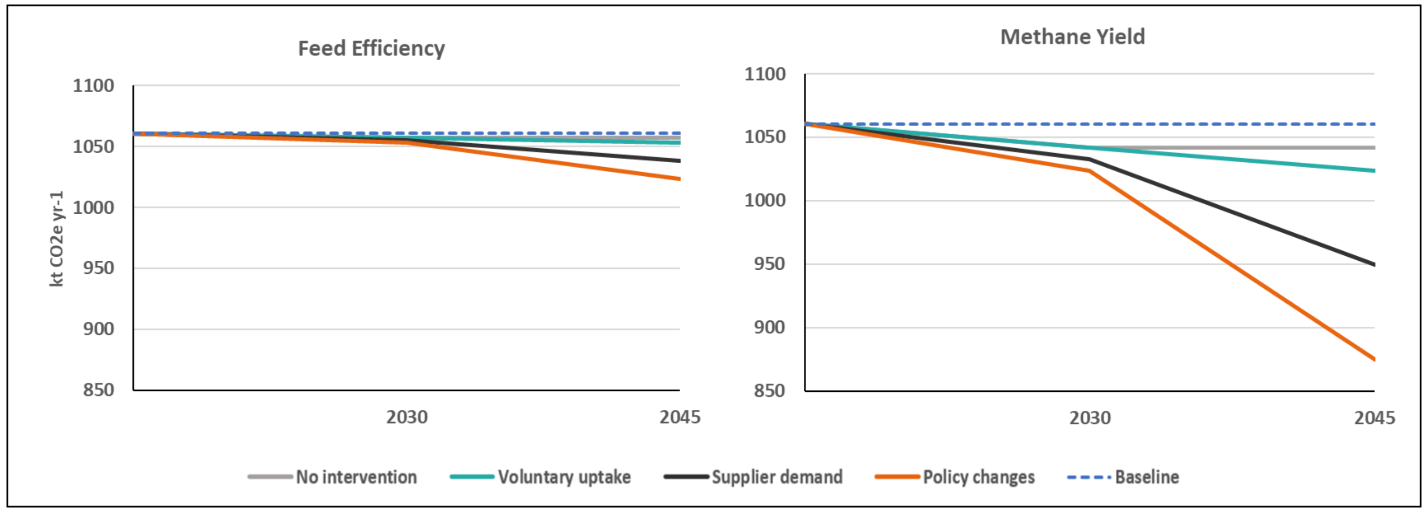


Figure 3. Methane emissions for sheep traits against the 2021 baseline enteric emissions of sheep in Scotland. Please note the y-axes do not start at zero to allow for greater visibility of results.



6 Identifying policy drivers and behaviour change needs

This section examines actions to encourage behaviour change. We understand that behaviour change is needed by four stakeholder groups:

1) Government, which would be policy drivers
2) Post-farm gate market, such as supermarkets, wholesalers, caterers, hospitality etc
3) Pre-farm gate, such as livestock markets, breed societies
4) Farmers

We explored how actions taken by each stakeholder group can enable further behaviour change in the other groups, and present three national level case studies to show actions that promote breeding practices to reduce methane emissions. Examples from these case studies are dispersed through the report in text boxes where the surrounding information was relevant. The countries are as follows:

- Ireland, which has incentivised and subsidised breeding practices.
- Canada, which has incentivised and subsidised breeding practices.
- New Zealand, which has started to take a regulatory approach and has incentivised breeding practices.

All three countries have strong research programmes supporting their policies.

6.1 Government action

Scottish Government have an important role in supporting uptake of new breeding techniques through policy. Below are policy drivers that can influence behaviour changes across the other stakeholder groups (post-farm gate market, pre-farm gate actors and farmers).

6.1.1. Legislation and targets

Setting a legal target for methane reduction in Scotland can help to shift the focus of the agricultural industry to methane emissions and align with climate commitments that have been made, such as the Global Methane Pledge at COP26. Other countries have set separate targets for biogenic methane, nitrous oxide, and carbon dioxide, such as New Zealand.

Case study: New Zealand

New Zealand aims to achieve net-zero emissions by 2050 and has a target to reduce biogenic methane by 10% relative to 2017 levels by 2030 and 24 - 47% by 2050. This 'split-gas' approach helped focus policy development and action, informed by strong research programmes and stakeholder dialogue. A split-gas approach can also give farmers flexibility to determine the most efficient, cost-effective mitigation practices for their farms (Stakeholder comment, 2023).

A methane target for Scotland could encourage constructive conversations among stakeholders about how to reduce emissions, leading to a higher uptake of relevant practices.

6.1.2. Financial incentives

The concept of breeding livestock for reduced methane emissions may be new for many farmers in Scotland. Methane emissions from ruminant livestock are viewed by many as a natural part of livestock farming, particularly in upland farming systems (Bruce, 2013). Therefore, the economic benefits of breeding for reduced methane emissions will need to be clearly demonstrated to farmers.

Cost was mentioned by some stakeholders as a barrier to selecting livestock based on lower emissions. However, there was little understanding of what the specific costs are. Given this, the *perceived* cost of adopting new breeding techniques might become just as significant as the barrier of cost itself. However, measuring methane from individual animals in a herd using the technologies in Table 1 is labour intensive and not widely available, which creates financial and labour bottlenecks (CIEL, 2023).

6.1.2.1 Subsidies

Some stakeholders believe that new policies could drive financial incentives (Stakeholder comment, 2023). For example, payments for using the technologies presented in section 4.1.

Case study: Ireland

In Ireland, the Beef Data and Genomics Programme (BDGP) provided payments to suckler beef farmers to improve the genetic merit and GHG emissions of their herd through data collection and genotyping. It was succeeded by the Suckler Carbon Efficiency Programme.

6.1.2.2. Specific funds incentivising measuring emissions

New Zealand supported a programme via funding to enable every stud ram breeder to use PAC chambers to measure emissions. This service was oversubscribed in 2023, indicating that the adoption of measurement techniques could be encouraged by government funding.

Case study: New Zealand

The Cool Sheep™ Programme, launched in 2022, is a three-year programme aiming to offer genetic selection to every sheep farmer in New Zealand to reduce GHG emissions. It gathers phenotype data to provide a methane breeding value which will be available on NProve. Breeders wanting to produce low-methane rams can measure a proportion of their flock using a PAC.

6.1.2.3. Research

All three case study countries have strong Government funded research programmes. The outputs from these informs the policies and actions designed to reduce emissions. Scotland is at the forefront of research on breeding livestock for reduced methane, so this just emphasises the importance of focussing research in this area.

Case study: Canada

Canada's Agricultural Methane Reduction Challenge will award up to $12 million CD$ to innovators designing practices, processes, and technologies to reduce enteric methane emissions.

6.1.3. Education and advice

Effective communication around breeding for reduced methane and the climate benefits for reducing methane are essential to support uptake. Farmers are crucial stakeholders and while some may be confident in trialling new approaches, advice must be available to help all understand why and how to implement innovative techniques on their farm, manage their farm in a new system and where to ask for help (Stakeholder comment, 2023). Training could also be provided by the private sector.

Case study: New Zealand

The Pastoral Greenhouse Gas Research Consortium (PGgRc) published a series of factsheets to increase understanding of methane research.

Peer to peer learning is very successful as it provides an informal opportunity to ask practical questions of farmers who have already tried and hopefully succeeded.

Example: Northern Ireland farmers visit Scotland

As part of the Farm Innovation Visits, a group of dairy farmers from Northern Ireland visited farms in Scotland to see breeding technologies in practice, such as genetic reports and use of sexed semen.

Farm advisers would be essential to ensure consistent and clear messaging to farmers. Training and communication material could be provided for advisers through existing Government schemes such as the Scottish Farm Advisory Service.

Consumers should be made aware of the importance of reducing methane emissions and of the industry's associated actions .

6.1.4. Behaviour change

Table 10 shows the outcome of our review on possible Government actions that could lead to behaviour change among farmers, the post-farm gate market and pre-farm gate actors. The three key actions we identified are 1) legislative targets for methane reductions, 2) financial incentives and 3) education and advice programmes.

Table 9: Behaviour changes caused by actions taken by Government

Government actions	Behaviour changes due to Government actions		
	Farmers	**Pre-farm gate actors**	**Post-farm gate market**
Legislative targets for methane emissions reductions	Provides a legislative backstop that must be met. Increased awareness of emissions helps farmers to visualise their emissions and select practices for adoption.	Provides a legislative backstop that must be met. Livestock markets and breed societies prompted to support farmers by providing information on emissions from animals.	Provides a legislative backstop, therefore retailers may encourage suppliers to take on low-emission breeding practices.
Financial incentives	Farmers are more likely to invest time and money in adopting breeding practices if they receive payments for their efforts or if (real and perceived) financial barriers are reduced.	Stronger demand from farmers to understand emissions from livestock will drive breed societies and markets to provide information about emissions. If breed societies provide advice on reducing emissions from a herd, they could gain a competitive and possibly over time cultural advantage.	Reduced emission livestock products could be marketed for a higher price, aimed at more environmentally conscious consumers. Risk: if government subsidies were already supporting farmers adopting emission reduction practices, retailers may be less incentivised to pay a premium price.
Education and advice programmes	Increased awareness and clarity on breeding practices to reduce emissions may encourage increased uptake.	Advisers will be able to influence farmers.	Increased awareness of low emissions products may influence consumers to buy food produced using low emission breeding strategies. Risk: consumers will ask for one thing but often pay for something different

6.2 Post-farm gate market

The post-farm gate market includes supermarkets, farm shops, other retailers, consumers and food chain assurance schemes. It has an important role in supporting uptake of new breeding techniques through demonstrating demand and providing price signals. Using our review, we explored actions where the market can influence behaviour change across the other stakeholder groups.

6.2.1. **Price signals**

Stakeholders discussed the important role of supermarkets, retailers, hospitality businesses, and their suppliers and consumers as these groups can set standards for better prices or to meet customer/societal demands. For example, Tesco aims to be net zero from farm to fork by 2050 , Waitrose has committed to source only from net zero carbon farms in the UK by 2035, and Morrisons aim to be supplied by 'Net Zero' carbon British farms as a whole by 2030. Others along the supply chain may need to start to provide evidence of emission reductions as these different retailers and suppliers reduce their Scope 3 emissions, for example as outlined in the British Retail Consortium's Net Zero Roadmap for the Retail Industry.

Validation of the claims through assurance schemes are important to ensure trust in the food chain. A stakeholder said, "if you take an animal to a 'normal' livestock market and claim it has reduced methane emissions, you'll probably get the same price as any other animal regardless of the additional effort".

6.2.2. **Consumer demand**

Consumers paying a premium price are likely to drive new practice adoption. Transparent communication about low emission breeding practices, supply chains and actions on farm is important to demonstrate to consumers the benefits of their choices and reduce the risk of 'greenwashing'.

International example: Sweden

In 2022, methane-reduced beef was sold in Sweden. It was well received by consumers, selling out in less than a week. There was however backlash in the media with claims of greenwashing. This example emphasises consumers' interests in climate-friendly options. while ensuring transparency.

6.2.3. **Behaviour change**

How the market influences other stakeholders is explored in more detail in Table 10. The key actions are 1) improved price signals from retailers and 2) increased consumer demand which is realised at the sales point.

Table 10: Behaviour changes caused by post-farm gate market actions

Post-farm gate actions	**Behaviour changes as a result of post-farm gate actions**			
	Government	**Farmers**	**Pre-farm gate industry**	**Post-farm gate market retailers**
Price signals from retailers		Similar to government financial incentives, farmers are more likely to invest time and money in adopting breeding practices if they receive payments for their efforts. Risk: uptake by farmers could be inconsistent depending on which retailers adopt this action first.	Livestock markets or breed societies could display methane scores if they know this is something that farmers are looking for.	Retailers offering a premium for low-emitting products will encourage uptake of practices. Marketing low-emitting products will raise awareness among consumers, possibly increasing demand for low-emission products. Post farm gate actors own emission reduction targets to meet societal demand for low emission products will require farms to reduce emissions
Increased consumer demand for low emissions livestock products	Government may be encouraged to support low methane emissions breeding practices due to a higher demand. Procurement guidelines for catering in Government funded facilities could include low methane emitting meat.	Increased demand for low emissions products may prompt adoption of practices.	Due to farming in Scotland not being solely driven by the market, consumer demand alone may not influence the pre-farm gate industry. Yet it may lead to actions that prompt further actions related to emission savings.	Increased demand for low-emission products will incentivise retailers and hospitality to provide these, possibly paying a premium to farmers.

6.3 Pre-farm gate actors

Pre-farm gate actors refers to industry representatives, levy groups, research institutions, breed societies, and livestock markets. They have an important role in supporting uptake of new techniques through increasing understanding and supporting data collection. Below are actions that can influence behaviour change.

6.3.1. Improving data and data sharing

A key infrastructure need is an accessible database of genetic information, including methane emissions, to enable benchmarking (Stakeholder comment, 2023). Stakeholders noted that farmers may struggle to envision new practices on their farms, and a database can help to conceptualise the traits.

Case study: New Zealand

The ram selection tool nProve provides a user-friendly platform to select required traits in a ram, including methane production.

Existing platforms already used by farmers, such as ScotEID, the Beef Efficiency Scheme (BES), and SRUC's genetic tool EGENES could add new elements around methane (Stakeholder comment, 2023). For example, Nprove allows farmers to assess methane elements in a user-friendly way.

The Beef Efficiency Scheme (BES) required farmers and land managers to submit tissue samples and other metrics of their beef herd to develop an understanding of the genes within the herd to improve efficiency. Uptake from the industry was low, with only 30% of the national breeding herd participating in the scheme. It currently remains unclear in the literature if the captured data has been incorporated into any local breeding schemes or progressed following the end of the scheme. This scheme could provide valuable learning on the integration of positive genetic traits across the herd in Scotland.

In our review, a stakeholder commented that as only a handful of breeds make up most of the livestock sector in Scotland, the establishment of a database would not take long to create (Stakeholder comment, 2023). This comment however shows the lack of understanding that the genetic material for breeding for methane is independent of breed and based on individual animals.

Case study: Ireland

The Irish Cattle Breeding Federation (ICBF) launched the National Genotyping Programme (NGP) in 2023 to achieve a fully genotyped cattle herd in Ireland. The programme offers beef and dairy farmers a low-cost option to collect DNA samples from calves at birth. The collected information is used to identify specific traits which contribute to national genetic indexes, including methane traits. It also allows farmers to optimise the health and productivity of their herd, while reducing the emissions intensity. The ICBF further publish methane evaluations for AI sires when methane data has been recorded.

Ireland's NGP and New Zealand's N Prove provide examples of the development of national databases. In Ireland, the use of metrics like Residual Methane Emissions (RME) index and predicted transmitting ability (PTA) aim to provide an easy way of comparing livestock to the average and to other farmers. Stakeholders noted that a challenge in the Scottish context could be a reluctance by stakeholders to pool data. However this has been successfully achieved in the Scottish pig industry with a number of health and productivity benefits to the individual farmers and to the sector. The NGP also allowed for subsidising DNA sampling of calves which helps to genotype the national herd

Stakeholders discussed the potential for livestock markets to display information on methane emissions. In many markets, a screen displays the weight of the animal and the name of the seller; it could be possible to add the expected or benchmarked methane emissions.

Case study: New Zealand

A methane breeding value was launched in 2019 by Beef and Lamb New Zealand, giving the sector a practical decision making tool. This led to the development of The Cool Sheep™ Programme (see section 6.1.2).

6.3.2. Metrics for methane emissions

Stakeholders recommend adding methane as an estimated breeding value (EBV) as this would allow farmers to benchmark. Stakeholders emphasised that metrics would only be used if they are adopted consistently across Scotland (and perhaps the UK) with cross sector collaboration and there was some incentive for farmers to reduce methane emissions from their livestock. Similarly, to the adoption of RME and PTA figures in Ireland, regulation and guidance from Scottish Government would be advisable to make sure the most sensible metric was adopted.

Case study: Ireland

Residual methane emissions (RME) index is a metric to understanding the difference between the expected methane emissions based on feed intake and the actual emissions. High RME is undesirable and low RME is desirable.

ICBF methane predicted transmitting ability (PTA) values have been produced by recording methane emissions from over 1,500 animals from 19 breeds. These are publicly available for AI beef and dairy bulls. Bulls are classed as favourable or unfavourable compared with the average sire.

6.3.3. Behaviour change

The two key take-aways from our review are 1) improved data and data sharing amongst farmers, researchers and across stakeholders and 2) developing metrics for methane emissions to enable benchmarking between farmers and products. Table 12 describes how actions by pre-farm gate actors could support behaviour change among other stakeholders.

Table 11: Behaviour change due to actions taken by the pre-farm gate actors

Pre-farm gate action	Behaviour change due to pre-farm gate action			
	Government	**Farmers**	**Pre-farm gate actors**	**Post-farm gate market**
Improved data and data sharing	A database can inform policy.	Enables farmers to understand the emission reduction potential of their animals. Displaying methane information at markets can help choose livestock based on emissions.	More data would support more robust research, thereby increasing the output of Scotland-specific research. Markets around Scotland displaying methane data would raise awareness among farmers.	Better data would enable retailers to communicate sustainability data to customers, increasing trust in the food system.
Metrics for methane emissions	Scottish Government could ensure all relevant stakeholders are involved in developing a metric.	Metrics would enable farmers to make comparisons against individual animals when deciding which ones to breed or purchase.	Breed societies and livestock markets would be able to display methane emissions. Breed society representatives can discuss options for reducing emissions.	Retailers have a consistent metric they can use to communicate the methane emissions of products to consumers.

6.4 Farmers

Farmer behaviour change in this context relates to choosing animals with low methane traits to breed, and implementing systems on farm that support this. Some farmers could measure emissions from their livestock to verify the effectiveness of breeding for reduced emissions. Uptake of technologies outlined in section 4 provides the opportunity to better track genetics and traits in their herd.

Farmers will need support to make these changes and to enable behaviour change from the pre-market, post-market and government stakeholder groups identified in the sections above. In addition, the adoption of new practices will likely vary between dairy, beef and sheep producers, and the challenges they face will be different. Farmers who are already using reproductive technologies, such as sexed semen and AI, are expected to progress fastest in this area, given their familiarity with the processes. It is likely that the dairy sector will lead the way, and to a smaller extent, the beef sector. Rapid uptake of AI (and therefore sexed semen) in the sheep sector faces practical challenges, therefore it may be best to prioritise low-emitting traits in rams.

The financial benefit of farmers selecting methane traits is currently unclear. It is likely that the primary motivation will come from the supply chain; it will be important to have specific supply chain indicators. For example, if a milk buyer sets methane reduction goals, suppliers will need to respond. Behaviour change is also influenced by seeing neighbours or peers taking on new practices for example. Below are some points for each of the different livestock sectors groups that should be considered to enable the behaviour change actions identified in the previous sections.

Cummins et al (2022) advise that further research is needed on how breeding for low methane emissions affects the productive and profitable genes that make an animal appealing to farmers. However, research in New Zealand on genotyped low emitting sheep showed no negative impacts on physiology, productivity and health when selecting for reduced emissions and preliminary economic analysis shows that low-emitting sheep could lead to higher profits, primarily due to higher growth rates, a greater proportion of meat, and increased wool production. This section also briefly covers some actions that could be undertaken on farm to support farmers to shift to breeding lower methane emitting livestock.

6.4.1. Sheep farmers

Sheep farmers deal with a large number of animals which tend to be farmed extensively in Scotland, so using methane detecting technologies is potentially more difficult than for other livestock sectors. Despite this challenge, the shorter time to slaughter means that low-emitting traits can be introduced regularly and methane reductions can accumulate quickly (Stakeholder comment, 2023). In addition, other countries such as New Zealand have implemented programmes to begin to measure the national flock such as The Cool Sheep Programme (see section 6.1.2). Stakeholders discussed how the sheep sector produces a lower-value product compared to the cattle sector, so cash flow may be a prohibiting factor in taking on new practices.

6.4.2. Beef farmers

Stakeholders asserted that the beef sector is complicated by several commercial interests in the market which influence genetic improvement. Unlike the dairy sector, AI is not widely used in the beef sector (Stakeholder comment, 2023). However, there are opportunities to influence the genetics of the herd by encouraging bull breeders or bull stud farms to take on practices to support low-emitting traits.

As it is common for dairy cow offspring to enter the beef system, there is the opportunity to use lower emitting dairy animals to feed into emissions reductions in the beef sector (Stakeholder comment, 2023).

6.4.3. Dairy farmers

The dairy sector is the most advanced ruminant sector in using genetic technology and tools for selective breeding. For example, AI is fairly common practice, currently with the objective of increasing productivity rather than targeting emissions. Progress in the sheep and beef sectors is much slower due to challenges around practicalities, sufficient data and uptake of technologies in these sectors. The dairy industry also has a steadier cashflow than beef and sheep (Stakeholder comment, 2023), and is more progressive when it comes to real-time data collection and data management. This puts the dairy sector in a good position to advance breeding for reduced methane emissions.

6.4.4. Cross-farm actions to support breeding lower methane livestock

Strong and structured communication, sharing of ideas and engagement locally are important drivers to enable behaviour change in farming communities. Peer to peer support, for example through breeding groups, to share ideas, showcase technologies and discuss successful and disappointing technologies will enable neighbours and other local farmers to progress faster. Organising local workshops, either by Government supported advisers or leading farmers, would help to spread the word about the importance of breeding for reduced emissions and provide practical examples. The more discussion about the overall aim, the need to reduce emissions, the potential actions, outcomes and successes, the more likely that breeding for reduced methane emissions will become mainstream.

7 Gaps in the research

We identified the following gaps in research:

- **Timeline of availability for the technologies**. Due to a lack of robust information in many cases, we made an expert judgement on the availability of the technologies in Scotland up to 2030 and 2045.
- **Quantified impact of introducing methane traits in case study countries**. We did not find evidence for the actions and policies introduced in the case study countries reducing overall country emissions. A reason for this is that many of the examples presented in the case studies in the appendices are very recent, therefore there has not been enough time to quantify the emission savings. In addition, it could be challenging to see whether these actions had a specific impact emissions due to other surrounding factors, for example changes in stocking rate, or outbreak in disease.
- **Evidence for current level of uptake in Scotland and the UK**. The review did not find much evidence for current levels of uptake of breeding livestock for reduced emissions.
- **Mitigation potentials of some traits**. Many sources did not present methane emission values, but instead covered genetic correlations between traits. This meant that due to a lack of data many of the traits identified in the REA (see Table 5) were excluded from quantification. In other cases, some mitigation potentials were not comparative to the baseline used in our study because it presented changes from an entire lifecycle or system.
- **The interaction between traits**. Emission calculations were quantified for individual traits, rather than combining the mitigation potential for all traits because the relationship and interaction between traits is unknown.
- Due to the smaller quantity of literature available on methane efficiency focused traits, the reduction potential values may be less robust. **Greater consistency** in measurement, modelling, and presentation and their impacts on emissions savings and animal production would fill this knowledge gap.

8 Conclusions

We estimate that, by 2045, breeding for reduced methane emissions could achieve a reduction in enteric methane emissions of 9.5% from the baseline, including 6.8% reduction from beef, 6% from dairy and 17.5% from sheep assuming livestock numbers remain constant. This would be achieved by selecting breeding traits for methane efficiency (methane production, intensity and yield), feed efficiency, offspring carcass weight, milk yield and milk fat and protein. Selecting for these traits brings cumulative and permanent emission savings. A limited number of studies researched the impacts of selecting low-methane traits on productivity and health and found that these qualities were not compromised.

Scotland has a well-developed research base around breeding livestock for reduced methane emissions, placing it in good stead in developing further work and providing validation and trust. Research programmes in New Zealand, Canada and Ireland have successfully interacted with farmers, for example, by the development of user-friendly, accessible tools. Our stakeholder comments implies that a comparable interaction between research and on-farm activities and innovation is currently lacking in Scotland.

To achieve the emissions reductions, actions and behaviour change will be required by four stakeholder groups: Scottish Government, pre- and post-farm gate industry and markets, and farmers. Change will need to be co-created across the stakeholder groups.

The financial benefit of farmers selecting methane traits remains uncertain. Therefore, it is likely that the primary motivation will be the supply chain which will need supply chain indicators. For example, if a milk buyer sets methane reduction goals, suppliers will need to respond. Behaviour change is also influenced by neighbours or peers taking on new practices.

The key barriers to uptake are around knowledge and perceived cost. To alleviate these, Government funding could be targeted towards more data collection and research with farmer involvement to improves robustness. Investment in adviser training and farmer peer-to-peer will enable local farmers to progress faster. Organising local workshops, either by Government supported advisers or leading farmers, would help to spread the word about the importance of breeding for reduced emissions and provide practical examples. The more discussion about the overall aim, the actions, outcomes and successes, the more likely it is that breeding for reduced methane emissions will become mainstream.

The technologies we estimate could be mainstream by 2030 include a national breeding programme, sexed semen, artificial insemination (AI) and estimated breeding values (EBVs). However, their success will be about but the interactions between them. For example, data will inform EVBs, which in turn will inform a national breeding programme. If the constant use of methane detecting technologies is required, this may be difficult to implement in extensive farming systems. However, if a proxy measurement was used or the breeding stock was known to provide the necessary traits, this would allow existing systems to continue.

On this basis, we think there is a strong foundation for breeding for reduced emissions to become part of Scottish Government's commitments.

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10 Appendix / Appendices

10.1 Technologies involved in breeding for reduced methane, full tables

Table 12. Examples of the detection methods involved in the process of breeding livestock for reduced methane emissions.

	Description	Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations in Scotland
						Beef	Dairy	Sheep	
Respiration chamber	A sealed chamber taking samples from an animal in a controlled environment. The animal is typically kept in the measurement chamber for a couple of days and is provided with food and water (Zaman et al., 2021).	All	Methane concentration	Believed to be the most accurate way to measure methane from livestock (Zaman et al., 2021). Measurements taken over several days increases robustness (Manzanilla-Pech et al., 2021).	Restricts normal animal behaviour and movement (Zaman et al., 2021; Manzanilla-Pech et al., 2021). High capital cost. Limited to a few or one animal per chamber (Manzanilla-Pech et al., 2021).	2030: E 2045: E	2030: E 2045: E	2030: E 2045: E	Used in research facilities in Scotland, however there is limited scope to use them on farms due to the high cost (Stakeholder comment, 2023).
Sniffers	Non-dispersive infrared unit that can be installed in feeding areas or milking parlours (van Breukelen, 2023; de Haas et al., 2021).	All	Methane and CO_2 concentration	Non-invasive, can be incorporated into existing milking technologies (de Haas et al., 2021). Offers large scale recording (de Haas et al., 2021).	A spot measurement, not a true reflection of emissions per day. Limited to indoor measuring (Cummins et al., 2022). More difficult to introduce in beef and sheep sectors compared to dairy due to frequent milking.	2030: FP 2045: FP	2030: E 2045: E	2030: FP 2045: FP	In 2021 'the first' was installed at a Dutch dairy farm for research (CRV, 2021). No evidence found for use on farms in the UK.
SF6 tracer gas	A tube containing sulfur hexafluoride (SF6) tracer gas is placed inside the rumen and collection lines are used to collect breath samples (Cummins etal., 2022).	All	Methane concentrations	Measurements can be taken from confined, free range, and grazing animals (Manzanilla-Pech et al., 2021).	Invasive measure which has animal welfare concerns (de Haas et al., 2021). SF_6 is a greenhouse gas itself (Tedeschi et al., 2022). Daily canister collection means high labour (Cummins etal., 2022).	2030: E 2045: E	2030: E 2045: E	2030: E 2045: E	No evidence was found for use in UK trials and research, but it used widely in globally. It would be beneficial in Scottish research due to measuring livestock while grazing.
Automated head chamber system (e.g. GreenFeed)	A transportable head chamber unit that can be positioned in housing or pasture. Feed is used to attract livestock to the unit (van Breukelen, 2023; Zaman et al., 2021).	All	Methane and CO_2 concentrations	Non-invasive. It can be set up in grazing fields or in housing.	High purchase and running costs. A spot measurement, not a true reflection of emissions per day. Feed to attract livestock increases costs.	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	No evidence was found for use in UK trials and research. However it is potentially a feasible option for Scotland due to the benefits of transportability and measuring grazing livestock.
Mid-Infrared (MIR) data	MIR spectroscopy is used to predict the fat and protein content of milk. As methane is linked to milk composition, it can be used as a proxy to predict methane emissions (Dehareng et al., 2012; Semex, 2023)	Dairy	Milk component such as lactose, protein and fat	MIR technology is already used in milk recording, so could provide an existing infrastructure to integrate methane reporting into.	Because it is a proxy, validation of results (for example with a respiration chamber) is required (Denninger et al., 2020).	NA	2030: I 2045: I	NA	No evidence found of MIR being used in the UK to estimate methane, but European examples were found. As data could become available through existing milk recording schemes, it could be introduced by innovators by 2030. If the need for verifying results via detection methods is removed, this could be mainstream by 2045.

	Description	Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations in Scotland
						Beef	Dairy	Sheep	
Portable accumulation chambers (PAC)	A portable respiration chamber which takes measurements over a short period of time (e.g. 1 hour) (Cummins et al., 2022).	All	Methane and CO_2 concentrations	Quick measurement period reduces animal stress (Cummins et al., 2022). Transportable (NZHerald, 2023).	Feeding and management protocols must be followed prior to measurements (Duthie et al., 2024). Not suitable for long-term measurements (Cummins et al., 2022).	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	A promising option for Scotland, given its transportable between farms. SRUC recently acquired a PAC for sheep in the UK. However current research needs to be completed before they can be used widely (Duthie et al., 2024).
Handheld lasers	A handheld device originally developed to detect gas leaks can measure concentrations of methane in livestock breath (Sorg, 2021).	All	Methane concentrations	Non-invasive and portable. Can take measurements from grazing livestock. Can take measurements from several animals in one day. Results can be sent to a smart phone (Sorg, 2021)	Has a lower accuracy, measurements are highly affected by environmental conditions (de Haas et al., 2021; Sorg, 2021)	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	No evidence found for use in UK research. However, the benefit of taking measurements from several animals in the same day may make it an attractive option for Scotland. Its widespread use may depend on supporting infrastructure such as reporting systems.
Rumen microbial composition	The rumen holds a variety of microorganisms that aid in the digestion of feed. By studying the microbes present in the rumen, those influencing the production of methane can be identified and used as a proxy to identify animals with the microbiome composition which emits lower methane (Miller et al., 2023).	All	Dry matter intake and methane concentrations	It can also be used to improve feed conversion and disease resistance (Duthie et al., 2024).	The composition of the microbiome is largely influenced by the ratio of feed (i.e. forage vs concentrate) so accuracy of results may be influenced by diet (Miller et al., 2023).	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	A technique being used in Scottish research in all sectors. Likely to remain an experimental technology, with future trials on some farms in the future.
Feed efficiency index	An indicator showing how efficient a cow is at converting feed into product, for example, into milk. Research shows that selecting for feed efficiency reduces methane emissions (Manzanilla-Pech et al., 2022).	Dairy, beef	Feed efficiency, feed intake + milk yield (dairy) / meat quality (beef)	Helps to reduce the amount of feed required and therefore associated costs.	It's important that selecting for feed-efficiency does not compromise growth.	2030: M 2045: M	2030: M 2045: M	2030: M 2045: M	No evidence found of this being done with the aim of reducing methane emissions in the UK, but it is used in the UK to improve efficiency in dairy.

Table 13. Examples of data management tools involved in the process of breeding livestock for reduced methane emissions.

	Description	Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations related to the feasibility in Scotland
						Beef	**Dairy**	**Sheep**	
ScotEID	A multispecies database which records and tracks livestock information. It may be possible to build on this in the future to introduce information relevant to methane.	All	Births, deaths and movements.	A familiar platform for farmers in Scotland.		2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	An established infrastructure exists and is familiar to the industry, therefore a promising option to repurpose to include methane traits.
nProve	A free tool for New Zealand farmers to use to choose rams for breeding. They can choose the terminal or maternal traits that fit their breeding goals. When choosing maternal traits, methane production is an option.	Sheep	Reproduction, lamb growth, size, meat, wool, health indices	Very user friendly, guides the user through the selection process. Contact details are provided for breeders that meet chosen criteria. Farmers can choose rams based on location, breed and exclude certain flocks from results.		NA	NA	2030: FP 2045: I	To be successful in Scotland, genetic evaluation and measuring methane from sheep would need to be common practice. There are existing tools such as ScotEID which records births, deaths and movements, and RamCompare which presents data from performance recorded rams i.e. carcass weight, that could be repackaged to incorporate methane production. But success would also depend on wide use of PAC (as done in New Zealand).
Selection index	Combines information to predict an animals estimated breeding value (EBV). It can be used to select traits for breeding goals, for example, milk production, feed efficiency and health to maximise future profit (Wellmann, 2023; de Haas et al., 2021).	All		It is possible to apply weightings to traits in relation to its importance in the breeding goals	Before a trait can be added to a selection index, it needs to be "clearly defined, recordable, affordable, have phenotypic variation, be heritable, and the genetic correlations between other traits in the index need to be known" (de Haas et al., 2021).	2030: E 2045: I	2030: E 2045: I	2030: E 2045: I	In 2023, Semex introduced a methane index for Holsteins in Canada. Availability in Scotland depends on the progress of measuring methane.
National breeding programme	A programme which plans and identifies breeding objectives, traits and information on selection criteria.	All		It can optimise gains and trait changes (De Haas et al., 2021).	To be successful at a national scale, significant data and cooperation is required. For a trait to be included in a programme it must be environmentally important, express genetic variation and be measurable (Teagasc, 2012).	2030: M 2045: M	2030: M 2045: M	2030: M 2045: M	In 2023, The National Sheep Association began a 3-year initiative to measure methane from 13,500 sheep. The aim of this is to measure production traits to incorporate into breeding programmes. With progress like this, it is possible that national breeding programmes will be mainstream by 2030.
Multi-country database	An international database that contains performance/production (trait-related) records from a large number of livestock (Manzanilla-Pech et al., 2021).	All		An increased dataset Improves robustness (Manzanilla-Pech et al., 2021)	Combining data from different countries can be challenging due to differences in reporting and recording, technology, favoured breeds and management style (Van Staaveren e al., 2023).	2030: FP 2045: FP	2030: E 2045: I	2030: FP 2045: FP	A significant amount of collaboration is required to make this effective. Due to having to overcome the data sharing challenges, it is possibly unlikely this will be available with the aim of reducing methane emissions by 2045. There may be some progress in the dairy sector however due to the introduction of the methane index in Canada.

	Description	Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations related to the feasibility in Scotland
						Beef	Dairy	Sheep	
Efficient Dairy Genome Project	An international initiative that combines data from 6 countries (Australia, Canada, Denmark, United Kingdom, United States, and Switzerland) aiming to build one genomic reference population and a unique database of DMI records.	Dairy	DMI, milk, methane was measured in 4 of the 6 countries participating in the initiative	The overall objective is to potentially improve feed efficiency (cost benefit) and reduce methane emissions (environmental benefit).	Combining data from different countries can be challenging due to differences in areas such as reporting and recording, technology, favoured breeds and management style (Van Staaveren e al., 2023).	NA	2030: I 2045: I	NA	
Bull catalogues (such as Genus Bull	This index allows farmers to see the scores of certain traits in bulls. One of these traits is called Feed Advantage which can identify bulls with the greatest feed conversion (ABS, 2023).	Dairy, beef		Farmers can choose bulls with the desired characteristics to use in breeding.		2030: M 2024: M	2030: M 2024: M	NA	These are already available for farmers to use, so we would estimate them to be mainstream by 2030.
Beef Efficiency Scheme	A 5-year scheme funded by Scottish Government to help improve the efficiency, sustainability and quality of beef herds – helping to increase genetic value and reduce GHG emissions. The scheme focused on cattle genetics and management practices on-farm.	Beef	Tissue samples - genotyping blood samples, calving data, culling/death reasons, dam data (docility)	Funding was provided to farmers for data collection and entry. A free advisory service was also provided to assist farmers in developing their beef herd.		2030: FP 2045: FP	NA	NA	This scheme ended in 2021. It may be possible to build on and repackage the scheme to consider methane traits in the future.

Table 14. Examples of reproductive technologies involved in the process of breeding livestock for reduced methane emissions.

	Description	Sector	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M)	Future possibility (FP) Not applicable (NA)Practical considerations related to the feasibility in Scotland			
						Beef	Dairy	Sheep	
Semen freezing	A technique to preserve semen.	All	Provides security in an instance that could risk a breed's survival (Jones et al., 2020)	Variable success rate using thawed semen.		2030: M 2045: M	2030: M 2045: M	2030: I 2045: I	

	Description	Sector	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M)			Future possibility (FP) Not applicable (NA)Practical considerations related to the feasibility in Scotland
					Beef	**Dairy**	**Sheep**	
Artificial insemination (AI)	A technique to inseminate females, using fresh or frozen semen.	All	High success rate for cattle. Not required to have a bull on the farm. Better guarantee of uniform calving.	To be most efficient, livestock are required to come into heat at the same time as AI takes place. This is done artificially by the farmer, adding additional labour. AI in sheep is often done laparoscopically, which is a surgical procedure performed by a vet. Due to the scale and extensive nature of sheep farming, this brings practical challenges. Relies on sufficient infrastructure to collect and store semen of which there are limited facilities in Scotland (in particular for the sheep sector) (Stakeholder comment, 2023).	2030: M 2045: M	2030: M 2045: M	2030: I 2045: I	AI is already common practice in the dairy sector, with some use in the beef sector too. It's likely this will be mainstream by 2030 for cattle. However, due to the practical challenges in sheep, it may still only apply to innovators.
Sexed semen	A method which allows control over the sex of the offspring by separating sperm cells based on their X or Y chromosome content. By focusing on females for example, there is the potential to reduce methane by reducing the number of unwanted males (Duthie et al., 2024).	All	Increases the selection of females in the dairy sector. Improves productivity.	Success relies on the uptake of AI.	2030: M 2045: M	2030: M 2045: M	2030: I 2045: I	This is widely practiced in the dairy sector. Use in the beef sector is currently lower, however by 2030 there is the potential for this to be mainstream. Progress is determined by the uptake of AI in the sector. Due to the practical challenges associated with AI, it will likely remain an innovative practice.
In-vitro fertilisation (IVF)	Harvested oocytes are taken from donor cows and fertilised in a petri dish with semen to create an embryo.	Beef, dairy	Less semen required	Nutrition and diet need to be consistent in the lead up to extracting oocytes.	2030: I	M	NA	Process is conducted in a lab under sterile conditions.
Embryo freezing	A method for cryopreservation of embryos for long-term storage or transport. This tends to occur in conjunction with MOET.	All			I?	I?	I?	Lack of suitable laboratories
Conventional breeding	The use of bull/ram to cow/ewe breeding. Enhanced tools to select lower than average emitting bulls or rams.	All	Minimal technical input. Familiar management practice for farmers.	Little control over selecting desirable traits. It requires waiting for offspring to become fully grown before seeing if they have taken on the desired traits.	M	M	M	

Table 15. Examples of animal genomics involved in the process of breeding livestock for reduced methane emissions.

	Description	Sector	Data collected	Benefits	Risks	Timeline of availability in Scotland: Experimental (E), Innovators (I), Mainstream (M), Future possibility (FP), Not applicable (NA)			Practical considerations in Scotland
						Beef	**Dairy**	**Sheep**	
Microbiome-driven breeding	Emphasis is on selecting livestock with a rumen microbiome composition which is more efficient at fermenting of feed so that less excess hydrogen and thus less methane is produced. Livestock genetics and therefore breeding influences the composition of the microbiome which therefore affects the amount of methane released.	All	Rumen fluid samples - sequencing of microbial DNA	There is a growing demand for livestock that emit less methane. Potential method for improving animal health and reduce environmental impact.	This is a relatively new field, and much is unknown about how the gut microbiome develops and is maintained over time. It is unclear how much influence the animal may have over those processes.	2030: E 2045: E	2030: E 2045: E	2030: E 2045: E	Good early signs but still at research stage.
Genomic breeding values (GEBVs)	Values that are based on information from livestock DNA and measured performance. Can be used with EBVs to improve accuracy of breeding programmes. (Meat Promotion Wales. 2013).	All	DNA and performance records	Can be used to identify traits that are difficult to record Beneficial for traits measured in only one sex Useful for accurately measuring traits that occur later in life (Scholtens et al., 2020).	Accuracy of the estimate is dependent on the number of animals included in the reference population (Scholtens et al., 2020).	2030: E 2045: I	2030: E 2045: I	2030: E 2045: E	For the UK beef industry, GEBVs are currently available for a number of carcass traits in Limousin cattle (Business Wales, 2016)
Estimated Breeding values (EBVs)	Calculated from the performance data of recorded animals. Environmental factors (e.g. feeding) are filtered out to provide a genetic value for each trait (Stout, D. 2021).	All	Performance records – parentage and traits of interest (e.g. weight traits).	Provides a more objective (data driven approach) towards selection. Genetic selection based on EBVs leads to faster rates of genetic gain and flock improvement (compared to selection based on raw data or basic observation)	Allows comparisons within breeds, not between breeds.	2030: M 2045: M	2030: M 2045: M	2030: M 2045: M	Use as a tool to aid in the selection of healthy and structurally sound animals.
Genotyping	The process of determining/comparing the genetic variation of DNA sequences (or whole genomes) amongst individuals or populations.	All		Aids in genomic selection of both desirable (and harmful) traits.	Prediction accuracy of genomic selection is influenced by the type (male/female, previous generations) and number of animals that are genotyped (Mohammaddiyeh et al., 2023)	NA	NA	NA	Farmers cannot use this method themselves and therefore require the use of external service providers.
Genetic markers	Genetic markers identify desirable traits in animals which can then be selected for breeding (Meat Promotion Wales. 2013).	All		DNA marker information can be obtained from animals at birth (Hayes et al., 2013). Can be used to select for traits that are difficult to record.	Genetic progress in slow given the relatively long generation interval in cattle and sheep	NA	NA	NA	Farmers cannot use this method themselves and therefore require the use of external service providers.
Gene editing	A method for editing individual genes within the genome of a cell, embryo or ovum to bring about a desired genetic change.	All		The ability to eliminate undesirable traits. Accelerates rate of genetic improvement. Introduces variation into a population e.g. disease resistance	Identifying the appropriate genes/ genomic site can be challenging, time consuming and expensive.	FP (provided a change in policy)	FP (provided a change in policy)	FP (provided a change in policy)	Gene editing is not legal in the UK and the Scottish Government is opposed to the use of GM in farming.

10.2 Appendix A: REA and stakeholder interviews methodology

10.2.1. REA methodology

The REA methodology used for this project aligned with NERC methodology (Collins et al., 2015) and comprised of the following steps.

1. **Define the search strategy protocol, identify key search words or terms, define inclusion/exclusion criteria.** This step helped to focus the review on the most relevant sources. Inclusion and exclusion criteria were also defined. For example, studies related to reducing emissions through feed additives were excluded.
2. **Searching for evidence and recording findings.** Due to the short timescales of this REA, we searched for literature using Google Scholar, utilising our accounts with Science Direct and Research Gate to access restricted pdfs where required**.** For each search, we recorded the date, search string and number of results found, each search string was assigned a reference number. Examples of search strings include:
   a. breeding for reduced methane emissions
   b. policy drivers for reduced methane emissions in livestock "breeding"
   c. breeding for reduced methane emissions in livestock "Scotland"
3. **Screening.** Evidence was then screened, initially by title and a selection of sources were screened by the abstract, applying the criteria developed in step 1. This step ensures the relevance and robustness of the evidence that was included in the study.
4. **Extract and appraise the evidence.** Evidence was then extracted from the papers after screening, this included methane reduction values, traits that lead to reduced emissions and the technologies involved in the process.

10.2.2. Stakeholder interview methodology

Stakeholder interviews were used to collect information that may have been absent from the literature, for example on trials currently taking place that will not yet be included in publications. The stakeholders included researchers and individuals from farmer representative groups. We invited farmers for interview, however, only confirmed one farmer for an interview.

The semi-structured interviews took place over Microsoft Teams, with questions covering all parts of the study. For instance, asking for views on the key traits to select for, any examples of farmers choosing livestock based on emissions and the benefits and risks.

We did seven one-to-one interviews (with four stakeholders based in Scotland) and a group interview with nine stakeholders, all located in Scotland. The group interview was done to allow space for conversation and discussion between stakeholders. During this meeting, we presented the key themes raised in the one-to-one interviews. This included the barriers and drivers to uptake, the availability of technologies and the structural needs to support uptake.

10.3 Appendix B: New Zealand sheep case study

10.3.1. Country information

New Zealand is an island nation in the South Pacific and has many similarities to Scotland in terms of its geography and climate. Agriculture is integral to the New Zealand economy with the sector accounting for 10% of gross domestic product (GDP), over 65% of export revenue and almost 12% of the workforce. In 2023 there were 26,821,846 sheep in New Zealand, down from approximately 70,000,000 in the 1980s.

Around half of GHG emissions in New Zealand (49% in 2021) and 91% of biogenic methane emissions stem from agriculture, with sheep farming a key contributor.

New Zealand has relevant targets, including the Global Methane Pledge, and the Climate Change Response (Zero Carbon) Amendment Act 2019, which sets a net zero target by 2050. There is a specific reduction target for biogenic methane of 10% relative to 2017 levels by 2030, and 24 - 47% by 2050. New Zealand also has emissions' budgets and emissions' reduction plans which sets out policies and strategies for meeting the budgets.

Accelerating new mitigations such as breeding for low-methane sheep is seen as an important way to reduce emissions alongside the pricing of agriculture emissions, as well as support initiatives.

10.3.2. Relevant research, programmes and technologies

The New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) and the Pastoral Greenhouse Gas Research Consortium (PGgRc) are key leaders in the robust and comprehensive programme of research in New Zealand.

- The NZAGRC is a Government funded centre which invests and coordinates research for practical and cost-effective reductions of agricultural GHG. One of its main targets of reducing enteric methane emissions.
- The PGgRc is a joint initiative of the New Zealand Government and the agricultural sector which funds research into ways to reduce methane emissions, including from sheep, such as breeding. It also provides knowledge and tools for farmers to help mitigate GHG, for instance research reports ('Sheep farmers now able to breed "low methane" sheep'), and fact sheets, with the aim of increasing understanding around the research.

The NZAGRC and PGgRc led the following research programmes related to breeding for reduced methane emissions:

- Low emitting sheep were genotyped and markers were used to identify low emitting traits which confirmed a genetic basis for the variation in methane emissions. After 13 years of selecting for low emitting traits, a 16% difference in methane emissions was found between low and high emitting sheep. Other key findings include no negative impacts on physiology, productivity and health when selecting for reduced emissions. Predications have also been made that with the low emitting flock a 1% decrease in methane emissions per year is achievable The low emitting flock has been producing more wool and leaner meat and the emissions savings are both permanent and cumulative. This programme is ongoing and has produced one of the most comprehensive datasets in the world.

- A methane breeding value was launched in 2019 from research undertaken by NZAGRC and PGRC. This was made available to selected ram breeders through Beef + Lamb Genetics and gives the sector a practical tool to make decisions with. This has then led to the development of the Cool Sheep Programme.
- The Cool Sheep™ Programme was launched in 2022. This three-year programme aims to provide every sheep farmer in New Zealand the chance to use genetic selection to reduce GHG emissions. As well as supporting farmers, this programme gathers phenotype data which feeds back into research. This is available to farmers who are reviewing rams for selection on N Prove. Breeders wanting to produce low-methane rams do so by measuring a proportion of their flock using PAC. When combined with other information and sheep genotyping, this is used to provide a methane breeding value. In November 2023, bookings for use of the PAC chambers by stud breeders were fully subscribed, indicating uptake is high. They note that progress is slow in terms of methane emissions reduction around 2-3% per year, with single trait selection, although this is cumulative.

The four workstreams of the project are:

1. Ram supply: Measuring rams with PAC to make low-emitting rams available for breeding.
2. nProve enhancement: adding methane to nProve.nz.
3. National Impact: using GHG calculators on farms to show methane reductions, rewarding farmers for their efforts.
4. Awareness and outreach: increasing knowledge for farmers, improving public awareness of efforts to reduce emissions while improving national productivity.

10.3.3. Key policies

There is no government policy legislating livestock breeding for reduced methane emissions in New Zealand. However, there are policies that that may contribute to introducing this in the future.

The **Emissions Trading Scheme (ETS)** is a key tool in New Zealand to help reduce emissions. Under the ETS, businesses must measure and report on their GHG emissions, and surrender one 'emissions unit' (an NZU) to the Government for each tonne of emissions emitted. They do this by purchasing NZU. The Government sets and reduces the number of NZU supplied into the scheme over time. This limits the quantity that emitters can emit, in line with emission reduction targets. Businesses who participate in the ETS can also buy and sell units from each other i.e. emitters can buy NZU from forestry companies or farmers to offset emissions. The price for units reflects supply and demand in the scheme. All sectors of New Zealand's economy, apart from agriculture, pay for their emissions through their ETS surrender obligations. The agriculture sector must report its emissions but does not have surrender obligations.

Currently, no major incentive exists for agricultural producers to reduce their emissions. The ETS was not seen as the right mechanism to price agricultural emissions.

Instead, Government, industry representatives and Māori formed the He Waka Eke Noa – Primary Sector Climate Action Partnership (the Partnership) to reduce agricultural emissions. It is committed to designing an on-farm pricing system that ensures New Zealand's agricultural products remain internationally competitive while reducing emissions.

10.3.4. Key Stakeholders

Key stakeholders involved in the research, technologies, programmes and policies include:

- Agricultural Greenhouse Gas Research Centre, Government-funded centre which invests and coordinates research for reductions of agricultural GHG.
- Crown Research Institutes, Crown-owned companies that carry out scientific research.
- Beef + Lamb New Zealand, a farmer-owned, industry organisation representing New Zealand's sheep and beef farmers.
- Dairy Companies Association of New Zealand, representing dairy manufacturing and exporting companies.
- Dairy NZ, industry organisation that represents all dairy farmers.
- Farmers.
- He Pou a Rangi – Climate Change Commission, an independent Crown entity that provides advice to government on climate issues
- Iwi Māori, tribal entities and largest social units in Māori society that represent a group of people and land area
- Māori Landowner groups, groups that represent Māori land that is governed and protected under specific statutes
- Meat Industry Association, voluntary trade association representing red meat processors, marketers and exporters
- Ministry for the Environment, New Zealand Government's primary adviser on environmental matters
- Pastoral Greenhouse Gas Research Consortium, provides knowledge and tools for farmers, to mitigate GHG
- Public
- Scientists and academics

10.3.5. Successes of research, technologies, programmes and policies

There are many successes in New Zealand for identifying emissions savings, policy drivers and behaviour change which would lead to improved breeding for reduced emissions.

- Full subscription of the Cool Sheep programme to use genetic selection to reduce GHG emissions highlights the keen interest in this programme from farmers

Research indicated that sheep can be bred to produce less methane without sacrificing productivity.

Within the proposal for emission pricing, there have been the following successes that are likely to help drive behaviour change to uptake methane emission reduction breeding selection:

- A farm level, split-gas levy gives farmers flexibility to determine the most efficient, cost-effective mitigation practices for their farms (Stakeholder comment, 2023).
- The He Waka Eke Noa partnership involved key stakeholders discussing practical solutions to reducing emissions (Stakeholder comment, 2023).
- While a policy for pricing agricultural emissions has not yet been legislated and implemented, discussions about a policy helped make New Zealand farmers more aware of their emissions and how to manage them.

10.3.6. Challenges of research, technologies, programmes and policies

There are some challenges with the New Zealand scenario that are relevant for identifying emissions savings, policy drivers and behaviour change which would lead to improved breeding for reduced emissions.

- The fully prescribed uptake of the Cool Sheep programme in 2023 may highlight potential challenges with sourcing enough infrastructure to support all farmers interested in the programme.

In particular, there are challenges related to the agriculture emissions pricing:

Mitigation options under proposed policies are more currently more suited to dairy farmers than sheep and beef farmers.
The sheep and beef sectors are expected to be impacted by the pricing of emissions more than other farming sectors. There are likely to be disproportionate impacts on Māori due to the large proportion of Māori ownership in the sheep and beef sectors and historical context.

Potentially ancillary challenges and unforeseen challenges from the proposal such as environmental and social challenges due to land use changes due to the need to reduce emissions i.e. increased planting of forest may lead to landscapes changes etc.

The recent change in Government has posed a challenge. The 2025 implementation target for implementing the pricing of emissions is expected to be pushed back until 2030 (Stakeholder comment, 2023) and uptake of other methane related programmes could waver too.

10.3.7. Relevance in Scotland

There are some key learnings from the New Zealand scenario that are relevant for identifying emissions savings, policy drivers and behaviour change which would lead to improved breeding for reduced emissions.

- At this stage, it is hard to determine exactly what has encouraged uptake of the Cool Sheep Programme and PAC measurements by sheep farmers. However it is assumed that discussions around agriculture emissions pricing and increased awareness, as well as financial assistance, has no doubt contributed to uptake.

- The He Waka Eke Noa partnership highlighted that each livestock sector has different requirements. In Scotland, for example, stakeholders interviewed for this project suggested that it may be difficult to introduce breeding practices in the sheep sector due to its extensive nature. In addition, there is less frequent cashflow in the sheep and beef sectors compared to dairy, making it more difficult to introduce new practices. In New Zealand suggestions have been made that the dairy industry has had a better lobbying influence in the development of the policy than the sheep and beef industry and have been more successful at influencing a policy that better suits their needs (Stakeholder comment, 2023). Therefore, any consultations or partnerships must include different livestock types and stakeholders, and consider the differences between upland or lowland systems.

New Zealand is one of the first countries in the world to attempt to price agriculture emissions therefore can provide a huge amount of learning that should be considered by Scotland in developing policy around methane reduction.

Having an emissions number to reduce from makes it easier to see how actions will impact. This will encourage the consideration of emission reductions as part of general on-farm decision making, on-farm investment decisions and other considerations.

- The policy impacts on certain farmers and Māori may be of relevance to island farmers and crofters with unique challenges, who may be disproportionately impacted by any climate policies in Scotland.
- Research from the NZAGRC and the PGgRc has produced schemes like the Cool Sheep Programme.
- The ram selection tool nProve provides a user-friendly platform for farmers to select the traits they want from a ram, including methane production. It gives farmers a tool to compare emissions between different animals before purchasing a ram, bull or semen. Because of the Cool Sheep programme and because there are planned policies to reduce emissions, there may be an incentive to use this metric. It may be possible to build on existing tools such as ScotEID and RamCompare in the future to create a similar platform (not only for sheep).

  A policy for pricing agricultural emissions has not yet been legislated and therefore whether it has/will contribute to reduced emissions is yet to be realised. However government modelling suggests that the levy could achieve sufficient emissions reductions to meet or exceed methane targets. Discussions about a policy helped make New Zealand farmers more aware of their emissions and how to manage them.

10.4 Appendix C: Canada dairy case study

10.4.1. Country information

Canada has similarities in climate and geography to Scotland. Agriculture is a key aspect of the Canadian economy with agriculture and the agri-food system generating $143.8 billion Canadian Dollars (CD$) (around 7%) of Canada's GDP. Canada is also the fifth-largest exporter of agri-food and seafood in the world. Dairy is a key part of the sector and is a top commodity in five of Canada's provinces/territories.

In 2020, agriculture was responsible for 30% of Canada's total methane emissions, with 86% of that being attributed to enteric fermentation. Canada has an emissions reduction target of 40% below 2005 levels by 2030 and to be net-zero by 2050 and joined the Global Methane Pledge. The advocacy group, Dairy Farmers of Canada, have voluntarily set a goal to reach net-zero by 2050.

10.4.2. Description of relevant research, programmes and technologies

Canada is undertaking research and programmes focused on breeding and new genomic technologies for reduced methane emissions in dairy production systems:

- The Efficient Dairy Genome Project (EDGP) developed genomic-based methods for selecting dairy cattle with reduced methane emissions and improved feed efficiency. The project was underpinned by an extensive database used for genomic analysis. For example, correlating MIR with reduced methane emissions. The project also recognised the necessity of featuring the economic, environmental and social benefits of selecting for reduced methane emissions.
- The Resilient Dairy Genome Project (RDGP) aims to integrate genomic approaches to improve dairy cattle resilience and industry sustainability. The project builds on the EDGP, with a focus on additional data collection, management and visualisation to support genomic analyses. Researchers noted an essential component is understanding the interaction between enteric methane emissions and specific farm conditions. For example, predicting methane emissions of individual animals and whole herds using milk MIR spectroscopy. By acknowledging the crucialness of collaboration with industry partners, the project will ensure results will render user-friendly products to enable technological uptake.
- An ongoing commercial endeavour between genetic evaluation provider, Lactanet Canada and genetics supplier, Semex Alliance aims to develop a reliable methane efficiency index that can be easily integrated with common selection indices such as fertility, disease resistance and lifetime profitability.

10.4.3. Description of key policies related to reducing methane emissions through breeding

There are currently no government policies legislating livestock breeding for reduced methane emissions in Canada, however there are some policies that are likely to eventually incentivise it.

- Agricultural Methane Reduction Challenge provided funding awarding up to $12 million CD$ to innovators designing practices, processes, and technologies to reduce enteric methane emissions.

10.4.4. Key Stakeholders

Key stakeholders involved in the research, technologies, programmes and policies include:

- Dairy Farmers of Canada, an advocacy group represent over 10,000 dairy farms, and have set a goal to reach net-zero by 2050
- National Farmers Union, representing Canadian farmers to achieve policy and reform
- Semex the world's largest provider of cattle genetics
- Genome Canada, a non-profit organisation funding EDGP and RDGP
- University of Guelph, and University of Alberta, orchestrate EDGP and RDGP

10.4.5. Successes of research, technologies, programmes and policies

There are many successes in the Canadian scenario that are relevant to identifying potential emissions savings, and in identifying policy drivers and behaviour change which would lead to improved breeding for reduced emissions.

- Researchers from the EDGP and RDGP recorded enteric methane emissions of reference populations predominantly via a GreenFeed system, a device measuring air composition exhaled by each cow during feeding. Exploiting the correlation between milk composition and emissions instigated the proposal of a genomic evaluation of methane efficiency without sacrificing other production traits. The projects demonstrated a 30% difference either side of average in enteric methane emissions between Holstein cows. This result highlights the importance of genetic selection if breeding for reduced methane emissions is to be an effective option.
- Public-Private Partnerships (PPP) between research and industry can be accredited for the establishment of Canada's major EDGP and RDGP, and were paramount in the development of the sophisticated database. Stakeholders Lactanet Canada and Semex Alliance effectively utilised this database, and in April 2023, Canada became the first country in the world to commercially market dairy semen containing methane efficiency as a relative breeding value (RBV). Their database and AI catalogue now includes 26 Holstein bulls with proven methane reduction capabilities, and a further 165 predicted. Semex Alliance also estimate widespread adoption of the low-methane trait could reduce methane emissions from Canada's dairy herd by 1.5% annually, and up to 20-30% by 2050. The collective effort of all members of the Canadian dairy industry has enabled significant progression, to which the inclusion of a methane efficiency genetic valuation can be traced to.
- A GHG Offset Credit System can incentivise farmers to undertake innovative projects that reduce GHGs for financial reward.

10.4.6. Challenges of research, technologies, programmes and policies

There are some challenges with the Canadian scenario that are relevant to identifying potential emissions savings, and in identifying policy drivers and behaviour change for improved breeding for reduced emissions.

- Scottish dairy farmers will likely question the validity of the two major Canadian research projects, as the methane efficiency RBV derives from controlled experimental environments. While this research does account for breed type, it does not reflect Scottish production systems including specific types of feed, pasture type and composition, etc, which may lead to lack of assurance. Furthermore, some Canadian dairy industry officials believe that cattle selected for reduced enteric CH_4 emissions may develop digestion problems, an allegation which generates considerable doubt of widespread adoption success.

10.4.7. **Relevance in Scotland**

There are some key learnings from the Canadian scenario that are relevant for Scotland in terms of identifying potential emissions savings, and in identifying policy drivers and behaviour change for improved breeding for reduced emissions.

- When compared to other livestock sectors, the data gathering process in the dairy industry is unique as daily milking and feeding activities provide a non-invasive opportunity to measure individual animals without major management changes. Coupling the simplistic nature of data collection with advanced existing genetic databases and the widespread use of artificial insemination (AI), the Scottish dairy industry is capable of reducing enteric methane emissions efficiently. Applying knowledge or making predictions from existing information has great potential to eliminate and/or significantly reduce cost, data collection periods and the requirement of on-farm experimentation.
- Genetic change is a simple and low-cost approach to reduce enteric methane emissions in dairy production systems. Owing to modern technologies and transport capabilities, the methane efficiency RBV developed in Canada is compatible with the Scottish dairy herd and can be purchased and administered via AI to help begin reducing enteric methane emissions.
- Canada has precedented instigating good working relationships with farmers, a goal achieved by highlighting the primary objective of research is to enhance industry sustainability. In response, many Canadian dairy farmers have also recognised constructive engagement with research and industry is fundamental. The establishment of a comprehensive and transparent database has provided assurance and confidence to adopt new best management practices.
- Scotland could consider monitoring the effectiveness of the Offset Credit System currently being considered in Ottawa to see if it incentivises behaviour change or changes finances and markets.
- Canada does not currently offer incentives for low-methane cattle breeding, and livestock breeders do not charge a premium for methane efficiency traits. However, discussions on this topic are ongoing between stakeholders and policy makers and it is looking likely a financial benefit will be introduced in the future.

10.5 Appendix D: Ireland beef case study

10.5.1. **Country information**

Ireland has a similar climate and geography to Scotland. Agriculture is key aspect of the Irish economy with the agriculture, forestry and fishing GDP valued at €3,672m in 2020. In 2020, 55% of farms were specialist beef, with many others including cattle as part of a mixed farm.

In 2022, agriculture was responsible for 38.4% of GHG emissions, making it the sector with the biggest share of emissions. 62.6% was caused by enteric fermentation.

Ireland is part of the Global Methane pledge and legally obliged as an EU Member State to reduce emissions under the EU's Effort Sharing Regulation, including in agriculture. Ireland's 2030 target is to deliver at least a 42% reduction by 2030 compared to 2005 levels.

Ireland has developed the Food Vision 2030 Strategy for the Irish agri-food sector which commits to reducing biogenic methane. This includes the 'Ag Climatise' Roadmap, covering animal breeding, with an aim to genotype the entire national herd by 2030 to develop and enhance dairy and beef breeding programmes.

10.5.2. Description of relevant research, programmes and technologies

The Irish Cattle Breeding Federation (ICBF) launched the National Genotyping Programme (NGP) for cattle in 2023. This offers beef and dairy farmers a low-cost option to collect DNA samples from calves at birth which can be used for genotyping to identify specific traits or characteristics. The aim of the programme is to achieve a fully genotyped herd in Ireland. This has made national genetic indexes available to farmers, including methane traits. It also allows farmers to optimise the health and productivity of their herd, reducing its emissions intensity. The ICBF also publish methane evaluations for AI sires that have had methane data recorded.

Teagasc has an important role in the research in Ireland. Animal breeding is one of the four solutions from Teagasc to reduce methane emissions from livestock. Current research projects include:

- GREENBREED: Measured methane at the Tully Progeny Test centre using a GreenFeed automated head chamber system. This research led to the publication of genomic evaluations for methane emissions in Irish beef cattle and sheep. It found notable differences in methane emissions from livestock being fed the same diet, 11% of these in cattle were found to be due to genetic differences. This indicates that breeding programmes to reduce methane will be effective in Ireland.
- Collaborative research by Teagasc and ICBF found a 30% difference in methane emissions from beef cattle of a similar size. This lead to the residual methane emissions (RME)[10] index being identified as a metric to rank animals.

10.5.3. Description of key policies

There is no legislation on livestock breeding for reduced methane emissions in Ireland, but the following policies related to GHGs may support this.

- The Beef Data and Genomics Programme (BDGP) paid suckler farmers to improve the genetic merit of their herd through data collection and genotyping, with the aim of lowering GHG emissions by improving quality and efficiency.

[10] RME is the difference between the expected methane emissions from an animal based on its size and feed intake, compared to what it actually produces. High RME is undesirable and low RME is desirable.

  - Payments were made of €142.50/ha for the first 6.66 ha and €120/ha for the remaining eligible hectares (the equivalent of €95 for the first 10 cows and €80 for the remaining cows), farmers have to undertake specific requirements.
  - These requirements include calf registration, detailed surveys of animal characteristics, genotyping and tissue tag sampling, and implementing a replacement strategy based on high genetic merit animals.
  - Additional support in the form of the carbon navigator decision making tool and training courses for farmers are also provided.
  - Participants of the programme were found to be achieving improvements at a faster rate compared to farms not taking part. The impact of the programme can help to promote smaller, more efficient suckler cows to produce more efficient beef.
- The Suckler Carbon Efficiency Programme**:**

As part of its Common Agriculture Policy Strategic Plan (CSP), Ireland developed ENVCLIM (70) 53SCEP as a follow-on from the BDGP, providing support to beef farmers who implement breeding actions that aim to lower the overall GHG emissions. The BDGP was shown to deliver on both environmental and productive efficiency and emissions per suckler cow are being reduced through breeding strategies. Another measure in the CSP, 53SCT, targets training to complement the Suckler Carbon Efficiency Programme.

10.5.4. **Key Stakeholders**

Key stakeholders involved in the research, technologies, programmes and policies include:

- Teagasc, Agriculture and Food Development Authority providing research, advisory and training to the agriculture and food industry and rural communities.
- Department of Agriculture, Food and the Marine, Irish government department leading, developing and regulating the agri-food sector, protecting public health and optimising social, economic and environmental benefits.
- Irish Cattle Breeding Federation (ICBF), non-profit organisation charged with providing cattle breeding information services.
- Irish Environmental Protection Agency, independent public body to protect, improve and restore the environment through regulation, scientific knowledge and working with others.
- Irish Farmers Association, Ireland's largest farming representative organisation.
- Farmers.
- Food Vision Sheep and Beef Group, group of stakeholders established by the Minister for Agriculture Food and the Marine to identify measures that the sector can take to contribute to reducing emissions from the agricultural sector

10.5.5. **Successes of research, technologies, programmes and policies**

There are many successes in the Irish scenario that are relevant to identifying potential emissions savings, and in identifying policy drivers and behaviour change which would lead to improved breeding for reduced emissions.

- The NGP is a useable database of genotyped methane information available for farmers to use. This is the result of comprehensive research programmes, collaboration between breed societies, and creating useful systems for farmers to benefit from. Making this data easily available to all farmers across Ireland can encourage behaviour change and is a successful programme that could be considered in Scotland. The creation of the ICBF has been essential for this, as it means there is one body overseeing all genotyping and data storage.
- The BDGP is an example of how payments to farmers can be used to gather data and reward farmers for adopting positive practices.
- Research from GREENBREED indicates that breeding programs to reduce methane emissions will be effective for selecting low-emitting livestock, especially combined with the national genomic evaluations, and will have no negative impact on performance and profitability.
- Ireland has produced methane evaluations to enable farmers to identify opportunities to reduce emissions and improve the sustainability of their enterprise.
- Overall, the authors did not find evidence of a quantifiable impact from introducing methane related actions and policies. This may be because the relevant research, programmes and technologies as mentioned above are still relatively new and it is too early to quantify. For example, the NGP is to only be completed by 2027, whereas following on from data collected from methane evaluations, methods are still being developed on how best to incorporate methane traits into beef and dairy production.

10.5.6. Challenges of research, technologies, programmes and policies

Additional research would be required to understand how the policies and programmes were received by farmers and how successful the agricultural community views them to be. We contacted Ireland representatives for involvement in stakeholder interviews however we did not get a response.

10.5.7. Relevance to Scotland

There are some key learnings from Ireland that are relevant for Scotland in terms of identifying potential emissions savings, and in identifying policy drivers and behaviour change for improved breeding for reduced emissions.

- A national database was suggested by Scottish stakeholders (Stakeholder comment, 2023). Therefore, Ireland's NGP provides an example for Scotland if this was to develop. In particular:
- The use of metrics like Residual methane emissions (RME) index and predicted transmitting ability (PTA) could give Scottish farmers and crofters an easy way of comparing their livestock to other farmers and understanding where they are compared to the average.
- Challenges in the Scottish context could include reluctance on the part of different breed societies to pool data.
- Ireland have shown that emissions for cattle can be reduced through appropriate breeding strategies and incentives for farmers. Such as subsidising DNA sampling of calves which helps to genotype the national herd.

- The creation of the Food Vision Beef and Sheep Group to chart a path for the sector to meet the emissions emission targets is a potential model for ways that Scotland might bring key stakeholders into the development of key policies to reduce emissions.
- The main ways behaviour change has been encouraged is by making the programmes and policies mentioned above easy to access, for example, the ICBF also provides information to help farmers make decisions about their herd through HerdPlus.
- The BDGP and CSP provides training to farmers who are using the scheme, for which funding is provided.

10.6 Appendix E: Methodology and results for the quantification of potential emission savings

Methane emission savings are achievable through breeding and new genomic technologies. The main sources of methane from cattle and sheep in Scotland are enteric fermentation and managed manures. We have chosen to focus our calculations on emissions from enteric fermentation for two reasons:

1. Methane emissions from managed manures are much smaller.
2. Changes to livestock by selecting traits which lead to lower methane emissions will have a greater impact on the emissions from enteric fermentation rather than the emissions produced from livestock manures.

To align with the CCP's targets, of achieving net zero in Scotland by 2045 and a 75% reduction in emissions by 2030, we present data for potential emission reductions for 2030 and 2045. The following data were used to quantify the potential emission savings:

- **Key traits** leading to reduced methane emissions, from the REA.
- **Methane reduction values** associated with traits, from the REA.
- *Note: A particular challenge was identifying emission reduction values that were associated with specific traits, that we could use in our calculations. We have used the data available to draw conclusions.*
- **Baseline emissions data** for Scotland from the National Atmospheric Emissions Inventory (NAEI, 2023).
- **Uptake values (sector specific)** for adoption of chosen traits through breeding, based on findings in the REA, stakeholder interviews and expert judgement.

10.6.1. Baseline methane emissions

To calculate the baseline methane emissions for dairy, beef and sheep, the enteric fermentation emissions of the livestock types for Scotland in 2021 were extracted from the NAEI (2023)[11].

[11] © Crown 2024 copyright Defra & BEIS via naei.beis.gov.uk, licenced under the Open Government Licence (OGL).

10.6.2. **Current uptake rate for adoption of traits**

The current uptake rate is an estimated current baseline based on evidence gathered in the REA review of evidence and technical knowledge. This provides a baseline for additional uptake under the scenarios presented below.

Current uptake is set at 75% for dairy cattle, due to the high usage of reproductive technologies (see Section 4.1.3), in particular use of sexed semen and artificial insemination (AI) using Holstein Friesian semen, a key breed which already has proven methane efficiency ratings published as part of the breeding profile. It is understood that methane efficiency ratings are also being developed for other key dairy breeds as observed on UK dairy and beef cattle semen sales websites.

Beef cattle uptake has been set at a 40% baseline as findings show that methane efficiency ratings are less regularly published as part of the beef breed profile on UK semen sales websites. However, artificial insemination of beef cattle is relatively common, although it is not a standard practice as in the dairy industry. It is understood adoption of breeding for reduced emissions is developing and evidence is being gathered (see Section 4).

The current baseline for sheep has been set at 10% based on a comparison with New Zealand where there is an uptake rate of 30% (Rowe et al. in 2020). Following discussions with Scottish Government it is acknowledged that there is some technology usage around the world, but that adoption in Scotland is not yet as high as in New Zealand. Therefore, 10% has been chosen as the baseline. This links to understanding of technology uptake in Section 4.

10.6.3. **Scenarios**

The quantification of emissions savings was based on four different scenarios to reflect various levels of uptake:

- The **no intervention scenario** reflects an increase in uptake of 5% from the current baseline by 2030 and remains at the same level until 2045 for all livestock types.
- The **voluntary uptake scenario** is designed to reflect levels of uptake expected with no other push such as a financial incentive or a relevant policy. This scenario reflects a 5% increase in uptake from the current baseline by 2030, and an additional 5% increase in uptake by 2045 for all livestock types.
- The **supplier demand scenario** is based on companies along the supply chain offering financial incentives to farmers that implement breeding techniques to reduce methane emissions. This value is set at a mid-point between the voluntary uptake and the regulatory scenario.
- The **policy changes scenario** represents the uptake where legislation has been introduced that will require farmers to introduce methane reducing breeding techniques to their herds. This scenario reflects a 10% increase in uptake from the current baseline by 2030. By 2045 it is assumed there would be 100% uptake for dairy cattle due to the large-scale usage of AI within the industry and progress seen on methane efficiency profiling already published within the key breed profile. It is assumed that beef cattle

could reach 80% uptake by 2045, and sheep could reach a 60% uptake by 2045 under a regulatory scenario.

Scenario uptake values are presented for dairy, beef and sheep in Table 17.

Table 16. Scenario implementation values for dairy, beef and sheep

Type	Scenario	Current baseline	Change from current baseline to 2030	2030 uptake	Change from current baseline to 2045	2045 uptake
Dairy	1. No intervention	75%	5%	80%	5%	80%
	2. Voluntary uptake	75%	5%	80%	10%	85%
	3. Supplier demand	75%	7.5%	82.5%	17.5%	92.5%
	4. Policy changes	75%	10%	85%	25%	100%
Beef	1. No intervention	40%	5%	45%	5%	45%
	2. Voluntary uptake	40%	5%	45%	10%	50%
	3. Supplier demand	40%	7.5%	47.5%	25%	65%
	4. Policy changes	40%	10%	50%	40%	80%
Sheep	1. No intervention	10%	5%	15%	5%	15%
	2. Voluntary uptake	10%	5%	15%	10%	20%
	3. Supplier demand	10%	7.5%	17.5%	30%	40%
	4. Policy changes	10%	10%	20%	50%	60%

10.6.4. **Traits**

Traits and technologies with a possible relationship with methane emissions and emission reductions were identified through a REA of relevant literature (see Section 4).

Traits identified were further reviewed to assess their applicability to emission reduction calculations. When assessing each trait to quantify the emissions savings, appropriate values were found to be scarce in the literature. There were two key reasons that led to studies and/or traits being excluded from use in this task:

1. A significant portion of the literature did not present methane emission values and was instead looking at genetic correlations between traits. Therefore, literature that did not present methane emission values or change in methane emissions, either as absolute or relative values, were excluded.
2. Often the changes in methane emission were comparative to a baseline that was not appropriate for our calculations focusing on methane emission from enteric fermentation. For example, papers excluded in our review presented changes to emissions from the entire lifecycle or system.

A summary of the traits, where appropriate values were obtained, are presented in Table 17 below.

Table 17. Traits identified with appropriate methane reduction values used in the calculations of emissions savings

Sector	Trait Category	Trait Name	Unit of baseline	Value of methane reduction from baseline
Beef	Production	Feed efficiency	kg CO_2e/kg product	7%
		Offspring carcass weight	kgCO_2e/per kg meat per breeding cow per year	1.3%
	Climate	Methane yield	gCH4/kgDMI per generation	12%
Dairy	Production	Feed efficiency	kg CO_2e/kg product	5%
		Milk fat + protein	MJ CH4/kg milk	12%
		Milk yield	kg CH4/kg milk	15%
	Climate	Methane intensity	kg CH4/kg milk	24%
Sheep	Production	Feed efficiency	kg CO_2e/kg product	7%
	Climate	Methane yield	g CH4/kg DMI	35%

Feed efficiency

References: (Alford, A.R. et al. 2006; Worden, D. et al. 2020; Rowe, S.J. et al. 2021)
The ability of animals to optimally convert feed into liveweight with minimal losses of energy, meaning that animals with high feed efficiency consume less than their peers with equivalent liveweight and weight gain. This trait was identified across all three livestock types and has been highlighted by the stakeholders and the literature as a key trait for emission reductions (see Section 4).

Methane focused climate traits

References: (Quinton, C.D. et al. 2018; De Haas, Y. et al. 2021; Jonker, A. et al. 2018)
Methane traits are likely to have the greatest impact on methane emissions. Here the methane related traits were focused on manipulating the gut microbiome and selecting for animals with certain microbial populations that led to lower methane emissions. While methane traits were identified for all three livestock types, they were presented differently across the literature.

Offspring carcass weight – Specific to beef cattle

References: (Martínez-Álvaro, M. et al., 2022)
Focus on offspring carcass weight in beef cattle reduces methane emissions through increased quantity of product per animal, therefore reducing the number of animals required to produce the same amount of beef product.

Milk yield and Milk fat and protein – Specific to dairy cattle

References: (Bell, M.J. et al. 2010)
Traits reduce methane emissions per kg of milk while maintaining production levels and quality.

10.6.5. **Emissions reduction**

To calculate the emission reduction of different traits under the different scenarios the following formula is used:

$$E_S = E_b - (E_b \times U_y \times E_r)$$

Where:

E_S = Emissions savings (kt CH_4 for the livestock type)
E_b = Baseline emissions (kt CH_4 for the livestock type)
U_y = Uptake (U) for the projected year (y)
E_r = Emission reduction coefficient (%)

This formula calculates a percentage of emissions based on emissions reduction potential and uptake rate and subtracts this portion from baseline emissions. The result is an estimate of methane emissions if the reduction potential and uptake for the trait is achieved. The savings were then calculated by subtracting the estimated emissions from the baseline emissions, and both were calculated in units of percentage of baseline and absolute values (kt CO_2e). This calculation was completed for each trait found in beef, dairy, and sheep sectors, for the years 2030 and 2045.

Limitations in the data:

- All traits have been presented separately as the interaction between traits and the impact this would have on emission reductions is unknown.
- It is acknowledged that traits found within the literature are presented in different units (see Table 7). Traits selected from the literature also presented a percentage change which was used within the change calculations. The percentage change has been applied to total emissions from the relevant livestock sector due to limited data on specific emissions related to more specific production categories such as CH4 emissions per kg milk produced.
- Methane efficiency focused traits have shown to have the greatest methane reduction potential for all three livestock types. However, it is noted that there was less literature available on this subject compared to feed efficiency. Due to the smaller quantity of literature available the reduction potential values selected for methane efficiency could be less robust. Greater consistency in measurement, modelling, and presentation of methane efficiency traits and their impacts on emissions savings and animal performance production could be useful research to fill this knowledge gap.
- Traits reduction factors compiled within the review were presented in different units, however, all presented a percentage reduction. It has been assumed that the percentage reduction would be applicable to be used as a reduction factor as this would have a direct impact on methane reductions independent of the unit the factor was recorded in.

- Limited data was provided within the literature reviewed on the length of time until each trait reaches maximum potential within the population. However, it is assumed that once the trait has been bred into the total population there will be no additional improvements unless new breeding traits are selected. Within the calculations we have assumed that traits will account for their maximum potential to the selected population at the assessment point (i.e., in 2030 100% of the trait will apply to the current baseline uptake with the additional percentage uptake).
- There is the possibility that, due to the nature of genetics, when selecting for certain traits, that they will not fully spread throughout the entire population where the trait is applied. This is a complicated process, and it has been assumed that at each assessment point (2030 and 2045) each trait has reached maximum spread in the portion of the population that has taken up the measure (i.e., in 2030 100% of the trait will apply to the current baseline uptake with the additional percentage uptake).

10.6.6. **Results**

Figures 4-7 show that in each sector, up to 2030, the reductions are relatively steady, but there is a greater reduction at 2045, influenced by the proposed increase in uptake. Due to the proposed uptake percentages the policy change scenario presents the greatest reduction under all traits, with the no intervention scenario showing the smallest reduction due to a 5% increase in uptake in 2030 and no further uptake in 2045.

Figure 4 presents the methane emissions under the four scenarios for the three traits selected for beef cattle: feed efficiency, offspring carcass weight and methane production. The methane production focused trait has the largest emission reduction (reduction of 161.1 kt CO2e in 2045 under the policy changes scenario), whereas the offspring carcass weight focused trait has the smallest impact at less than 12.4 kt CO2e reduced by 2045 under the maximum reduction scenario.

In correlation with beef trait reductions, methane intensity traits have the largest reduction to methane emissions in dairy cattle, with a reduction of 35.4 kt CO2e observed under the policy change scenario by 2045, as presented in Figure 5. While breeding for methane reductions through feed efficiency has the least change at 7.4 kt CO2e reduced by 2045, this could be due to the work already completed on feed efficiency breeding within dairy. Traits focused on milk fat and protein and milk yield provide similar reduction level levels, however there is the potential for overlapping improvements with feed efficiency as breeding focused on improvements to milk production traits could also link to improvements to feed efficiency.

Reduction potential for sheep is presented in Figure 6 for the two selected traits: feed efficiency and methane yield. As with the cattle categories, the trait focused on methane improvements (methane yield) had the largest potential reduction at 185.6 kt CO2e reduced by 2045 under the policy change scenario, whilst feed efficiency traits saw a smaller reduction of 37.1 kt CO2e by 2045 under the policy change scenario.

Figure 4. Methane emissions for beef cattle traits against the 2021 baseline enteric methane emissions of beef cattle in Scotland. Please note the y-axes do not start at zero to allow for greater visibility of results.

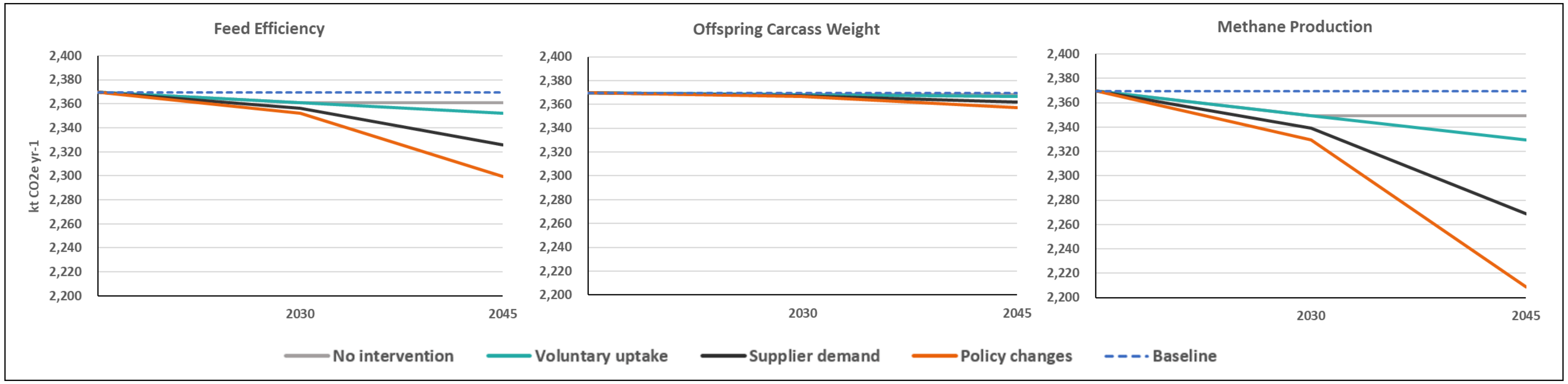


Figure 5. Methane emissions for dairy traits against the 2021 baseline enteric emissions of dairy cattle in Scotland. Please note the y-axes do not start at zero to allow for greater visibility of results.

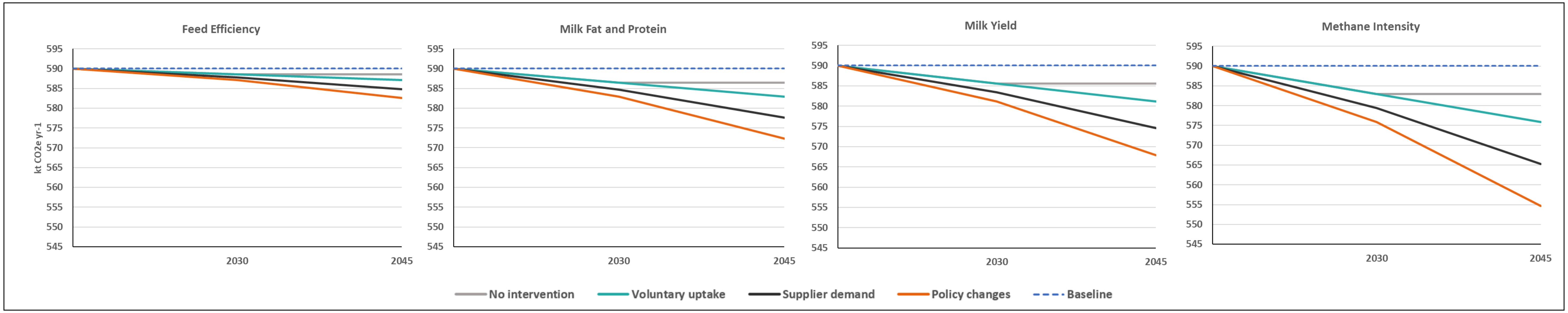


Figure 6. Methane emissions for sheep traits against the 2021 baseline enteric emissions of sheep in Scotland. Please note the y-axes do not start at zero to allow for greater visibility of results.

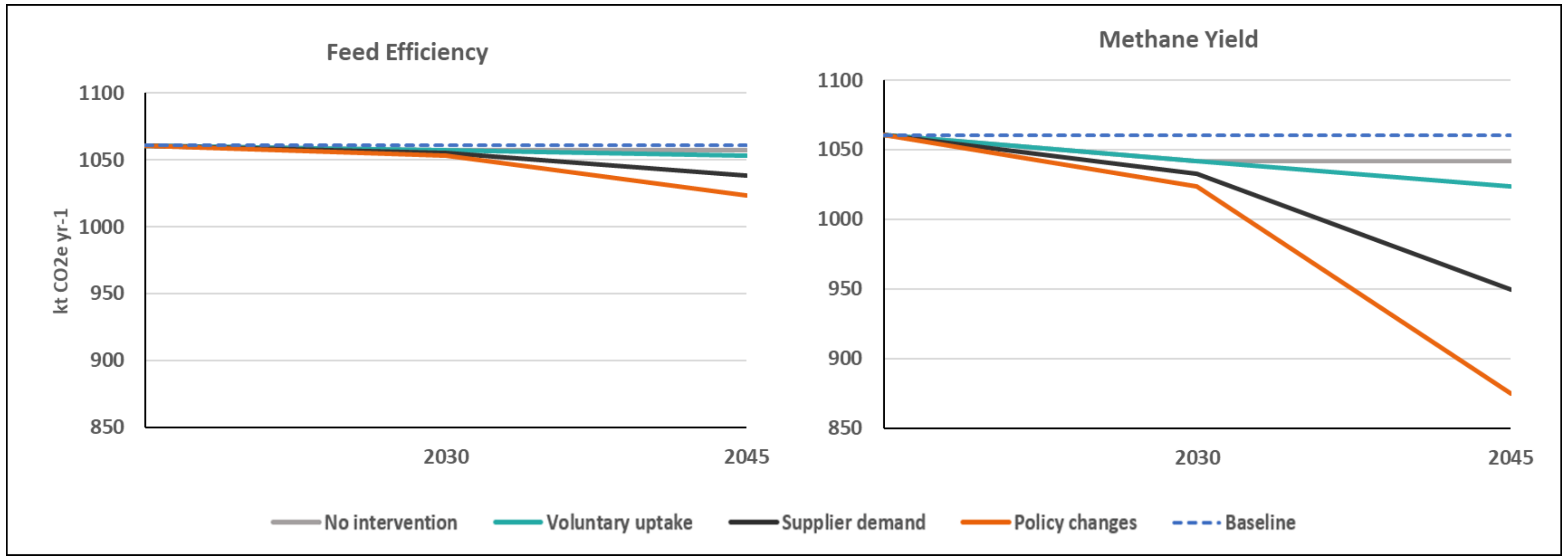
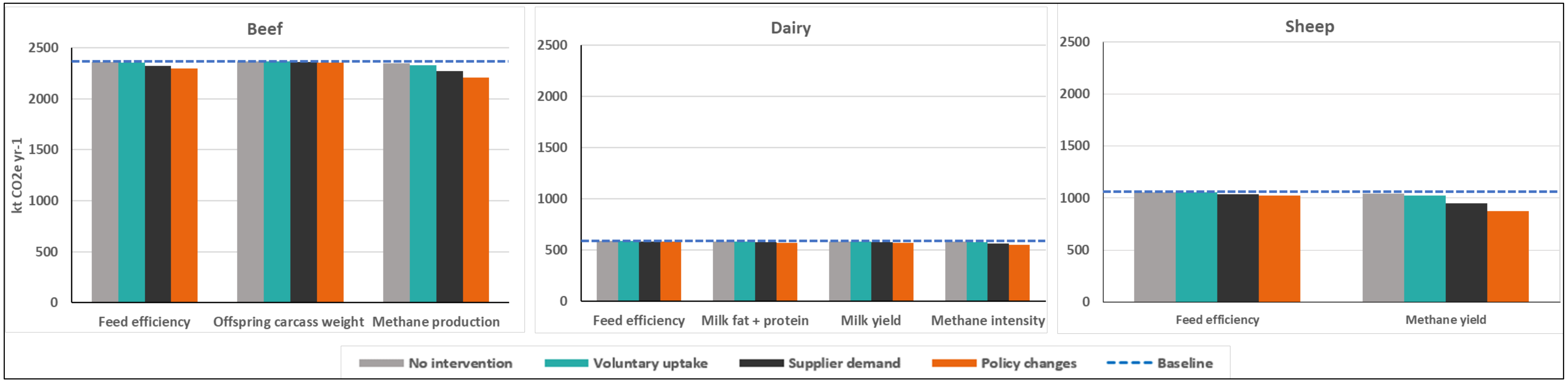


Figure 7 presents the methane emissions by 2045 under all scenarios for all traits for each livestock type. The difference in total enteric fermentation emissions for each livestock type can be seen by the dotted baseline line. Beef cattle emitted the majority of the methane from enteric fermentation in Scotland in 2021, with sheep emissions being less than half those of beef cattle, and dairy under a quarter those of beef cattle.

Figure 7. Methane emissions for all livestock for all traits presented against baseline enteric emissions of beef, dairy and sheep in Scotland.



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