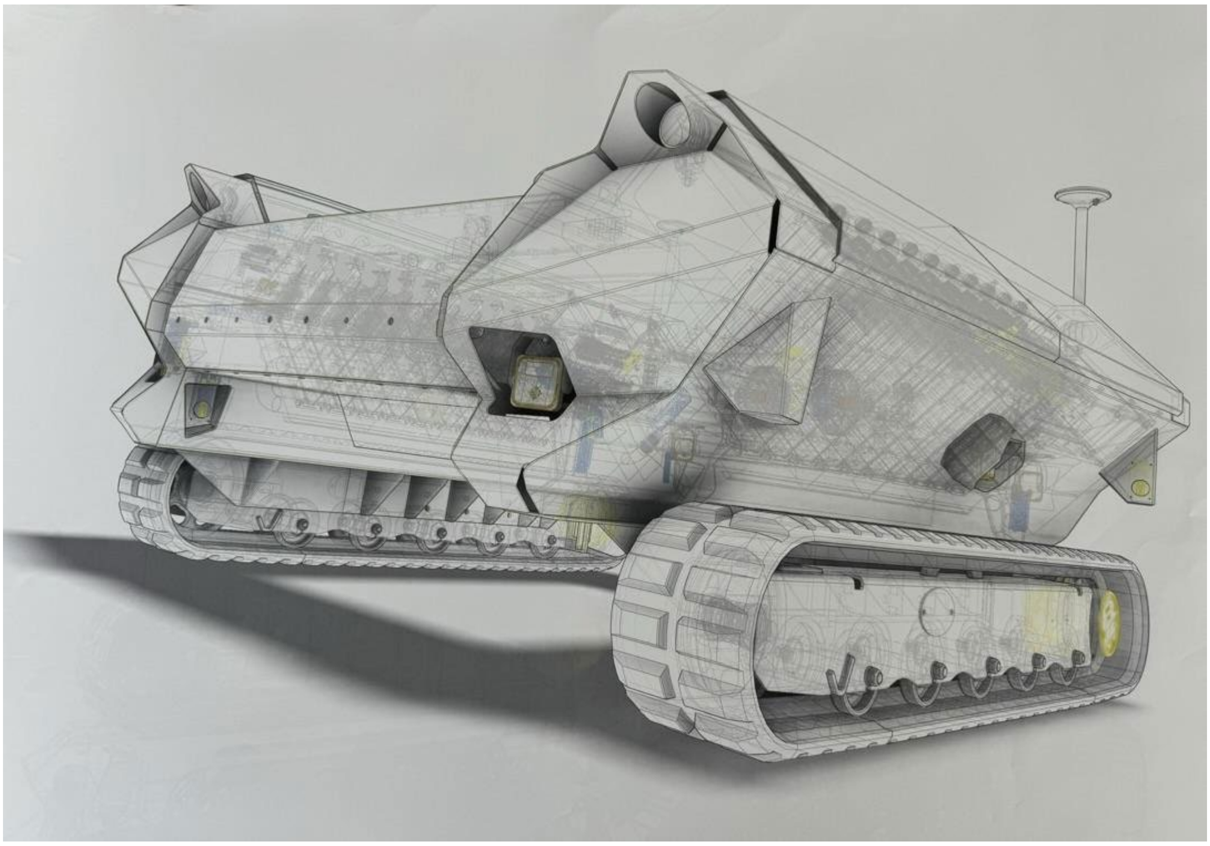
UPSCALING UK SRC WILLOW PLANTING AND HARVESTING CAPACITY:

NET ZERO WILLOW (RIC-293-1)

Final Report Phase 2



Prepared for: DESNZ Biomass Feedstocks Innovation Competition

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Date: 02/06/2025

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Acronyms

AI	Artificial Intelligence
ATRBV	All Terrain Robotic Base Vehicle
BFI	Biomass Feedstock Innovation Program
CAD	Computer Aided Design
CTP	Controlled Traffic Farming
GPS	Global Positioning System
Ha	Hectare
HVO	Hydrotreated Vegetable Oil
IP	Intellectual Property
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LiDAR	Light Detection and Ranging
LPG	Liquid Petroleum Gas
m^3	Cubic metres
MGT	Million Green Tonnes
NZW	Net Zero Willow
ODT	Oven Dried Ton
PES	Payment for Ecosystem Services
R&D	Research and Development
RHA	Rod Harvesting Attachment
RPA	Rod Planting Attachment
SFI	Sustainable Farm Initiative
SHL	System Hydraulics Ltd
SRC	Short Rotational Coppice
THBUS	Tracked Harvester and Bunker Unloading System
TRL	Technology Readiness Level
UK	United Kingdom
UKCA	United Kingdom Conformity Assessment
WRME	Wood Raw Material Equivalent

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Net Zero Willow Executive Summary

The Net Zero Willow (NZW) project, backed by the UK government's £36 million Biomass Feedstocks Innovation Programme (BFI) within the broader £1 billion Net Zero Innovation Portfolio (NZIP), aimed to revolutionise the UK's Short Rotation Coppice (SRC) willow sector. By developing innovative tracked and robotic technologies for automated planting and harvesting, NZW is crucial for supporting the UK's commitment to achieving net-zero emissions by 2050, directly contributing to the BFI's objective of increasing the UK's sustainable biomass supply. Automating these labour-intensive processes will enhance biomass production's economic viability, support a shift to a low-carbon energy system, boost domestic energy and biomaterial feedstock security, and bolster rural economies by creating new jobs. The project's success has the potential to significantly impact the UK's biomass sector and broader climate change mitigation efforts

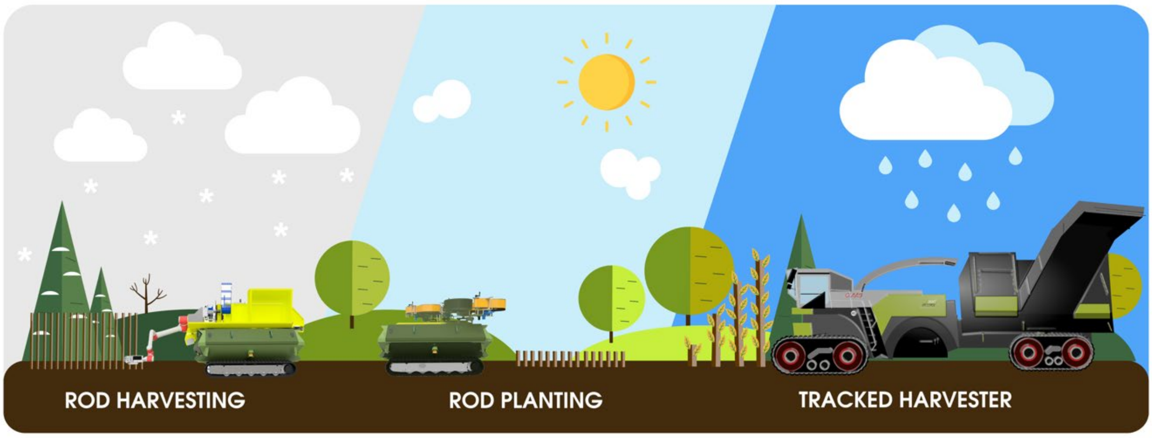

Figure 1: Illustration of the automated willow cultivation system: rod harvester, rod planter and tracked harvester.

Project Goals:

The project had the following goals:

- Increase willow production: develop technologies to significantly increase SRC willow planting and biomass yield.
- Improve efficiency and reduce costs: design and build state-of-the-art machinery that optimises efficiency and lowers production costs.
- Enhance sustainability: promote environmentally friendly practices by reducing greenhouse gas (GHG) emissions and improving land management.
- Strengthen indigenous supply chain resilience: Increase domestic biomass production and reduce dependence on imports.

Key Innovations:

The project involved the following innovations

- All Terrain Robotic Base Vehicle (ATRBV): A lightweight, autonomous, tracked platform designed to replace traditional tractors. The ATRBV can operate autonomously, navigate challenging terrains, minimise soil compaction and act as the base vehicle and power supply for a number of components with bespoke functions.
- Rod Harvesting Attachment (RHA): Automates the labour-intensive process of willow rod production for willow planting material. The RHA scans, cuts, and bales willow rods, maximising material utilisation and reducing costs.
- Rod Planting Attachment (RPA): Addresses the challenges of traditional planting methods by using robotic technology for precise planting of individual willow cuttings.
- Tracked Harvester and Bunker Unloading System (THBUS): Aims to maximise the willow harvesting season, reduce soil compaction and improve efficiency. This unloading system enables efficient chip transfer into storage areas or transport vehicles.

An additional innovation to produce a custom cutting drum for a modified forage harvester designed specifically for chipping SRC willow was aborted due to budget constraints.

Key Performance Indicators:

With all four innovations the aim was to improve on the current situation by maximising transformational gains. In summary, these are as follows:

Innovation	KPI	% improvement
ATRBV + RHA	Hectares of planting rods produced per 1 hectare multiplication bed	50% increase
ATRBV + RHA	Total cost of production of 1 hectare of plant material (15,000 20cm willow cuttings)	20% reduction
ATRBV + RPA	Cost of energy per hectare planted	91% reduction
ATRBV + RPA	Machinery weight	81% reduction
ATRBV + RPA	Establishment strike rate	10% increase
ATRBV + RPA	Overall cost to plant 1 hectare of willow (15,000 20cm cuttings)	57.5% reduction
THBUS	Harvesting cost per green tonne	13% reduction
THBUS	Minimum number of machines required to harvest willow	75% reduction
THBUS	Diesel required to harvest 1 green tonne of willow chip	30% reduction
THBUS	Potential amount of willow chips harvested per season	62.5% increase

THBUS	Area of willow harvested per season	62.5% increase

A Life Cycle Analysis (LCA) was conducted on the NZW innovations compared to current machinery. This suggests that for each green tonne of SRC willow biomass produced using the new innovations there would be a saving of 2.97 kg of CO_2 equivalent from current levels of 12.62 kg of CO_2 this represents a 23% reduction.

Commercialisation:

Our next steps focus on validating, and positioning the technologies for broad adoption within and beyond the UK SRC willow sector.

Short-Term Actions (2025–2028):

- Refine and validate innovations (ATRBV, RHA, RPA, THBUS) through long-term, on-farm trials in varied soil and weather conditions.
- Support commercial readiness by delivering on-farm demonstrations of ATRBV, RHA, RPA and THBUS to showcase performance, gather user feedback, and build grower confidence—alongside developing training resources and refinement plans based on real-world operator experience.
- Deploy innovations within our own operations to reduce costs, boost productivity, and improve consistency across willow planting and harvesting cycles.
- Engage existing biomass users (pyrolysis, gasification and power producers) to demonstrate cost and carbon savings.
- Explore cross-sector applications, including cassava cultivation (e.g. Ghana, Brazil) and Controlled Traffic Farming (CTF) with maize, silage, and whole crop cereals.

Mid-Term Actions (2028–2030+):

- Scale deployment across the UK, targeting a commercial footprint of 10,000+ hectares, supported by regional demonstration days and leasing/partnership models.
- Diversify into higher-value willow applications, including composts, cosmetics, pharmaceuticals, and agroforestry systems.
- Leverage growing market interest and evolving environmental policy (e.g. Biomass Strategy, Land Use Framework) to attract investment and secure funding routes.

1 Project Background

1.1 Company background

Rickerby Estates Ltd is a family-run business that established Willow Energy in 2013 to specialise in the cultivation and harvesting of Short Rotation Coppice (SRC) willow. Driven by a passion for sustainable agriculture and renewable energy, the company has cultivated and manages over 800 hectares of willow across the UK, gaining valuable expertise in all aspects of willow production.

With a dedicated team of three full-time staff and up to 10 subcontractors, Willow Energy has developed efficient operational practices, focusing on optimising growing conditions, harvesting techniques, and post-harvest processing methods. The company has consistently prioritised innovation and sustainability, embracing technology and environmentally friendly practices to enhance productivity and minimise environmental impact.

The UK has set ambitious climate change targets that necessitate a significant increase in the planting of perennial biomass crops. This presents both a challenge and an opportunity for Willow Energy to contribute to the nation's renewable energy and net zero goals.

Willow Energy aims to play a pivotal role in scaling up the UK's willow biomass production by expanding its operations, collaborating with industry partners, and exploring new markets. By implementing groundbreaking technologies, the company seeks to revolutionise the SRC willow cultivation industry, paving the way for a more efficient, sustainable and cost-effective future.

1.2 The challenge

Traditional methods of SRC willow cultivation present significant hurdles to achieving the UK's renewable energy and net zero targets. These methods rely heavily on manual labour, making them vulnerable to labour shortages and increasing costs. Furthermore, they are often hampered by unfavourable weather conditions such as excessive rainfall, which can significantly limit operational windows for planting and harvesting.

Recognising these limitations, Willow Energy identified critical bottlenecks within the existing system:

- The manual processes involved in willow rod production, including cutting and planting, are time-consuming, labour-intensive, and unsustainable for large-scale operations. This reliance on manual labour increases costs and can hinder the scalability of willow cultivation.
- Wet weather conditions severely restrict the operational window for traditional harvesting equipment, impacting productivity and increasing the risk of soil compaction.

To overcome these challenges, Willow Energy sought to develop innovative solutions that would enhance efficiency, reduce reliance on manual labour, and minimise environmental impact. This involved exploring advancements in automation and robotics to streamline critical stages of the willow cultivation process, from rod production to planting and harvesting.

2 Project Overview

This project focuses on the design and development of robotic and tracked solutions for the cultivation and harvesting of SRC willow. By recognising the limitations of traditional, labour-intensive procedures in SRC willow production, this project aims to enhance efficiency and minimise environmental impact through the implementation of advanced technologies.

2.1 Aims of the project

The project has the following aims:

- To transform the production capabilities of SRC willow biomass in the United Kingdom.
- Through the application of cutting-edge robotic and tracked technology, to address the critical challenges preventing the successful scaling of SRC willow industry.
- Significantly increase the SRC willow planting area and biomass yield while optimising efficiency and cutting costs.
- Increase the production of SRC willow in a more sustainable and environmentally friendly manner.
- Support the UK's transition to a carbon-neutral economy.

2.2 Project plan and objectives

The project deliverables and financial information are detailed in Annex 1. The project has the following objectives:

- Design and market state-of-the-art machinery to enhance the efficiency and sustainability of SRC willow production.
- Create innovative machinery that reduces reliance on labour-intensive and high-maintenance equipment, thus enabling the expansion of the willow industry and ensuring its future scalability.
- Improve the economic viability of SRC willow by reducing costs and increasing yields.
- Enhance the sustainability of the SRC willow industry by reducing lifecycle GHG emissions and improving land management practices.
- Stimulate rural economies and create new employment opportunities through the growth of the SRC willow industry.
- Strengthen UK energy and resource resilience by expanding domestic biomass production.

3 Technical Requirements

3.1 Project overview

The project focused on developing innovative technologies and practices to enhance the efficiency, reduce costs, and improve the environmental sustainability of SRC willow cultivation. The project aimed to be an integral part of the scaling up UK biomass crops production by reducing the restrictions on field-based activities imposed by the UKs maritime climate and reliance on manual labour. By achieving this the project would remove two of the major obstacles holding back the biomass crops sector.

The project centred around four key innovations:

- All Terrain Robotic Base Vehicle (ATRBV): A lightweight, autonomous, tracked platform designed to replace traditional tractors. The ATRBV can operate autonomously, navigate challenging terrains, and act as the base vehicle and power supply for a number of components with bespoke functions.
- Rod Harvesting Attachment (RHA): Automates the labour-intensive process of willow rod production for planting material. The RHA scans, cuts, and bales willow rods. This will maximise material utilisation and reduce costs.
- Rod Planting Attachment (RPA): Tackles the labour-intensive and inconsistent nature of manual willow planting by using robotic technology to plant individual 20 cm cuttings with precision. Initial field testing suggests it can reduce planting costs by up to 57.5%, while improving strike rates and enabling establishment in wet or compacted soils.
- Tracked Harvester and Bunker Unloading System (THBUS): Aims to extend the willow harvesting season, reduce soil compaction, and improve efficiency. This unloading system enables efficient chip transfer into storage areas or transport vehicles.

3.2 Prototype & iterated prototype creation process

All of the innovations followed a similar development path, beginning with computer-aided design and testing. Once the design team was satisfied, the innovations progressed to prototype development. The initial prototypes were tested to gather valuable insights and inform the development of iterated prototypes, which aimed to be as close to a commercial product as possible. Extensive real-world testing has been carried out. Further testing will continue beyond the phase 2 funding.

The development of the prototype began with creating a design using computer-aided design (CAD) software. This allowed our engineers to visualise and test the design in a virtual environment before proceeding to physical construction. Once the project team was satisfied with the performance of the design in the computer simulation, the drawings were approved for physical fabrication.

The innovations were built using laser-cut steel components, which were designed and procured using CAD software. This modular design allowed for easy replication by simply uploading the component drawings to a plasma cutter. After all the components were secured, the mechanical assembly of components and materials commenced.

The installation of the electrical control system was instigated once the mechanical assembly safety sign-off was complete. Following this, the entire electrical control system underwent pre-commissioning testing and programming in a controlled workshop environment. Once the project team was satisfied with the results, field commissioning and software testing began.

Once all field testing of the innovations was complete, the team focused on developing a new design iteration based on the learnings from the prototype testing phase. The revised design aimed to create a product that would be as close to the final commercialised version as possible by the project's conclusion.

3.3 All-Terrain Robotic Base Vehicle (ATRBV) innovation overview

The ATRBV innovation is designed to replace traditional tractors, offering a lightweight, tracked platform that can operate autonomously and safely. Equipped with a safety system, it can power other implements like the RHA and RPA. The vehicle can access land in challenging conditions, including wet areas where traditional tractors struggle.

3.3.1 ATRBV initial design requirements

The ATRBV was designed, constructed and tested by Systems Hydraulics in Cumbria. The conceptualised design of the ATRBV included the following requirements:

- Size and Weight: The vehicle was designed to be approximately 1,200 kilograms in weight, 2.1m wide and 2.1m long in order to ensure manoeuvrability and reduce soil compaction.
- Tracked Design: The tracked design would enable superior traction and stability, allowing the vehicle to operate in all terrains, including wet and muddy conditions and potentially expanding the operational window for SRC willow production by 4-8 weeks.
- Semi-Autonomous Operation: The vehicle is designed to operate in a semi-autonomous mode, allowing for human supervision and intervention while automating routine tasks. This approach would combine the benefits of autonomous operation, such as increased efficiency and reduced labour costs, with the flexibility and oversight of human operators to control multiple robots at once.
- Safety Systems: A comprehensive suite of safety systems would be incorporated, including obstacle detection, collision avoidance, and emergency stop mechanisms.
- Power Source: An efficient, low carbon energy source would be utilised. Initially a Liquid Petroleum Gas (LPG) driven system was considered but the final design included an electric battery low-carbon power source to better align with sustainability goals.
- Satellite Navigation and Tracking: A satellite navigation and tracking system would be integrated to enable precise positioning and monitoring of the vehicle.

3.3.2 ATRBV testing & evaluation of the prototype

The initial testing and evaluation of the ATRBV prototype was conducted in a controlled workshop environment. These tests were successful, leading the team to feel confident about taking the prototype into the field. Field testing involved operating the innovation in various conditions, starting on a flat, dry field. As the team gained confidence, they progressed to rougher terrain, including deeper ruts, water, and mud. The ATRBV proved to be highly capable, with minimal issues encountered even in the most challenging environments.

Once the field testing was complete, the project team analysed the collected data and findings. It was determined that the innovation should have increased ground clearance to prevent debris from getting caught underneath the vehicle. Additionally, mud was accumulating between the chassis and the track system. Furthermore, the energy consumption was considered quite high, and the forward speed was relatively low.

It was determined that the LiDAR safety system was insufficient for navigating dense SRC willow plantations, as it could not see through the vegetation. The project team recognised that a camera system alone would not be enough to ensure complete safety. Therefore, they focused on developing solutions to address these limitations.

3.3.3 Improvements to the ATRBV iterated prototype

The iterated prototype incorporates the following improvements:

- Increased ground clearance: The chassis was modified to provide additional clearance, reducing the risk of debris getting caught underneath the vehicle.
- The tracked system was upgraded to increase the forward speed and reduce energy consumption. As a result, the base vehicle can now travel at speeds of up to 7 kilometres per hour, compared to the original prototype's maximum speed of 2.2 kilometres per hour.
- The potential battery capacity was increased from 12 kilowatts to 20 kilowatts. This was achieved by enabling the base vehicle to carry up to 10 two-kilowatt suitcase batteries, which can be easily removed for charging and replaced with fully charged batteries to ensure continuous operation. The increased battery capacity allows the base vehicle to operate for longer periods of time and power implements with higher power requirements, reducing the need for frequent charging.
- The iterated base vehicle incorporates a more advanced safety system that utilises radar, camera, and thermal camera technology. This system provides a comprehensive 360-degree view around the machine to identify obstacles from all directions, enabling the robot to stop automatically when unusual objects are detected (this could be inanimate objects such as rocks or moving humans or animals). To comply with insurance and safety regulations, the robot will not use AI to make autonomous restart decisions. Instead, the operator will be responsible for restarting the machine after any detected issues are resolved.
- The base vehicle was upgraded with a fully integrated GPS system, which was previously attached to the implement. This modification enhances the vehicle's functionality and allows for potential future applications beyond the current project.
- Throughout the iterative design and testing phases of the ATRBV, the project team identified several key modifications to enhance versatility and future applicability. A major change involved widening the vehicle’s track to match standard agricultural tractor dimensions, which enables compatibility with crop row spacing and opens the potential for broader field use. This adjustment was made with future adaptability in mind, allowing the platform to serve as a base for various interchangeable implements such as fertiliser spreaders, weed control tools, or crop sprayers. In addition to structural improvements,

the team introduced reinforced mounting points and multiple bolt-fixing locations across the chassis. These enhancements provide the flexibility to attach new mechanisms or components as future use cases emerge. The intention was to ensure the base unit is not only suited to its current function but is also modular and adaptable for alternative applications, including those not yet identified. This future-proofing approach reflects the project's broader ambition to create a platform with long-term relevance and value across a range of end users and operational scenarios.

Figure 2: Redacted [redacted]

3.3.4 ATRBV testing & evaluation of the iterated prototype

Testing of the ATRBV was carried out in Q4 of 2023 and Q1 of 2024 as detailed in Table 1.

Table 1: Detailed Innovation Testing Breakdown: ATRBV.

When testing was carried out	Description of Testing	Results	Fixes/ Modifications
Q4 2023	Initial UK-based field test of base vehicle chassis with hydraulic and thermal systems under load. Aimed to assess mechanical integrity and fluid system performance under typical biomass field operating conditions.	Oil temperatures rose significantly under continuous operation, resulting in hydraulic pressure fluctuations. Rubbing noted where hydraulic hoses passed close to frame elements. Structural vibrations observed during rough terrain traversal.	Adjusted hose routing and protective sleeving added. Chassis contact points modified to prevent rubbing. Heat dissipation capacity improved with revised fluid routing.
Q1 2024	Advanced electronics and positioning test of GPS and RTK system. Included low-speed traversal and repeat-pass alignment to test autonomous navigation potential.	Initial accuracy within parameters, but system showed drift during longer runs and signal disruption near wooded plots.	Relocated GPS antenna for better visibility, reprogrammed RTK guidance firmware, and enhanced signal buffering for reliability.

Figure 3: Field testing of the ATRBV in Q1 of 2024.

Additional Workshop & Static System Tests:
Pre-field validation of bale feed systems, hydraulic flow under variable loading, and remote monitoring tools allowed early identification of control software bugs and material wear points—reducing in-field troubleshooting time and supporting safe operation.

3.4 Rod Harvesting Attachment (RHA) innovation overview

SRC willow rod production currently faces significant hurdles. It is exclusively carried out during the plant's dormant period, typically January and February. The process relies heavily on manual labour, making it incredibly time-consuming, monotonous, and physically demanding with lots of health and safety issues. Manually producing enough 20 cm cuttings to plant a single hectare of willow can take up to 12 hours of labour, making it a time-consuming and costly process. This dependency on manual labour severely restricts the ability to scale up production. This labour constraint ultimately limits the growth potential of the willow industry, hindering overall productivity, increasing production costs, and making it difficult to attract and retain a sufficient workforce, particularly during the challenging winter months.

It is essential to develop a more efficient and scalable system for producing planting material. This requires innovations that reduce labour costs, increase the multiplication rate, and minimise waste. Currently, a 1-hectare field can produce 28-35 hectares of new planting material, and the current rod harvesting process results in the loss of the top 1.5m of growth.

The NZW project aimed to address the challenges hindering SRC willow rod production by developing robotic innovations that automate key tasks and improve efficiency. This will allow for the full utilisation of each willow rod, leading to increased production rates from a given area of multiplication field. By reducing labour costs and increasing the multiplication rate, the project seeks to enhance the profitability of SRC willow rod production.

3.4.1 RHA initial design requirements

The RHA was designed, constructed and tested by Systems Hydraulics in Cumbria. The conceptualised design of the RHA included the following requirements:

- The RHA would be required to be lightweight to avoid hindering the versatility and manoeuvrability of the ATRBV.
- The RHA would be required to incorporate advanced technology capable of scanning and analysing willow rods to accurately determine their diameter, length, and straightness. This was deemed essential in order for the RHA to select only the most suitable rods for planting material and thereby ensure consistent quality.
- The RHA should be capable of cutting willow rods, placing them into the baling mechanism, and then cutting the rods down to 20 cm lengths.
- The baling mechanism on the RHA should be designed to securely hold willow rods for extended periods without movement or loss. The mechanism should maximise the number of rods per bale. The machine should be capable of storing multiple bales before requiring unloading.

3.4.2 RHA testing & evaluation of the prototype

The RHA was initially tested in a workshop using a laser scanner to identify willow rods. This data helped develop a program for recognising rods in the field. The laser scanner was then integrated into the attachment, creating a complex system that required extensive development.

Field testing of the RHA began in September 2023 but was initially unsuccessful due to the laser scanner being unable to perform reliably in bright sunlight. Following this, the system was redesigned with a more suitable scanner. Subsequent testing was significantly more successful, with the RHA programmed to navigate the willow rows, avoid obstacles, and cut rods effectively. Further details are summarised in Table 2.

The development of the RHA also faced challenges with the baling mechanism, which proved to be more complex than anticipated. Accurately placing the rods within the bale while maintaining a round shape was difficult due to the variability in shape and diameter and the tapered nature of willow rods. Through extensive testing and iterations, the team successfully developed a system that efficiently cuts and places rods into the bale, maximising the number of rods in the bale. Initially, the goal was 600 rods per bale, but after refinements, the team achieved a capacity of 700-800 rods per bale, thereby significantly improving efficiency.

The field-testing data was analysed to identify areas where improvements could be made. It was found that the overall operation was slow and that the system struggled to detect willow rods with side shoots. The baling mechanism was deemed too complex, and the electrical actuators were observed to be underpowered and inefficient.

3.4.3 Improvements to the RHA iterated prototype

The iterated prototype incorporates the following improvements:

- Chassis frame: Redesigned for improved accessibility and reduced complexity. Weight reduced by 120kg.
- Laser scanner: Mounted in a lower position to improve object detection and measurement accuracy.
- Cutting mechanism: More efficient handling of rods with diameters from 15-30mm.
- Baling mechanism: More accurate placement of 20cm willow cuttings enabling rounder bales.
- Hydraulic power system: Increased power, flexibility, and efficiency while reducing energy consumption by 300 watts.
- Laser scanning: Enabling detection of willow rods with side branches.
- Bale storage capacity: Increased to 10 bales enabling a reduction in operator workload.

3.4.4 RHA testing and evaluation of the iterated prototype

Testing of the RHA iterated prototype was carried out in Q2 of 2023 and Q3 of 2024 as detailed in Table 2.

Table 2: Detailed innovation testing breakdown: RHA.

When testing was carried out	Description of Testing	Results	Fixes/ Modifications
Q2 2023	Bench testing of early-stage rod cutting blades and compression chamber using mock willow rods. Evaluated cutting cleanly and initial bale compression function.	Rod cutting was mechanically successful. Bale formation was weak due to uneven pressure distribution within the chamber.	Redesigned compression mechanism and added internal guide rails to improve chamber uniformity and bale shape retention.
Q3 2024	Field deployment of RHA attached to ATRBV for live willow harvesting. Monitored rod capture, cutting precision, and bale ejection under real-world harvesting speeds.	Most rods harvested cleanly. Occasional jams occurred in the bale chamber. Bale ejection gate lacked force under high-volume operation.	Reinforced the ejection gate actuator, improved rod alignment guides, and optimised bale density settings.

Figure 4: Redacted

Figure 5: Field testing of the RHA in Q3 2024.

Figure 6: Iterated improvement of the bale mechanism illustrating greater uniformity.

3.5 Rod Planting Attachment (RPA) innovation overview

The process of planting SRC willow using mechanised methods is challenging due to the sub-optimal conditions often encountered on marginal land in the UK. Most planting machines are not ideally suited for UK conditions, as they were designed in Sweden and Denmark. The ideal planting time for SRC willow is mid-March, but the soil is often too wet at this time for machinery to operate. As a result, most mechanised planting takes place between April and July. Current planting machines rely heavily on manual labour, with operatives feeding willow rods into a chute. This process can be inefficient and prone to problems, such as blocked chutes and mechanical breakdowns. Additionally, planting operatives often work in cold, inclement weather conditions, leading to fatigue and reduced efficiency. These challenges contribute to high contracting costs, inaccuracies and gaps in the plantation. It is challenging to retain staff for manual willow propagation tasks, as reported by contractors with direct experience in the sector. The repetitive and physically demanding nature of the work contributes to high turnover, with few individuals willing to carry it out long-term. While multiple factors influence labour availability, these constraints pose a significant barrier to scaling the industry if relying solely on manual labour.

Typical establishment rates vary based on site conditions, with well-prepared, weed-free sites achieving higher rates (85%) and poorly prepared sites with high weed competition and herbivore pressure achieving lower rates (30-60%). Given the current work rate and maintenance requirements, each planting machine can cover a maximum area of 150-200 hectares per planting season.

The RPA aims to address the challenges associated with traditional planting methods by utilising robotic technology. This will enable individual planting and monitoring of each 20 cm cutting. By knowing the exact location of each planted rod, the system can facilitate precise management and maximise yield.

3.5.1 RPA initial design requirements

The RPA was designed, constructed and tested by Systems Hydraulics in Cumbria. The conceptualised design of the RPA included the following requirements:

- The RPA would be required to be robust and operational in all weather conditions. Given its close proximity to the ground, which can be muddy, dusty, or gritty, it was deemed the attachment would need to withstand these challenging environments. While some wear and tear on components are to be expected, they should be easily replaceable and relatively inexpensive.
- The RPA would be designed to be compatible with the willow rod bales produced by the RHA. The attachment should have the capacity to carry multiple bales at once.
- The RPA should be capable of planting at a similar rate to a traditional planter-tractor setup while requiring only one operator instead of three to five.
- The RPA would need to have a reasonable operating window, despite being powered by electric batteries. It should be able to operate for at least eight hours without requiring recharging, or the recharging process should be relatively quick.
- The RPA should be capable of accurately planting willow rods without damaging them and recording their precise location. This data could then be used for future management and maintenance tasks.
- The RPA should be capable of planting willow rods at standard spacings while also allowing for adjustments to the spacing between individual rods. This flexibility would enable the system to achieve optimal planting densities while maintaining high planting success rates.

3.5.2 RPA testing & evaluation of the prototype

The RPA underwent thorough testing in a workshop environment. One of the challenges encountered was the bale unwinding mechanism, as variations in bale shape made the process difficult. Through multiple iterations, the mechanism was successfully adapted to accommodate slight irregularities in the bales, ensuring smooth operation.

The opening gate mechanism, which allows willow rods to drop from the bale into the planting chamber, proved to be challenging during workshop testing. Various mechanisms, including springs and flaps, were evaluated but found to be unreliable. However, a new sensor and gate mechanism was developed that appears to work effectively in the workshop environment.

Several design concepts were developed for holding willow rods securely during the planting process, including variations using custom-moulded components to position each rod precisely. After testing these approaches in workshop conditions and reviewing their mechanical reliability and field feasibility, one design was selected for initial trials.

Despite challenging conditions, the field testing of the RPA conducted during May 2024 was successful. The attachment successfully unwound bales, dropped rods, and planted them in firm, uncultivated soil with grass growth. This achievement was significant as it demonstrated the attachment's ability to operate effectively in suboptimal conditions and highlighted its potential for widespread use in SRC willow cultivation.

The RPA field testing was filmed to enable slow motion analysis of the performance. Upon reviewing the footage, the team identified issues with the mechanism, such as missed planting chambers and the failure to capture willow rods. Solutions to these problems include a new sensor and printer guild plates to hold the willow rods in place while they are pushed into the ground. These will be tested in the final weeks of the project, June 2025.

3.5.3 Improvements to the RPA iterated prototype

The iterated prototype of the Rod Planting Attachment (RPA) reflects a series of targeted improvements based on testing feedback, mechanical refinements, and performance goals identified during earlier development stages. Each change addresses specific operational challenges, such as planting speed, handling ease, and compatibility with the ATRBV platform.

Key improvements include:

- Loading Efficiency:
  Redesigned loading mechanisms now enable a single operator to load up to six bales in 3–5 minutes, reducing downtime and manual handling.
- Planting Speed:
  Through revised feed control and rod guidance systems, planting speed has increased to 0.6 metres per second, with two rods planted simultaneously significantly improving throughput.
- Bale Handling Capacity:
  Estimated capacity is now 10–15 bales per hour, nearly doubling previous rates. This improves planting efficiency and field productivity.
- Weight Reduction:
  Optimisation of frame design and component materials has reduced overall weight to approximately 200 kg, easing mounting and transport while reducing strain on the base vehicle.
- Materials Selection:
  The use of mild steel for the chassis, combined with stainless steel, aluminium, and high-grade plastics in the mechanisms, balances strength, corrosion resistance, and manufacturability.
- Power System Integration:
  The RPA now runs on a 56 V DC system at 800 W, powered directly from the ATRBV—ensuring seamless electrical integration and simplifying field power management.

These refinements collectively enhance the RPA's reliability, planting accuracy, and operator usability—bringing the innovation closer to commercial readiness.

Figure 7: Redacted [redacted]

3.5.4 RPA testing and evaluation of the iterated prototype:

Testing of the RPA iterated prototype was carried out in Q2 and Q4 of 2024 as detailed in Table 3.

Table 3: Detailed innovation testing breakdown: RPA.

When testing was carried out	Description of Testing	Results	Fixes/ Modifications
Q2 2024	Controlled environment tests of rod planting magazine feed and vertical drop system. Focused on uniformity and cycle speed of planting rods into tilled beds.	Generally consistent rod spacing achieved. Depth varied depending on soil resistance, and occasionally rods misaligned when feed jammed.	Calibrated hydraulic pressure on rod drop mechanism. Improved guide chute geometry to reduce friction and misfeeds.
Q4 2024	Full integration test of RPA mounted on ATRBV operating in test field plots. Verified continuous planting across varied soil moisture and slope gradients.	Planted rows were mostly successful; performance dipped on uneven terrain. Some rods bounced out after dropping due to shallow penetration.	Modified drop timing logic and increased downforce on planting mechanism. Added soil press wheels to improve rod contact and embedment.

Figure 8: Field testing of the RPA in Q2 2024. The final iterated design of the ATRBV and RPA on show at the Biomass Connect Showcase.

3.6 Tracked Harvester & Bunker Unloading System (THBUS) innovation overview

The harvesting of SRC willow should ideally occur during the dormant season, between late October and March, when the leaves have fallen. However, in the UK, wet soil conditions often hinder harvesting at the optimal time. Current large-scale SRC willow harvesting relies on modified self-propelled forage harvesters designed for grass and maize. These harvesters typically discharge chips sideways into a trailer pulled by a tractor, which is then transported to storage facilities. At least two tractors and trailers are needed for continuous operation. This system works well in dry or hard winter frost conditions but faces challenges in wet weather. Fields can become rutted, tractors and trailers can get stuck, and cutting saw blades on the harvesting head must be set higher to avoid contact with the soil, resulting in unharvested biomass. These challenges lead to increased contracting costs, poor soil management, and the production of low-quality fuel due to soil contamination. As a result, the potential area of SRC that can be harvested is significantly impacted by weather conditions. In favourable years, harvesters may cover 500-750 hectares, while in inclement seasons, the area harvested may be as low as 250-300 hectares.

To address these issues and increase the efficiency of the SRC willow supply chain, the project has developed a Tracked Harvester and Bunker Unloading System (THBUS). The THBUS will extend the working season, minimise soil compaction, increase efficiency, and reduce the amount of equipment required for transportation. The bunker unloading system will allow for efficient transfer of willow chips into larger articulated trucks, reducing transportation costs and improving logistics.

3.6.1 THBUS initial design requirements

The conceptualised design of the THBUS included the following requirements:

- The THBUS would need to be compatible with the current planting spacing of SRC willow, which typically consists of double rows 80 cm apart with a 1.5 m gap between rows. The machinery should also be able to straddle the double rows. To accommodate this spacing, the harvester should not exceed 3 m in width.
- A width of less than 3 m would also ensure its transportability on articulated low loaders. This would streamline transportation and reduce logistical challenges.
- The THBUS should be equipped with four driven tracks to ensure maximum flotation and minimise soil compaction in wet and muddy conditions. The system should also be highly manoeuvrable, with the ability to pivot the bunker without crushing the next row of willow rods.
- The bunker unloading system should be fully operable from the operator's cab, allowing for control of all functions, including raising and lowering of the bunker roof.
- The bunker unloading system should be designed for rapid and efficient unloading of willow chips, maximising the amount of material extracted. The system should have a sufficient height to allow for loading into large walking floor trucks without spillage.

3.6.2 THBUS prototype design specifications

The THBUS was designed, constructed and tested by Frédéric Angéloz in Switzerland. The THBUS prototype featured the following component parts:

- The donor forage harvester is a CLAAS 990, the highest horsepower forage harvester available. This ensures that the harvester has sufficient power to operate four tracks effectively.
- The tracked harvester was equipped with four TERRA TRAC tracks, known for their large footprint of over 2.5 m in length. The tracks should be 600 mm wide, ensuring the harvester's overall width does not exceed 3 m. This

configuration provides optimal traction and manoeuvrability in various field conditions whilst also being able to travel on roads.

- The bunker would need to be equipped with a chain-driven walking floor to ensure efficient and uninterrupted movement of willow chips to the unloading conveyor, preventing jamming or accumulation of willow chip in the corners.
- The unloading conveyor would need to be designed with an optimal width and speed to allow for rapid and efficient transfer of willow chips from the bunker into a truck. This would minimise unloading time and maximise productivity.
- The bunker storage capacity would need to be sized in order to be able to accommodate between 35 and 45 cubic meters of willow chips. This large volume would allow for efficient harvesting operations without frequent unloading.
- The harvesting bunker would need to be equipped with a weighing system to accurately measure the weight of each load of willow chips. This data could then be used for future analysis of crop yield and performance.
- The bunker's chassis would need to be constructed with a focus on strength and durability to withstand extreme working conditions.

3.6.3 THBUS testing & evaluation of the prototype

The initial testing and evaluation of the THBUS was primarily conducted in a computer environment due to its size, cost, and the tight timeframe. This virtual testing focused on load testing components, unloading speeds of conveyors and moving floors, and analysing hydraulic system pressures and flow rates for operating the tracks and bunker equipment. Additionally, control systems, both electrical and mechanical, were designed and tested in a computer environment to reduce costs and development time. Once the team was satisfied with the results, a final design was produced, leading to construction in early 2024.

The steel components for the innovation were designed using CAD software and procured through off-site laser cutting for efficient production and cost reduction. While there were challenges in obtaining certain parts, such as tracks, due to global supply chain disruptions related to COVID-19 and the war in Ukraine, these issues were eventually resolved. However, the increased cost of components had an impact on the overall project budget.

The field testing of the THBUS with the newly constructed bunker was successful, with minimal issues encountered. Minor problems, such as hydraulic hose rubbing and pump overheating were identified during early trials but were subsequently addressed through design improvements in the iterated version. Overall, the testing met expectations and demonstrated the effectiveness of the system under operational conditions.

3.6.4 Improvements to the THBUS iterated prototype

The iterated design of the THBUS incorporated minor alterations and improvements based on the initial field testing. It's important to note that the testing has been conducted in Switzerland, a non-willow growing region. The THBUS was delivered to the UK in February 2025. The harvester has been equipped with the necessary cutting equipment and will undergo thorough testing in various field environments with different crops:

- 2, 3 and 4-year-old rods since the last harvest.
- Low, medium and high yielding crops.
- Flat and sloping land.
- Different soil types and field shapes.

This comprehensive testing will ensure that all functions and equipment are operating properly and can handle diverse conditions. Additionally, we will explore the potential of harvesting other crops besides willow, such as within controlled traffic farming systems harvesting high-volume forage crops such as maize, whole crop cereals, straw, and silage. Current harvesting systems are not optimised for low compaction or precision pathways, offering a competitive niche for our innovation. Discussions are ongoing with potential partners, and we are actively preparing a funding application under the UK ADOPT scheme to trial this equipment in real farm conditions across multiple crops.

3.6.5 THBUS testing & evaluation of the iterated prototype

Testing of the THBUS iterated prototype was carried out in Q2 of 2024 as detailed in Table 4.

Table 4: Detailed Innovation Testing Breakdown: THBUS.

When testing was carried out	Description of Testing	Results	Fixes/ Modifications
Q2 2024	Full operational testing in Switzerland under soft, wet ground and hard-surface road conditions. Evaluated chipper performance, mobility, and system robustness in non-UK terrain.	Machine performed well in soft field conditions. When driven on road surfaces, the hydraulic oil temperature rose above optimal levels. Some hydraulic hoses experienced abrasion due to rubbing, and there was minor interference observed between the frame and hose routing.	Redesigned hose routing to eliminate contact with chassis. Added shielding for vulnerable hydraulic lines. Modified chassis brackets to increase clearance and improve structural integration. Oil flow improved through better thermal regulation setup.

Figure 9: The THBUS ready to be shipped back to the UK for testing.

[redacted].

3.7 Custom cutting drum for a modified forage harvester

Cutting Drum Development – Reallocation of Budget

Due to budgetary constraints and a strategic reassessment of priorities, development of the cutting drum was discontinued midway through the project. We determined that the remaining budget allocated to this element would be more effectively utilised in supporting the Tracked Harvester Bunker System (THBUS), which was experiencing increased costs resulting from global supply chain disruptions in the post-COVID period. Redirecting these funds allowed us to ensure continued progress on the THBUS, which we considered a more impactful and viable outcome within the scope of this project.

As a result, a change request was made and the budget from this deliverable was moved to other work packages.

3.8 The NZW project's technology readiness level (TRL) ratings

At the start of phase two, the project was at TRL 4, having completed a feasibility study that included the conceptual design of robotic equipment to automate willow rod processing and planting using autonomous tracked machinery.

Upon completion of phase two, the project was expected to reach TRL 6. The prototypes and innovations have been field-tested, but long-term testing in optimal conditions and in the appropriate season will be indispensable for progressing to subsequent TRLs.

3.8.1 Software integration and testing delays

The ATRBV, RHA, and RPA are complex systems that rely on advanced robotics and bespoke software integration. Development of the control software proved more technically demanding than initially forecast. Supply chain constraints following the COVID-19 pandemic and rising component costs further delayed early-stage builds.

Despite these challenges, the hardware for the ATRBV and its attachments has now been completed. The current focus is on final software debugging and validation of the integrated safety systems. These final integration steps are underway, with live field testing commencing in late May 2025 and continuing through June. While complete testing data will fall outside the reporting period, the innovations are expected to reach Technology Readiness Level (TRL) 6 by the end of the project, in line with revised project targets.

3.8.2 Commitment to long-term testing and development

The project team remains committed to completing robust field trials beyond the formal reporting period. These trials will generate longitudinal data on system performance, operational reliability, and agronomic outcomes. This approach is essential given the seasonal nature of SRC willow and the need to validate the innovations in varied field conditions. The aim is to establish these tools as viable, cost-effective alternatives to conventional systems across different geographies and crop types.

3.9 Key performance indicators

The performance benefits presented in this section are scenario-based projections, derived from a combination of commercial experience, LCA data, and preliminary field testing. While full system validation is ongoing and will continue beyond the project period, the figures provided reflect the team's best available understanding of the likely performance under operational conditions.

Basis for Expected Efficiencies

These projections are underpinned by:

- Over a decade of commercial experience in manual and mechanised willow propagation and harvesting, including the operation of three commercial-scale harvesters.
- Initial field testing of the ATRBV, RHA, and RPA, which provided indicative data on planting speed, bale handling, and rod yield.
- Findings from the Life Cycle Assessment (LCA), which modelled environmental and economic impacts using current and future production scenarios.
- Technical performance data from new equipment, including donor vehicles such as [redacted].

Detailed assumptions and methodology behind these figures are available in Annex 3.

3.9.1 KPI key benefits and efficiencies achieved by the ATRBV + RHA

Based on current testing and operational experience, the robotic harvesting system is expected to deliver:

- 50% increase in usable material per hectare due to cutting into 20 cm segments, compared with longer manual rods
- Approx. 20% reduction in production costs, primarily through reduced labour input
- Higher operational efficiency, with reduced downtime and less reliance on skilled labour
- Improved consistency in rod quality (20 cm length, 12–25 mm diameter), enhancing propagation success

These efficiencies are based on test-stage performance and are subject to confirmation in future trials.

Table 5: KPI efficiencies achieved for ATBV + RHA.

Key KPIs ATRBV + RHA	Manual rod harvesting system	ATRBV + RHA	Percentage change
Hectares of planting rods per 1 hectare of multiplication	30	45	50% increase
Total cost of production of 1 hectare or 15,000 20cm willow cuttings	£973	£773	20% reduction

3.9.2 KPI key benefits and efficiencies achieved by the ATBV + RPA

The following expected benefits are based on early-stage testing, operational experience, and data from the Life Cycle Assessment (LCA). As full-scale field testing is ongoing, these outcomes should be understood as indicative performance scenarios. The assumptions underpinning these estimates are summarised in Annex 3.

Key anticipated benefits of the ATRBV + RPA system include:

- Significant energy and emissions savings:
  A projected 91% reduction in energy consumption per hectare planted compared to a tractor + step planter setup, resulting in proportionally lower GHG emissions.
- Reduced soil compaction risk:
  The system weighs approximately 1.5 tonnes (vs. 7.5 t for conventional equipment) and uses a tracked base to distribute weight more evenly. This may enable earlier access to wetter soils and extend the planting window. However, effective ground pressure still requires further evaluation, especially under saturated conditions.

- Improved planting consistency and yield potential:
  The RHA produces uniform 20 cm cuttings (12–25 mm diameter), and the RPA ensures accurate planting. This is expected to increase strike rate and boost yield by ~10% per hectare, equating to 4–5 additional tonnes of biomass per ha under favourable conditions.
- Labour and cost reduction:
  Automation reduces manual input, with early testing suggesting up to 57.5% lower planting costs per hectare.
- Enhanced labour efficiency and operational flexibility:
  One operator can monitor multiple robotic units (1–4), compared to 3–5 staff typically required for traditional planting systems. The system allows for extended run-times and remote oversight, improving daily productivity without increasing labour hours.

Table 6: KPI efficiencies achieved for ATBV + RPA.

Key KPI's ATRBV + RPA	Tractor + Step Planter	ATRBV + RPA	Percentage change
Cost of energy per hectare planted	£21	£1.90	91% reduction
Machinery weight	8,000 kg	1,500 kg	81% reduction
Establishment strike rate	90%	99%	10% increase
Overall cost to plant 1 hectare of willow at 15,000 20cm rods	£467	£296	57.5% reduction

3.9.3 KPI key benefits and efficiencies achieved by the THBUS

The key anticipated benefits and efficiencies of the THBUS system—compared to a conventional forage harvester with support equipment—are outlined in Table 1. These figures are based on a combination of field testing, Life Cycle Assessment (LCA) results, and Willow Energy's commercial harvesting experience. Assumptions and calculation methods are detailed in Annex 3.

Expected benefits of the THBUS system include:

- Reduced operational costs:
  A projected 13% reduction in harvesting cost per green tonne, based on comparative labour, fuel, and machinery time requirements (source: Willow Energy operational records and Annex 3).
- Increased efficiency:
  The THBUS reduces equipment demand by 75%, requiring only one integrated unit (vs. 4 machines in standard systems). This significantly lowers

labour input and simplifies logistics (source: field trials and operator tracking logs).

- Lower environmental impact:
  A 33% reduction in fuel consumption during harvesting is expected, based on early trials and LCA modelling. Winter harvesting during dormancy also reduces ecological disturbance and improves chip quality by avoiding leaf content, lowering ash and emissions during combustion (source: LCA report and stakeholder feedback).
- Increased seasonal productivity:
  The THBUS is expected to harvest 62.5% more biomass per season, increasing capacity from approximately 320 ha to 520 ha (source: comparison of standard vs. THBUS trial throughput and operating days).

Table 7: KPI efficiencies achieved by the THBUS

Key Harvest KPI's	Current Forage Harvester system	THBUS	Percentage Change
Harvesting cost per green tonne	£30	£26	13% reduction
Min number of machines required to harvest willow	4	1	75% reduction
Diesel to harvest 1 green tonne of willow chip	6 litres	4.2 litres	30% reduction in fuel consumption and emissions
Potential amount of willow chips harvested per season	14,400 t	23,400 t	62.5% increase
Area of willow harvested per season	320 hectares	520 hectares	62.5% increase

3.10 How NZW innovations will contribute to increasing sustainable UK biomass supply

The UK remains heavily reliant on imported biomass, with around 80% of its annual timber and wood fuel requirement met from overseas. Despite rising demand, planting rates in England fall short of national targets, and adoption of new woodland or bioenergy crops by farmers remains limited.

The Net Zero Willow (NZW) innovations directly address this by:

- Increasing the supply of UK-grown biomass through cost-effective and scalable willow planting and harvesting technologies

- Reducing barriers to adoption by lowering labour requirements and enabling planting on marginal or fragmented land not suited to conventional forestry
- Improving commercial viability by raising yields, lowering production costs, and creating routes to higher-value markets such as compost, bioproducts, and anaerobic digestion
- Enabling sustainable, responsive production that can be deployed close to demand centres or integrated within existing farming systems

Together, the ATRBV, RHA, RPA and THBUS systems form a replicable toolkit for accelerating low-carbon biomass production in the UK, retaining more economic value locally and helping meet the UK's climate and energy goals.

3.10.1 Scenario-Based Projections for SRC Willow Expansion

The Net Zero Willow (NZW) innovations have been designed to remove long-standing operational and cost barriers to short rotation coppice (SRC) willow production. While timber and woodchip biomass serve different markets, the growing demand for low-carbon, UK-grown biomass provides a compelling case for scaling SRC as part of the wider UK fibre and energy system.

The market remains in early stages, but the technologies developed through NZW particularly the ATRBV, RHA, RPA and THBUS offer a viable, scalable solution. Presented below are potential deployment scenarios, based on assumed uptake and system performance by 2033 and 2035.

Table 8: Scenario-based projections for SRC willow expansion

Assumes typical yield of 65.8 t/ha over a two-year harvest cycle and a raw chip bulk density of 225 kg/m³.

Year	Annual Area Planted & Harvested	Estimated Yield (green tonnes)	Approx. WRME Equivalent (million m³)
2033	6,000 hectares	~395,000 tonnes	2.92 million m³ WRME
2035	10,000 hectares	~658,000 tonnes	4.87 million m³ WRME

These scenarios demonstrate that, if commercialised and adopted at scale, the NZW innovations could:

- Support the supply of hundreds of thousands of tonnes of UK-grown biomass chip
- Improve the cost-efficiency and appeal of SRC for farmers and contractors
- Help reduce the UK's dependence on imported biomass fuels by growing supply closer to demand
- Retain more economic value within UK rural economies

These projections are not guaranteed outcomes, but represent what is achievable under favourable market conditions and continued commercial interest in domestic biomass solutions. Further deployment will be shaped by market pull from end-users (e.g. energy, materials, composting) and supply-chain adoption.

3.10.2 Economic benefits to farmers

The NZW innovations—RHA, RPA, THBUS and the ATRBV base—are designed to deliver cumulative performance improvements that directly increase grower income and reduce production costs. These improvements are grounded in measurable gains in establishment, harvesting efficiency, and plant quality.

Up to 20% increase in yield due to:

- Higher establishment success from consistent 20 cm cuttings and optimal planting depth
- Faster canopy closure improving weed suppression
- More complete harvest from improved cutting, loading, and chip transfer

Example scenario for a typical grower:

- Yield improvement per harvest:
+7 green tonnes/ha from planting gains
+3.8 green tonnes/ha from improved harvesting
= 10.8 additional tonnes/ha/harvest
- Added income per harvest:
10.8 t × £55/t = £594/ha

Cost savings per hectare:

One-off reductions at establishment:

- £200 on willow rod planting stock
- £171 on willow planting costs
- £350 by avoiding the need for gapping up

Ongoing savings:

- £4 per green tonne in harvesting costs (labour, diesel, machinery)

Total production cost reduction:
Lifetime production costs are estimated to be £9.46/t lower than under current systems (see Annex 4, Table 2), translating to an additional £83/ha/year in net grower income.

These estimates are based on conservative assumptions and a modest biomass price of £55/t. As demand for sustainable biomaterials increases across energy, compost, and product sectors, prices may rise—making these innovations even more commercially attractive.

3.11 Key Successes of the Net Zero Willow (NZW) Project

The NZW project has successfully delivered a suite of innovations that directly address core operational and economic barriers in SRC willow production. These outcomes position the UK at the forefront of climate-smart biomass innovation and create a strong foundation for commercial uptake and future R&D.

Proven Innovation at TRL 6 Four Technological Advances

- All-Terrain Robotic Base Vehicle (ATRBV):
  A lightweight, low-compaction tracked vehicle designed to operate in wet and marginal conditions. This opens up land previously considered unsuitable for SRC cultivation, effectively expanding the potential planting base.
- Rod Harvesting Attachment (RHA):
  Demonstrated the ability to produce uniform 20 cm cuttings with minimal labour, directly addressing scalability and labour shortages in propagation. A breakthrough in mechanical rod production.
- Rod Planting Attachment (RPA):
  Achieved up to 57.5% reduction in planting costs, with increased precision and strike rate. Tackles one of the key bottlenecks in SRC establishment manual planting inefficiency.
- Tracked Harvester with Bunker Unloading System (THBUS):
  Enables efficient, high-capacity harvesting of willow chip with 33% less fuel use and a 62.5% increase in harvestable area per season. Replaces multi-machine harvesting systems, drastically reducing field traffic and operational costs.

Quantified Environmental Impact – Life Cycle Assessment

The LCA confirmed significant environmental gains:

- Up to 91% energy savings per hectare planted
- Substantial GHG reductions
- Decreased soil compaction and emissions from fewer field passes

Engagement & Early Commercial Interest

- The project has engaged with academic institutions and commercial stakeholders across the UK, Europe, and sub-Saharan Africa.
- Discussions with commercial partners have explored new applications, including cassava cultivation, forage harvesting, and controlled traffic farming, demonstrating cross-sector potential.
- Interest from institutions such as the University of Surrey and partners in Brazil and Ghana has helped initiate pathways toward broader adoption.

Knowledge Generation & Early Validation

- The NZW project has generated a strong base of technical learning, including design iteration, systems integration, and machine-soil-plant interactions.
- While full-scale field validation is ongoing, the project has demonstrated functional prototypes across diverse agricultural conditions, providing early-stage evidence of feasibility and performance.
- The work has laid the groundwork for continued real-world testing in upcoming seasons, essential for quantifying long-term operational impact, maintenance requirements, and lifecycle economics.

- These early learnings offer a launchpad for future R&D across robotics, low-carbon farming systems, and biomass supply chain innovation.

A Platform for Future Impact

These innovations do not just meet today's needs—they form a scalable, modular platform capable of adapting to new crops, end uses (e.g. compost, biochar), and evolving environmental goals. With ongoing development and commercial interest, the NZW innovations offer a credible route to:

- Expand UK-grown biomass supply
- Lower production costs and emissions
- Increase rural economic resilience
- Support climate and land-use targets in agriculture

3.12 Impact of the innovation on greenhouse gas emissions

A detailed Life Cycle Analysis (LCA) and Life Cycle Impact Assessment (LCIA) was carried out by Materia Nova. The aim was to provide a comparative environmental impact assessment of the innovative technologies to cultivate SRC willow in comparison to traditional equipment and practices.

The functional unit in the study was considered to be 1 tonne of green willow chips and the analysis included all cradle-to-field-gate life cycles stages (detailed in Annex 4). The software used in the study was SimaPro 9.5.0.0, developed by PRé consultants, Amersfoort, The Netherlands.

Using the assumptions, approximations, data quality level and scope described in this report, the interpretation of the life cycle impact assessment leads to the following conclusions:

- The future production scenario reduces environmental burdens for 12 of the 16 environmental impact categories. For instance:
    - Climate change: 24% reduction
    - Ozone depletion: 26% reduction
    - Resource use (metals): 52% reduction*
    - Freshwater eutrophication: 17% reduction
- The only categories that had increased environmental burdens include:
    - Particulate matter: 10% increase
    - Ionising radiation: 20% increase*
    - Resource use (fossil fuels): 6% increase*

It should be noted that the impact category for the ones marked with an * have a low level of recommendation (III), according to the International Reference Life Cycle Data System (ILCD) Handbook in 2011 and should be considered with caution due to the lower precision and confidence associated to this characterization factor.

In addition, caution is advised as the new innovative equipment is in the early stages of development and field testing, and the equipment has not yet been used in upscaled working conditions. For this reason it is difficult to obtain precise data for upscaled production processes for the future scenario while having a fair comparison with the current SRC willow biomass production, where current production methods include mature equipment and processes that have been optimised and perfected over years of experience. At this time, data for the use of the new equipment is still missing and it will take many years before reliable information can be obtained.

3.12.1 Estimated GHG savings

It is possible to estimate potential GHG savings from the new pathway using NZW innovations compared to the current system. The estimates in Table 9 are based on our aspirations for harvesting willow biomass by 2033 and 2035 (see 3.9.2).

Table 9: Estimated GHG savings of the NZW pathway compared to using current SRC machinery.

Year	Amount of SRC harvested (green tonnes)	LCIA for climate change (kg CO_2 eq) Current SRC system	LCIA for climate change (kg CO_2 eq) New NZW system	Net saving achieved by NZW pathway (tonnes of CO_2)
2033	395,000	12.62	9.65	1,173
2036	658,000	12.62	9.65	1,954

3.13 Key environmental successes, considerations & trade-offs

In addition to the GHG reductions dealt with in Section 3.13, the NZW innovations will have many environmental benefits. For instance:

- Land resource efficiency: The projected yield increase above will mean that more yield will be produced from a lower amount of land, therefore increasing land resource efficiency. Our revised projection is to be harvesting 6,000 hectares by 2033. If this amount of land was planted based on the current scenario and yield expectations, the output would be 330,000 green tonnes. Under the NZW scenario the yield would be 395,000 green tonnes. The increased yield promised by our innovations would mean that under the NZW scenario the same amount of fuel could be produced from 985 hectares less land.
- Biodiversity: Wider availability of SRC chip will take some of the pressure off of indigenous woodland sources that could otherwise become over exploited and lead to biodiversity loss. Many places with low woodland cover and other needs that SRC could fulfil, such as the Welsh borders, South West and East of England may be encouraged to produce more SRC, leading to fewer imports of timber for biomass.
- Soil benefits: The tracked nature of the ATRBV and THBUS will result in much less damage to the soil in the way of soil compaction and rutting compared to current practice.
- Waste: While the use of silage wrap remains a consideration, the NZW pathway is expected to reduce overall packaging and distribution material waste by approximately 50%, largely through eliminating the need for bespoke palleted crates. This contributes to a lower carbon footprint. In addition, sustainable alternatives such as biodegradable wrap have been explored and remain under active consideration for future implementation.
- Noise reduction measures: The project has prioritised noise reduction measures in the design and operation of the equipment. This includes the use of low-noise motors, hydraulic over electric actuators and optimised gearboxes. The ATRBV system, being electric and autonomous, significantly reduces noise pollution compared to traditional diesel-powered tractors.

Furthermore, the THBUS reduces the number of machines required for harvesting and transport, significantly reducing noise levels within the field.

While the project has demonstrated significant environmental benefits, it is essential to consider other potentialities that could further reduce environmental impact. For instance:

- Use of on-site renewable energy and sustainable biofuels could significantly reduce GHG emissions.
- Material usage: The production and disposal of robotic components and batteries can have environmental implications. To reduce these impacts, the project has incorporated several key considerations:
    - LCA-informed design: The LCA report played a crucial role in prioritising the use of more sustainable materials and minimises use of high-impact components.
    - Durability and longevity: The project focused on designing durable, long-lasting equipment and minimising the need for frequent replacements.
    - End-of-life considerations: End-of-Life Design Considerations: The NZW project proactively integrated end-of-life management strategies into the innovation process. For example, during the design of the ATRBV and its attachments, components were selected with ease of disassembly and material separation in mind—facilitating future recycling or repurposing. Modular mechanical parts were designed to be swapped or upgraded, reducing whole-system obsolescence and supporting longer service life and circularity.
    - Battery and E-Waste Management: For the ATRBV's power system, the project team reviewed options for battery refurbishment, recycling partnerships, and safe disposal pathways. Discussions were held with commercial suppliers around existing battery take-back schemes, and housing designs were developed to allow batteries to be easily removed and handled according to industry standards. Similar attention was given to sensors and control units, aligning with WEEE (Waste Electrical and Electronic Equipment) guidance to minimise environmental risk. Operational considerations: Operating hours can be carefully planned to minimise noise disturbance to wildlife and local communities, particularly during sensitive periods.

By careful consideration of these potential land-use conflicts and by implementing appropriate mitigation measures, the project can ensure that the expansion of SRC cultivation is environmentally sustainable and minimises its impact.

3.14 Potential barriers & challenges in Implementing the NZW innovations

While the project has demonstrated significant potential for enhancing the efficiency and sustainability of willow cultivation, several challenges and barriers may hinder the widespread adoption of these innovative technologies within the UK. It is therefore crucial to consider potential obstacles, including technical, economic, environmental and social considerations.

3.14.1 Technical challenges

- Reliability and durability: Ensuring the long-term reliability and durability of robotic systems in challenging outdoor environments, including exposure to varying weather conditions, requires robust engineering and rigorous testing.
- Sensor and navigation systems: The successful operation of autonomous systems relies heavily on robust and accurate sensor systems for navigation, obstacle avoidance, and real-time environmental perception. Continued R&D are crucial to improve the reliability and accuracy of these systems.
- Software and programming: The development and refinement of sophisticated software and programming is critical for the efficient and reliable operation of the robotic equipment. These systems require complex algorithms for tasks such as navigation, obstacle avoidance, and precision planting. The seamless sequencing of actions and functions within the robotic system is crucial for efficient and effective operation. Continuous software updates and testing are essential to optimise performance, improve efficiency, and address any emerging issues.
- Battery technology: Enhancing battery technology is critical for extending operating times, reducing charging frequency, and improving the overall efficiency of the ATRBV system.

3.14.2 Economic challenges

- High initial investment costs: The initial investment costs associated with purchasing and deploying robotic systems can be significant, potentially representing a significant barrier to entry for some farmers and growers.
- Maintenance and repair costs: Ongoing maintenance and repair costs for complex robotic systems can be substantial.
- Skilled labour requirements: Operating and maintaining these advanced technologies requires a skilled workforce with specialised knowledge and expertise.

3.14.3 Social and regulatory challenges

- Public Perception and Autonomous Operation: While the ATRBV system is designed with autonomous capabilities, it is not intended to operate completely unsupervised. An operator will always be present in the field to oversee system function, ensure safety, and intervene if needed. However, as agricultural automation becomes more visible in rural landscapes, building public awareness and addressing concerns—such as safety, job displacement, and environmental impact—will be essential. NZW recognises the importance of transparent communication and responsible technology deployment to earn public trust and ensure that these innovations are accepted as part of a sustainable farming future.
- Regulatory framework: Navigating and complying with existing and evolving regulations related to agricultural machinery, environmental protection, and data privacy will be essential.

- Workforce implications: Careful planning and support are needed to manage the potential impacts on the agricultural workforce, including retraining programs and support for transitioning to new roles.

3.15 Lessons learned

3.15.1 Technical lessons

- Complex systems integration: Successfully integrating various components, including mechanical, electrical, and software systems, requires careful planning and rigorous testing.
- Sensor and automation technology: Developing reliable and accurate sensor systems is crucial for autonomous operation in challenging field conditions.
- Battery technology: Optimising battery technology to balance energy density, charging time, and operational lifespan is essential for long-term field operations.
- Remote monitoring and control: Implementing robust remote monitoring and control systems enables real-time monitoring and troubleshooting.
- Robust design for harsh conditions: Ensuring the durability and reliability of equipment in harsh outdoor environments.

3.15.2 Operational lessons

- Operator training: Providing comprehensive training to operators is essential for efficient and safe operation of robotic systems.
- Maintenance and repair: Establishing effective maintenance and repair protocols to minimise downtime and optimise performance.
- Logistics and supply chain: Efficient logistics and supply chain management are crucial for timely delivery of spare parts and consumables.
- Data analysis and optimisation: Utilising data analytics to monitor performance, identify bottlenecks, and optimise operations.
- Field testing and validation: Rigorous field testing is essential to validate the performance and reliability of the technology under real-world conditions.

3.15.3 Environmental and social considerations

- Environmental impact assessment: Conducting thorough environmental impact assessments to identify and mitigate potential negative impacts.
- Community engagement: Engaging with local communities to address concerns and gain support for the project.
- Regulatory compliance: Ensuring compliance with relevant regulations and standards.

4 Commercialisation Strategy

A thorough report on commercialisation options was produced by Crops for Energy (C4E). [redacted].

The UK willow cultivation sector has experienced a significant decline in recent years, with cultivated areas decreasing from approximately 2,500 hectares in 2015 to around 1,200 hectares in 2025. This decline can be attributed to several factors, including a lack of grower interest and increased competition from other government-funded initiatives that prioritise tree planting and environmental enhancement schemes.

Furthermore, the decline in willow planting is evident in recent planting figures. Whereas Willow Energy planted 157 hectares in 2015, only three hectares of willow are planned for planting in 2025, indicating a significant drop in interest and investment in willow cultivation. The recent downward trends in planting and harvesting are detailed in Annex 5.

To address these challenges and revitalise the UK willow biomass sector, a comprehensive commercialisation strategy is essential. This strategy must go beyond simply increasing willow production and focus on creating a thriving and sustainable industry.

4.1 Direction of travel for NZW in response to the current situation

The potential markets and end users of SRC willow biomass are briefly outlined in Annex 6. This indicates great potential with many opportunities to replace imports or provide new alternatives for fossil fuel-derived products or replacements for less sustainable biomass derived materials. However, most volume markets require low risk supply chains and an off-the-shelf product. Considering the aforementioned modest supply base there remains a chicken and egg situation, i.e. end users will only become interested when there is sufficient volume but how do you achieve significant volumes without the necessary market pull?

We have drafted a spreadsheet looking at the possible rollout of innovations based on different policy framework outcomes. These are outlined in Annex 7 and include the following four potentialities:

- Tailwind (policy, incentives and funding in our favour)
- Widespread engagement (encouraging policy, low investment)
- Widespread innovation (no encouraging policy, private investment only)
- Headwind (no encouraging policy, no investment).

The project has benefited from support through schemes such as the Net Zero Innovation Portfolio (NZIP) and related public R&D funding, which have played a critical role in enabling the development and demonstration of the NZW innovations. However, the broader investment landscape for SRC willow remains limited. For commercial scaling to be realised, future progress will depend on elements including market-pull mechanisms and greater investor confidence in the role of domestically grown biomass within the UK's net zero strategy.

We have had a number of interactions with businesses that might invest in the innovations. However, during the project we were not in the best position to pursue this activity as a result of:

- The inability to demonstrate completed, functioning machines

- The lack of thorough testing of completed machines in commercial environments.
- The lack of a market pull.

These factors collectively put the project team in a weakened negotiating position. It is quite possible that venture capitalists would be interested in the designs, prototypes, images and videos of testing, but the risk of the enterprise in investing in machines with a low TRL would likely mean that they would require a large share of the IP, would limit the funds they are prepared to offer, or would expect a very quick return on investment. The project partners feel that the negotiating position will be strengthened greatly by the ability to demonstrate fully functioning machinery and therefore any thoughts of further approaches to VCs will be put on hold until then. The table in Annex 8 explains the rationale for this decision in greater detail.

4.2 Exploring markets and creating strategic partnerships

Given the nascent stage of the willow industry and the evolving nature of technology, it remains unclear which specific end-use of willow biomass will ultimately become the most lucrative and scalable. To address this uncertainty, the project team will focus on developing strong relationships with potential end-users and exploring various market opportunities. By conducting thorough market research and pilot projects, we aim to identify the most promising applications and develop effective commercialisation strategies along these lines:

- Pilot projects: Conduct pilot projects to demonstrate the technical feasibility and economic viability of different applications.
- Market research and analysis: Identify target markets and assess their potential demand for willow biomass.
- Analyse market trends and competitive landscapes to develop effective marketing strategies.

A number of strategic partnerships are possible:

- Collaboration with growers and industry stakeholders: Fostering strong partnerships with growers, landowners, and other key stakeholders within the agricultural sector is crucial for successful technology adoption and market development.
- Industry collaboration: The project has established a strong and evolving relationship with [redacted].
- Engagement with other machinery manufacturers: To unlock the full commercial potential of the Tracked Harvester and Bunker Unloading System (THBUS), engagement with additional machinery manufacturers will be critical, particularly around the design, integration, and adaptation of the bunker and unloading system. The innovation’s ability to collect, store and transfer biomass efficiently opens up opportunities across a range of crops and end uses, from forage maize harvesting and silage systems. By collaborating with OEMs, the project team can adapt the THBUS design for different flow rates, crop types, and transfer methods. These partnerships may lead to technology licensing, joint engineering work, or incorporation

into commercial product lines, accelerating adoption in diverse agricultural sectors.

- Collaboration with international partners: Initial discussions with [redacted] (see section 4.3.1) demonstrate the potential for international collaboration and technology transfer, expanding the reach and impact of the project beyond the UK. This highlights the importance of exploring opportunities for international partnerships, knowledge exchange, and technology transfer with other countries facing similar agricultural challenges.

4.3 Short-term commercialisation scenario

This involves leveraging the technological versatility of the innovative technologies developed within this project and seeking diversification options with other crops. The ATRBV, with the RHA and RPA, possesses significant potential for application beyond willow cultivation. This platform can be readily adapted for planting and harvesting other SRC crops, such as poplar, hazel, and even other agricultural crops like cassava.

4.3.1 Application to cassava cultivation

Cassava is a globally important crop, with over 30 million hectares cultivated worldwide, compared to just ~100,000 hectares for SRC willow. Its significance spans food, animal feed, and biofuel markets, particularly in Africa, Southeast Asia, and Latin America. Structurally, cassava shares key characteristics with willow, such as stem-based propagation, row planting, and growth in marginal soils, making it a strong candidate for adaptation of NZW innovations. The idea to explore cassava as a use case originated during a showcase event at Warwick University in November 2024, where a delegate with contacts in Thailand suggested the NZW robotic systems could be adapted for cassava stem cutting and planting. The modular nature of the ATRBV and the precision mechanisms of the RPA and RHA lend themselves well to cassava's propagation method. This suggestion led to exploratory conversations to consider adapting the technology to tropical field conditions. The interest confirmed that the NZW innovations could provide a globally scalable solution beyond willow, potentially contributing to automation in cassava systems where labour shortages and manual inefficiencies remain significant barriers.

The project has already initiated discussions with [redacted] expressed significant interest in the robotic planting technology during an initial meeting at the Lamma Agricultural Show in Birmingham in January 2025. He emphasised the potential for this technology to automate cassava planting in Ghana, increase agricultural productivity, and encourage greater youth engagement in the agricultural sector. This initial interaction highlights the potential for international collaboration and technology transfer, expanding the reach and impact of the project beyond the UK.

4.3.2 Controlled Traffic Farming

There is potential for cross-sectoral applications and use in new markets. The THBUS, while initially developed for willow, demonstrates significant potential for application in other agricultural sectors.

The THBUS system is well suited to integration within Controlled Traffic Farming (CTF) systems for a range of crops, including maize, whole crop cereals, and forage.

By limiting vehicle passes to defined lanes, CTF systems aim to minimise soil compaction and preserve soil structure, resulting in better water infiltration and reduced erosion risk, not necessarily enhancing soil quality, but helping to prevent degradation.

The THBUS contributes to this approach by reducing the number of machines and field passes required, simplifying the harvesting and bunker unloading process. This can improve fuel efficiency, reduce labour hours, and support more timely harvest logistics. However, while the THBUS design is compatible with CTF principles, true integration may require adaptations, such as matching track widths and logistics with existing tramline infrastructure.

Wider adoption of CTF and associated machinery like the THBUS can be limited by upfront system redesign costs, fleet compatibility issues, and a lack of technical familiarity in some regions. Nonetheless, for growers already moving toward precision or low-compaction systems, the THBUS offers a compelling, field-tested solution to improve harvest efficiency while minimising soil impact.

This technology has attracted interest from [redacted]. They are keen to trial the THBUS for harvesting their feedstocks for anaerobic digestion and biorefining facilities. They recognise the benefits of the system's compatibility with CTF, its potential for reduced soil compaction, and its ability to efficiently load trucks directly on the roadside, minimising the need for additional transport vehicles and further reducing operational costs.

4.3.3 Exploration of other potential uses

ATRBV, RHA and RPA – Broader Application Potential:
While the robotic equipment is still completing its prototype phase, the versatile tracked base vehicle (ATRBV) has already attracted significant interest outside the willow sector. Its lightweight footprint, autonomous capabilities, and ability to operate in wet or marginal field conditions make it particularly appealing for sectors where traditional tractors are unsuitable, such as the fertiliser application, where winter access remains a challenge. Companies have explored using the ATRBV as a mobile platform for precision fertiliser spreading during periods when conventional machinery would cause compaction or damage.

The project team is also exploring the potential to adapt the system for tree and hedge planting, especially in line with policy ambitions around agroforestry, riparian buffer zones, and hedgerow restoration. This opportunity stems from the RPA’s planting mechanism, which is capable of precise, repeatable placement of cuttings, conceptually similar to stem-based tree or hedge transplants. However, adapting the technology to new species will require:

- Custom tooling for different stem sizes and root forms
- Calibration of planting depth and angle for species survival
- Field validation under varied soil types and establishment regimes

These adaptations are technically feasible due to the system’s modular design, but would require additional investment and partner trials. While willow remains the primary focus, these adjacent markets represent credible commercial pathways, particularly as policy incentives for natural capital planting and regenerative land use continue to emerge.

A significant opportunity has arisen to showcase the base vehicle at the 2026 LAMMA International Agricultural Machinery Show. A leading fertiliser manufacturer has expressed interest in displaying the vehicle alongside their products, leveraging its potential as a power source and transport solution for fertilisers in challenging conditions. This collaboration will significantly increase the visibility of the technology, attracting potential customers and partners who may identify additional applications for the base vehicle and its attachments. By demonstrating the versatility and adaptability of the technology, we can expand its market potential and generate further interest in the core application of willow cultivation.

THBUS: The THBUS has generated significant interest within the agricultural industry, even without active marketing efforts. This organic interest highlights a strong demand for innovative solutions in the sector. Numerous agricultural publications have expressed keenness to feature the machine once it has undergone rigorous field testing and proven its capabilities, and it has already featured in CLAAS Harvest Times April 2025 publication. This early interest underscores the potential impact of this technology in revolutionising agricultural practices.

A major biorefining and anaerobic digestion company [redacted] has expressed significant interest in THBUS. They see the potential of this technology to revolutionise their controlled traffic farming operations, particularly for harvesting forage crops like maize and whole crop silage. This interest validates the market demand and commercial viability of our technology.

4.4 Longer term scenario 2028-30+

We anticipate that markets for UK grown willow biomass will grow significantly over the next five years. Rising energy prices, increased scrutiny on imported biomass sustainability, and renewed government focus on land use for net zero and biodiversity are all creating a stronger demand signal for indigenous, low-carbon feedstocks like SRC willow.

We are confident that natural capital solutions will become central to how land is managed and valued, in part thanks to growing private sector interest in nature-based offsets, flood mitigation services, and soil carbon markets. Willow is uniquely positioned to provide these benefits in a stacked, multifunctional way, generating both biomass and ecosystem services. Its capacity to improve water quality, reduce flood peaks, provide shade, enhance biodiversity, and stabilise soils makes it a powerful tool for integrated land management (see Annex 7).

The NZW innovations align directly with this opportunity. By reducing the cost, labour, and risk associated with planting, harvesting, and managing SRC willow, these technologies make it practical and profitable for landowners to adopt willow as a multifunctional land use. [redacted].

Already there have been recent announcements regarding CCUS Clusters and the Hydrogen Allocation Round that includes opportunities of hydrogen from biomass[1],[2], significant increase in interest in sustainable bio-based materials such as for packaging[3], and the prioritisation of secondary use biomass for sustainable aviation fuels [4].

The NZW project benefited from DESNZ funded Catapult Accelerated Support throughout the project, totalling 12 meetings. Discussions have focussed on:

- Business model innovation
- Intellectual property
- Branding
- Patents
- International support

A commissioned report focused on the commercial aspects of the project and explored potential end-uses and markets for the technology. The report underscored the need for NZW to adapt its business model to capitalise on emerging market opportunities and navigate policy constraints to achieve commercial success.

We have taken on board the following advice:

- Explore other end uses for willow chip
- Explore other uses of the innovations
- Research international markets and crops
- Identify shifting trends in markets for willow biomass
- Develop strategies to increase demand for willow biomass
- Explore opportunities for international trade and export

We have already been proactive in exploring new markets by commissioning a report from [redacted].

4.5 Patenting and IP rights of the innovations

The intellectual property (IP) generated through the development of these innovations will be retained by Rickerby Estates Limited. [redacted].

[redacted].

As the anticipated market for NZW is likely to remain small for the foreseeable future, we will continue with the in-house development of the innovation. We are convinced that, as markets develop for willow products, that there will be a market pull for the NZW innovations.

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[1] https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-track-2

[2] https://www.gov.uk/government/collections/hydrogen-allocation-rounds

[3] https://bbia.org.uk/bio-based-and-biodegradable-materials/

[4] https://www.gov.uk/government/collections/sustainable-aviation-fuel-saf-mandate

In both cases, scaling up would involve new manufacturing facilities. This would only happen if there was clear future demand for these innovations. [redacted].

5 Secondary Project Benefits

The NZW project has provided the project team with a great opportunity to gain valuable exposure at a national and international level. This has enabled us to share our knowledge and look to build partnerships as we seek to commercialise the innovations. A full list of knowledge exchange events is detailed in Annex 10.

5.1 Dissemination activities

We have introduced farmers and other stakeholders to the NZW machinery concepts at open days and other events put on by Biomass Connect and Envirocrops.

5.1.1 Biomass Connect events

The NZW project has been introduced to farming audiences at six Biomass Connect open days show/tells around willow crops. At the Biomass Connect Innovation Showcase in November 2024, we presented the all-terrain robotic base vehicle and planting attachment. We were excited to receive significant interest from a delegate regarding the potential application of this technology for producing and planting cassava cuttings.

Figure 10: Jamie Rickerby presenting at the Biomass Connect Showcase and Kevin Lindegaard of C4E at the International Poplar Commission(see section 5.1.5).

5.1.2 Trade shows and conferences

The NZW project has maintained a strong presence across key industry events and conferences, using these platforms not just to exhibit prototypes, but to build partnerships, influence thinking, and validate market potential. Engagement at these events has yielded several tangible benefits:

- Commercial interest and adaptation ideas: Showcasing the ATRBV, RHA, RPA and THBUS at events like Groundswell, the Low Carbon Agri Show, and the All-Energy Conference generated strong industry interest, particularly in the robotic platform’s adaptability for crops beyond willow. Stakeholders in forage, cassava, and compost sectors raised credible adaptation pathways, which are now being explored further.

- Policy visibility and positioning: Participation in national-level platforms such as the NZIP Innovation Showcase and Supergen stakeholder events helped position the NZW innovations as exemplars of UK low-carbon agricultural innovation, strengthening links with DEFRA and DESNZ stakeholders and contributing to strategic discussions on sustainable biomass.
- Cross-sector learning and validation: Presenting at events ranging from BIAZA to Reverse Coal Open Days broadened the project's exposure beyond energy and agriculture. These engagements helped the team gather feedback on ecosystem services, natural capital applications, and new end uses such as animal bedding, biochar, or compost media.
- Strengthened networks and collaboration: Through trade stand collaborations with Envirocrops and Biomass Connect, the project benefited from shared outreach, expanding its network of commercial contacts, researchers, and land managers across the UK and EU.

These activities played a key role in validating the innovations, attracting interest for future demonstration trials, and shaping the commercial strategy. A full list of events and participation is provided in Annex 9.

5.1.3 USA and Canada interactions

[redacted].

5.1.4 European visits

[redacted].

5.1.5 International Poplar Conference (IPC) in Bordeaux

The International Poplar Commission (IPC) is a leading global forum for fast-growing woody crops such as willow, eucalyptus, and robinia. Its 2024 conference, held in Bordeaux (22–25 October), brought together over 150 researchers, policymakers, and industry leaders from across Europe, Asia, the Americas, and Oceania. The NZW team's presentation, featuring video demonstrations of the autonomous robotic systems, was met with strong interest. Delegates responded positively to the engineering quality, precision, and scalability of the ATRBV and its attachments, recognising their relevance to global biomass and agroforestry sectors.

The event generated valuable connections with European forestry institutes, Canadian willow breeders, and bioeconomy policy advisors, laying the groundwork for potential collaborations, regional demonstrations, and knowledge exchange. These interactions confirmed a growing international appetite for scalable, autonomous solutions in climate-smart land management and reinforced the NZW project's visibility and export potential.

5.1.6 Awards

The project has been shortlisted in REA's British Renewable Energy Awards 2025, which will increase visibility of each innovation. The finals are due to take place in London in June 2025.

5.2 Job creation

While the initial development phase of the NZW project has created roles in engineering design, mechanical fabrication, software development, and field testing, the longer-term potential lies in building a new high-skill agricultural tech sector rooted in rural areas. As the innovations transition from prototype to commercial deployment, we anticipate the creation of jobs across a range of fields including:

- Robotics support and servicing for autonomous machinery
- On-farm system operators with skills in digital oversight and machine learning integration
- Specialist biomass advisors and logistics planners
- Manufacturing, assembly, and retrofit services tailored to low-carbon agricultural equipment

Importantly, these technologies could help transform the image of farming from one of manual, labour-intensive work to a modern, tech-enabled profession. By introducing automation, data-driven tools, and precision systems into biomass and land management, there is an opportunity to attract a new generation of talent including young people who might not otherwise consider a future in agriculture. This aligns with broader aims to revitalise rural economies, improve environmental outcomes, and create meaningful, future-proof employment through innovation.

5.3 New partnerships

While no formal long-term partnerships have been established yet, the project has fostered valuable collaborations. Key collaborators are [redacted].

6 Project Management

6.1 Key risks & mitigations

The project faced several challenges, primarily related to time constraints and supply chain issues. The initial two-month delay and subsequent reduction in the project timeline put significant pressure on the team.

The following issues impacted the project:

- Global supply chain disruptions caused by the pandemic and geopolitical events led to increased costs, issues with availability of steel, and delays in procuring components and materials
- Subsequent inflation and the Cost-of-Living Crisis exacerbated this problem.
- The exchange rate of sterling against the euro was unfavourable when we had to make time-sensitive purchases of key equipment.
- We were required to pay for insurance to indemnify our sub-contractors who needed to be paid for materials as they were purchased.

System Hydraulics Ltd. has demonstrated strong commitment to the NZW project, playing a central role in the development and integration of the robotic control systems. While mechanical and hydraulic systems were delivered on schedule, the software integration component has proven more complex than originally anticipated, particularly in achieving seamless coordination between autonomous navigation, sensor input, and actuator control.

To accommodate this, a three-month project extension was approved, moving the final delivery date to 30 June 2025. System Hydraulics made steady progress throughout the extension period and successfully completed the remaining integration tasks within the revised timeframe. While previously identified as a key delivery risk on the project's critical path, this milestone was achieved as planned prior to closure. Plans are in place to support ongoing field testing and refinement activities beyond the funded period, ensuring the innovations reach full commercial readiness.

6.2 Project management lessons learned

While the project team successfully navigated numerous challenges, additional resources could have further optimised the project's execution. A larger project management team would have enabled a more focused approach, alleviated the administrative burden, and allowed for greater attention to technical details. This would have potentially accelerated the project timeline and enhanced overall efficiency. Early feedback from a Stage Gate Review increased the focus on project management and recording, which was a major benefit.

7 Conclusions & Next Steps

7.1 Conclusions

The Net Zero Willow project focused on developing innovative technologies and practices to enhance efficiency, reduce costs, and improve environmental sustainability of SRC willow cultivation. The project aimed to be an integral part of the scaling up UK biomass crops production by reducing the restrictions on field-based activities imposed by the UKs maritime climate and reliance on manual labour. By achieving this, the project would remove two of the major obstacles holding back the biomass crops sector.

The project has achieved considerable progress in the development of the All-Terrain Robotic Base Vehicle, Rod Harvesting Attachment, Rod Planting Attachment and Tracked Harvester and Bunker Unloading System. Getting such complex innovations to TRL 6 has to be considered a huge success.

NZW innovations bring about the following benefits:

- Increased productivity: Robotic systems significantly increase productivity through automation and efficient operations.
- Reduced labour costs: Automation reduces the need for manual labour, leading to significant cost savings.
- Improved efficiency: Robotic systems can operate for longer hours and at a faster pace, maximising efficiency.
- Reduced environmental impact: Lower fuel consumption and reduced soil compaction contribute to a smaller environmental footprint.

- Enhanced flexibility: Tracked harvesters and ATRBVs offer increased flexibility, allowing for harvesting and planting in wet conditions and on challenging terrain.
- Consistent quality: Automated systems can maintain consistent harvesting and planting quality, leading to healthier and more productive willow crops.
- Scalability: Multiple robotic systems can be operated by a single operator, allowing for rapid scaling of operations to meet increasing demand while reducing labour requirements.

The NZW project has unfortunately been hampered by world events that impacted supply chains and raised costs. The development of a willow-specific cutting drum was halted due to budgetary constraints.

The NZW innovations can help upscale the production of SRC, but this market push needs to be accompanied by a market pull. Despite a great many potential end uses, the planted area of SRC has reduced during the lifetime of the project. In addition, markets for SRC willow biomass have yet to mature and there have been no new market developments to encourage farmers to grow the crop.

Despite these issues the NZW team have been tireless in trying to promote SRC willows and the NZW technology that we are convinced will play a major part in meeting the upscale challenge required to meet Net Zero targets. By focusing on technology validation, strategic partnerships, and expanding market opportunities, the project team aims to position NZW technology at the forefront of sustainable agriculture and biomass production.

As part of our commercialisation strategy, we have identified several opportunities for utilising the NZW machinery with other crops and farming systems. These include cassava cultivation and Controlled Traffic Farming (CTF) systems for various crops, including maize and whole crop harvesting. Exploiting these as part of a short-term plan will put the NZW team in a good position to commercialise the innovations in readiness for upscaling willow cultivation when market conditions improve.

7.2 Next steps

To fully realise the potential of these technologies and reach TRL level 7, further field testing is required in the appropriate conditions and seasons. This will allow for a comprehensive evaluation of performance, reliability, and durability. By achieving this level of maturity, the project can contribute to the scaling up of the UK's biomass supply and support the nation's Net Zero targets.

With regards the NZW machinery, we will be looking to create partnerships with overseas organisations in Ghana, Brazil and North America. In terms of stimulating homegrown markets for willow biomass, we will be focussing on bioactive animal bedding compost, biochar and fodder. All of these uses are viewed more positively than bioenergy and should increase the value of the raw willow wood chips. Several of them could fit in with new emerging policies on agroforestry.

In order to harness the multifunctional environmental benefits of SRC willow we intend to set up a new initiative based on delivering willow solutions. This will focus on offering clients turnkey project management services using willow for flood mitigation, water quality protection and biodiversity net gain.

Annexes

Annex 1: Deliverables and financial information

Schedule, deliverables, and financial information:

Project Schedule

The provided source covers project activities and financial data spanning from April 2022 to January 2025.

Key Project Milestones:

- April 2022: Project Kick-off Meeting
- October 2022: 1st Stage Gate
- April 2023: 2nd Stage Gate
- September 2023: Site Visit from BEIS and Monitoring Officer
- November 2023: 3rd Stage Gate
- February 2024: Site visit from BEIS and Monitoring Officer
- May 2024: 4th Stage Gate
- November 2024: Draft Final Report for Phase 2
- February 2025: Final Report for Phase 2 + Public Facing Report
- March–June 2025: Project Closure Activities (Revised Timeline)
  With the project formally extended to 30 June 2025, closure activities have been rescheduled accordingly.

Deliverables

The project is structured into Work Packages (WP), with each WP encompassing specific tasks and deliverables. The source provides a detailed breakdown of these WPs, including descriptions of the work involved.

Work Package 1 - Project Management:

This WP focuses on project coordination, monitoring, and reporting.

Deliverables include:

- Regular meetings with the Monitoring Officer (fortnightly and monthly).
- Quarterly team meetings.
- Quarterly reports.
- Stage Gate Reviews.
- Site visits from BEIS and the Monitoring Officer.

- Draft and Final Reports for Phase 2.

Work Package 2 - Life Cycle Analysis (LCA):

This WP involves conducting LCAs for different stages of the machinery development.

Deliverables include LCA reports for:

- Baseline machinery.
- Prototype machines.
- Finished machines.

Work Package 3 - Design, Development, and Testing of an Autonomous, Tracked, Rubber-Tracked, Branch and Vine Remover (ATRBV):

This WP covers the design, construction, and testing of the ATRBV prototype.

Deliverables include:

- Procurement of materials and components (e.g., GPS systems, hydraulic systems, chassis materials).
- Testing of conceptual designs in a computer-based environment.
- Preparation of designs for prototype manufacture and assembly.
- Mechanical assembly of the ATRBV.
- Safety sign-off of the completed prototype (mechanical and electrical).
- Pre-commission testing and programming in a controlled workshop environment.
- Commissioning testing and software programming in the field.
- Prototype testing in the design environment during the seasonal window.
- Iteration manufacture, including the purchase of components, safety sign-off, commissioning, and prototype testing.
- Monthly review and update of the UKCA Technical File.
- Creation and updates to the Operations and Maintenance (O&M) manual.

Work Package 4 - Design, Development, and Testing of a Rod Harvesting

Attachment (RHA):

- This WP is similar in structure to WP3, focusing on the development of the RHA.

- Deliverables follow a similar pattern, including procurement, design testing, prototype assembly, safety sign-off, commissioning, testing, iteration manufacture, UKCA Technical File updates, and O&M manual creation.

Work Package 5 - Design, Development, and Testing of a Rod Planting Attachment (RPA):

- This WP follows the same pattern as WP3 and WP4, focusing on the RPA.
- Deliverables include similar stages of procurement, design, assembly, testing, iteration, UKCA compliance, and documentation.

Work Package 6 - Integration of Equipment:

- This WP focuses on integrating the developed attachments (RHA, RPA) with a forage harvester and constructing a tracked willow chip bunker.

Deliverables include:

- Procurement of equipment (e.g., cooling pump, steel for bunker, unloading motors, forage harvester).
- Construction of the forage harvester to bunker pivot point and the tracked willow chip bunker.
- Assembly of the hydraulic system.
- Assembly and programming of the electrical and control system.
- Pre-commission testing.
- Prototype testing in the design environment.
- Iteration manufacture, including procurement, assembly improvements, and testing.
- Manufacture of custom guarding for the harvester and bunker.
- Full season of testing and stakeholder engagement.
- UKCA Technical File updates.
- O&M manual creation.
- Final assembly and testing in Switzerland.
- Factory acceptance testing (FAT) in Switzerland.
- Site acceptance testing (SAT) in the UK.

Work Package 7 - Development of a Willow Cuttings Drum:

This WP concentrates on designing and fabricating a specialized drum for willow cuttings.

Deliverables include:

- Material procurement.

- Prototype design and fabrication.
- Fitting the drum to the harvester.
- Pre-commission testing.
- Prototype testing.
- Preparation of designs for iteration manufacture.
- Iteration fabrication and fitting of the drum.
- Iteration testing.
- Full season of testing and stakeholder engagement.

However, due to budgetary pressures and strategic project reprioritisation, this work package was curtailed midway. The project team concluded that the remaining financial resources would be more effectively deployed in supporting the Tracked Harvester, Unloading and Bunker System (THBUS), which was experiencing increased costs due to global supply chain issues and post-COVID impacts. As a result, development of the cutting drum was halted, and the associated UKCA Technical File updates were removed from scope. This reallocation was made in alignment with project objectives to ensure the most viable and impactful innovation could be completed within the revised project budget and timeline.

Work Package 8 - Evaluation and Analysis:

This WP encompasses evaluation and analysis activities related to various machinery components.

Deliverables include:

- In-house evaluations of the Rod Harvesting Attachment, Rod Planting Attachment, and Willow Harvester.
- Independent evaluation, analysis, and verification of machinery testing.
- Site visits by BEIS.
- Analysis and reporting.

Work Package 9 - Commercialisation:

This WP is dedicated to the commercialisation aspects of the project.

Deliverables include:

- Development of a commercialisation plan.
- EU and non-EU policy analysis.
- Identification of important contacts abroad.
- Exploration of patenting and IP rights.
- B2B discussions with machinery manufacturers and venture capitalists.
- Farmer demonstrations.

- Hosting a trade mission.
- A report on commercialisation.

Work Package 10 - Holding Milestone for Willow Header Fund:

This WP seems to be a placeholder for a funding allocation.

Financial Information

The source provides a detailed breakdown of forecasted (baseline) costs and actual spending for each Work Package and task.

Total Project Costs:

Forecast (Baseline): £3,997,886

Actual (Invoiced to Date): £3,993,386

Annex 2: [redacted]

Annex 3: Key Performance Indicators matrix

The figures presented in this table represent estimated performance improvements based on a combination of early field testing, engineering modelling, operational logic, and commercial experience. While precise outcomes will require further post-project validation, the rationale provided reflects the project team's current understanding of the innovations' likely benefits. The column titled "Basis for Estimate" should be interpreted as a summary of rationale and influencing factors, rather than a strict list of technical assumptions.

Innovation	KPI	Current situation	New situation based on successful deployment of the innovation	% improvement	Basis for Estimate	Confidence Level
ATRBV + RHA	Hectares of planting rods per 1 hectare of multiplication	30	45	50% increase	Usually, each 2m rod used in the conventional Step Planter method requires one whole rod. The top 1.5-2m of material is wasted. The NZW can use this material.	Very
ATRBV + RHA	Total cost of production of 1 hectare or 15,000 20cm willow cuttings	£973	£773	20% reduction	Reduction in labour	Very
ATRBV + RPA	Cost of energy per hectare planted	£21	£1.90	91% reduction in energy consumption and emissions	The current system uses a heavy tractor and requires diesel. The new system uses a light machine powered by batteries.	Very
ATRBV + RPA	Machinery Weight	8,000 kg	1,500 kg	81% reduction		Certain

Innovation	KPI	Current situation	New situation based on successful deployment of the innovation	% improvement	Basis for Estimate	Confidence Level
ATRBV + RPA	Establishment strike rate	90%	99%	10% increase	The current system presents a best-case scenario - a well-prepared seed bed, good quality rods, a good planting team and well serviced machinery. In many cases the strike rate will fall below 90%. The current system has lots of opportunity for mechanical and human error. The NZW system maximises quality and simplifies the process.	Very
ATRBV + RPA	Overall cost to plant 1 hectare of willow at 15,000 20cm rods	£467	£296	57.5% reduction	The cost of red diesel is £0.80 per litre and the cost of charging batteries is £5.40. Planting one hectare requires 20 litres of diesel and 3 persons costing £90. The robot would require 6 kWh of battery power and one person operating the unit costing £30.	Reasonably
THBUS	Harvesting cost per green tonne	£30	£26	13% reduction	The current system requires one harvester, two tractors and trailers and three persons costing £1500 per hectare. The new system would require the harvester and one person costing £1300 per hectare. There is also a 30% reduction in diesel used.	Reasonably
THBUS	Min number of machines required to harvest willow	4	1	75% reduction	This based on current harvesting system	Certain

Innovation	KPI	Current situation	New situation based on successful deployment of the innovation	% improvement	Basis for Estimate	Confidence Level
THBUS	Diesel to harvest 1 green tonne of willow chip	6 litres	4.2 litres	30% reduction in fuel consumption and emissions	The current system requires one harvester and two tractors and trailers. The new system would require just the harvester. The latter is bigger than the current harvester but still a lot less because there is no need for the additional tractors and fuel wasted on double handling	Reasonably
THBUS	Potential amount of willow chips harvested per season	14,400 t	23,400 t	62.5% increase	The seasonal window for the current system is much less than the new system. The current harvester can cut 34 tonnes per hour whilst the new system will be able to cut 32 tonnes per hour but be able to operate for 35 more days per year. The new system is more robust and there will be fewer breakdowns.	Very
THBUS	Area of willow harvested per season	320 hectares	520 hectares	62.5% increase	The seasonal window for the current system is much less than the new system. The current harvester can cut 4 hectares per day whilst the new system will be able to cut 200 tonnes per day but be able to operate for 35 more days per year. The new system is more robust and there will be fewer breakdowns.	Very

Note on Confidence Ratings:
These are qualitative assessments based on the maturity of development, early-stage testing results, and engineering certainty.

- *Certain*: Outcome is already observed or proven under field conditions.
- *Very*: High confidence based on modelling, design data, or partial validation.
- *Reasonably*: Supported by logic or preliminary testing, but needs further validation.
- *Somewhat*/*Low*: Early-stage estimate with significant unknowns or dependencies.

Annex 4: Economic benefits for SRC willow growers and users

Table 1: Savings in production costs and increases in grower income based on replacing the current SRC scenario with a Net Zero Willow alternative.

	Total yield from 1 hectare over 22 yrs (odt) Establish-	ment costs £/ha	Harvest-ing £/ha	Transport £/ha	On site handling and Storage £/ha	Process-ing costs £/ha	Total costs per hectare over 22 yrs	Production costs £/odt	Production costs £/tonne @ 30% MC	Production costs **£/green tonne**	Grower Income Life-time	Grower Income Per harvest	Grower Income Per year
Current scenario	**165**	£2,275	£5,133	£3,667	£1,833	0	£12,908	£78.23	£54.76	**£35.20**	£7,700	**£1,100**	£350
Net Zero Willow scenario	**204**	£1,696	£5,440	£4,533	£0	0	£11,670	£57.20	£40.04	**£25.74**	£9,520	**£1,360**	£433
Net differential	**39**	£579	-£307	-£867	£1,833	£0	£1,239	£21.03	£14.72	**£9.46**	£1,820	**£260**	£83

The above table is based on medium yields. We have assumed the following:

Scenario	Scale & locality
Current scenario	20-hectare planting, reasonably close (<100 miles round trip) from planting/harvesting contractor and <50 miles from power plant.
Net Zero Willow scenario	20-hectare planting, reasonably close (<100 miles round trip) from planting/harvesting contractor and <50 miles from power plant.
	Yield
Current scenario	Yield of 165 odt equals first harvest yield of 7 odt/ha/yr and 6 subsequent harvests of 8 odt/ha/yr.
Net Zero Willow scenario	Yield of 204 odt equals first harvest yield of 8 odt/ha/yr and 6 subsequent harvests of 10 odt/ha/yr.
	Establishment
Current scenario	£2,275 made up of £950 for plant material and transport, £575 for planting charge and £400 cultivations, sprays and £350 for gapping up.
Net Zero Willow scenario	15% savings on plant material (£807.50) and contract planting (£488.75). Gapping up not required.
	Harvesting
Current scenario	Seven harvests over a 22-year period. Cost of £14/green tonne harvested.
Net Zero Willow scenario	Seven harvests over a 22-year period. Costs reduced by ~15% to £12/green tonne harvested. Higher overall costs due to higher yields.
	Transport
Current scenario	Assumes relatively good transport links and <30km from power station. No difference as cost of transport to end user will be the same.
Net Zero Willow scenario	Assumes relatively good transport links and <30km from power station. No difference as cost of transport to end user will be the same.
	On site handling and Storage
Current scenario	On site storage and handling costs of £5/green tonne due to use of tractors, trailers and loaders.
Net Zero Willow scenario	No onsite handling costs as material is taken straight away to the end user.
	Processing costs
Current scenario	No processing, as assumed end user is a power station or biomass trader.

Net Zero Willow scenario	No processing, as assumed end user is a power station or biomass trader.
	Production costs
Current scenario	Calorific value of oven dry SRC chip is 5,140 kWh per tonne. Moisture content is 55% at harvest.
Net Zero Willow scenario	Calorific value of oven dry SRC chip is 5,140 kWh per tonne. Moisture content is 55% at harvest.
	Grower income
Current scenario	Assumes end user paying £21 per green tonne ex farm.
Net Zero Willow scenario	Assumes end user paying £21 per green tonne ex farm.

Table 2: Savings in production costs and reduction in delivered energy costs based on replacing the current SRC scenario with a Net Zero Willow alternative.

	Total yield from 1 hectare over 22 yrs (odt)	Establishment cost £/ha	Harvesting £/ha	Transport £/ha	On site handling and Storage £/ha	Processing costs £/ha	Opportunity costs £/ha	Total costs per hectare over 22 yrs	Production costs £/odt	Production costs **£/tonne @ 30% MC**	Production costs £/green tonne
Current scenario	**165**	£2,800	£5,133	£0	£3,667	£3,667	£4,950	£20,217	£122.53	**£85.77**	£55.14
Net Zero Willow scenario	**204**	£1,893	£5,440	£0	£3,400	£4,533	£4,950	£20,216	£99.10	**£69.37**	£44.59
Net differential	**39**	£908	-£307	£0	£267	-£867	£0	£1	£23.43	**£16.40**	£10.54

The above table is based on medium yields. We have assumed the following:

Scenario	Scale & locality
Current scenario	5-hectare planting. Replacing 200,000 kWh of purchased biomass with SRC chip. A very long way (~500 miles round trip) from planting/harvesting contractor.
Net Zero Willow scenario	5-hectare planting. Replacing 200,000 kWh of purchased biomass with SRC chip. A very long way (~500 miles round trip) from planting/harvesting contractor.
	Yield
Current scenario	Yield of 165 odt equals first harvest yield of 7 odt/ha/yr and 6 subsequent harvests of 8 odt/ha/yr.
Net Zero Willow scenario	Yield of 204 odt equals first harvest yield of 8 odt/ha/yr and 6 subsequent harvests of 10 odt/ha/yr.
	Establishment
Current scenario	£2,800 made up of £1,050 for plant material and transport, £1,000 for planting charge and £400 cultivations, sprays and £350 for gapping up.
Net Zero Willow scenario	15% savings on plant material (£892.50) and 40% on contract planting (£600). Gapping up not required.
	Harvesting
Current scenario	Seven harvests over a 22-year period. Cost of £14/green tonne harvested.
Net Zero Willow scenario	Seven harvests over a 22-year period. Costs reduced by ~15% to £12/green tonne harvested. Higher overall costs due to higher yields.
	Transport
Current scenario	No transport costs as material moved direct to storage.
Net Zero Willow scenario	No transport costs as material moved direct to storage.
	On site handling and Storage
Current scenario	On site storage and handling costs of £10/ green tonne due to use of tractors, trailers and loaders.
Net Zero Willow scenario	On site storage and handling costs of £7.50/ green tonne.
	Processing costs
Current scenario	Dying using biomass - assumed £10 per wet tonne.
Net Zero Willow scenario	Dying using biomass - assumed £10 per wet tonne.
	Opportunity costs
Current scenario	Assumes lost farm income of £225 per hectare (£90 per acre) for 22 years.
Net Zero Willow scenario	Assumes lost farm income of £225 per hectare (£90 per acre) for 22 years.
	Production costs

Current scenario	Calorific value of oven dry SRC chip is 5,140 kWh per tonne. Moisture content is 55% at harvest.
Net Zero Willow scenario	Calorific value of oven dry SRC chip is 5,140 kWh per tonne. Moisture content is 55% at harvest.
	Delivered energy costs
Current scenario	Assumes calorific value of 5,140 kWh per oven dry tonne.
Net Zero Willow scenario	Assumes calorific value of 5,140 kWh per oven dry tonne.

Tables 3 & 4: Improvements in farmer revenue based on 10,000 hectares of willow planted under the Net Zero Willow pathway.

Savings during cultivation	Current price per hectare	Future price as a result of innovation	Saving per hectare	Farmer saving for 10,000 hectares One off saving	Farmer saving for 10,000 hectares Saving over 21 years (7 harvests)
Planting material per hectare	£950	£808	£143	**£1,425,000**	n/a
Contract planting	£575	£489	£86	**£862,500**	n/a
Contract harvesting	£733	£628	£105	£1,050,000	**£7,350,000**
					£9,637,500

Increased revenue from sales	Current yield per hectare per harvest (green tonnes)	Future yield per hectare per harvest (green tonnes)	Current yield per hectare per harvest (boiler ready tonnes)	Future yield per hectare per harvest (boiler ready tonnes)	Increase yield per hectare	Avg sale price per tonne	Farmer revenue increase for 10,000 hectares	Farmer revenue increase over 21 years (7 harvests)
Increased yield and increased quality	55	65.8	35.36	42.3	6.94	£110	£7,634,000	**£53,438,000**

Total benefit over 21 years	**£63,075,500**
Total benefit per hectare	£6,307.55

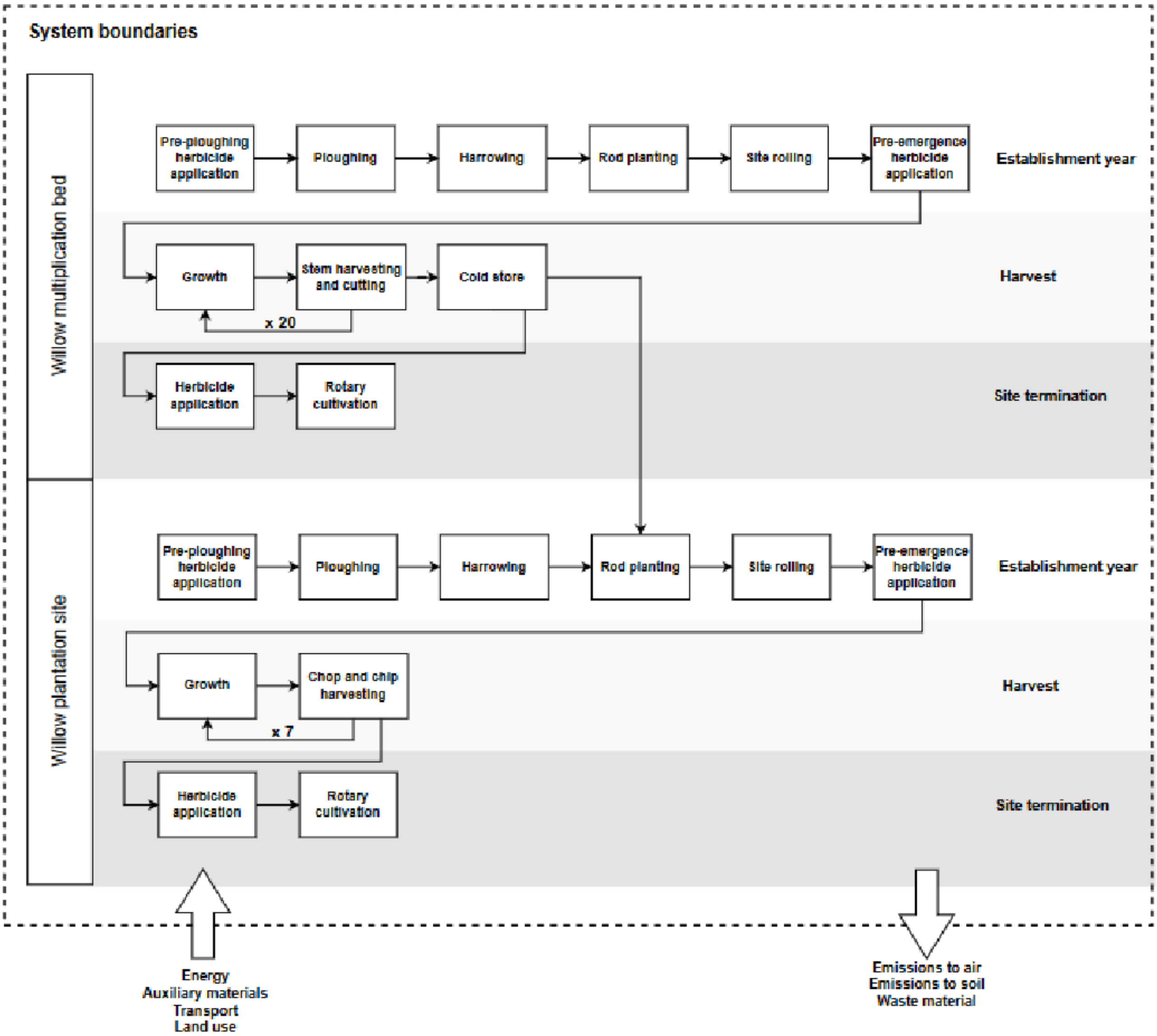
Total benefit per hectare per year	£420.50

Annex 5: Life Cycle Analysis

Summary of process steps to produce willow biomass chips.

Life cycle stage	Short description of the processes included
Establishment year	This stage involves pre-planting field preparation by applying a herbicide, which is followed by ploughing and harrowing. Willow rods are then planted (the current model uses a tractor and step planter, while the future model uses an ATRBV and RPA), followed by site rolling to ensure the rod is in good contact with the soil. Later in the year a pre-emergence herbicide is needed to control competition from weeds.
Rod harvesting	Two years after planting, the multiplication bed is harvested yearly. In the current model harvesting is done by hand and consists of cutting 3 m stems. 1 m is then cut and discarded from the top to produce a 2 m rod ready to be used with a step planter. In the future model 20cm rods are harvested with an ATRBV and RHA.
Cold storage	After harvesting, the willow rods are stored in a cold dark place to keep the plants dormant until they are ready to be planted.
Transport to plantation site	Planting and chip harvesting equipment, along with willow rods for propagation, are driven or transported to different plantation site locations.
Chop and chip harvesting	Each 3 years after the initial establishment year the plantation site is harvested using a chop and chip harvester. The current model consists of a harvester accompanied by a tractor and trailer that follows alongside to collect the freshly chopped willow chips. The future model is based on a harvester pulling a bunker to collect willow chips. In this case both the harvester and bunker have tracks.
Site termination	At the end of the site lifetime the site is terminated by applying a herbicide and turning the soil with a rotary cultivator.

Life cycle flow diagram to produce willow biomass.



Annex 6: Willow Energy year on year involvement in SRC planting & harvesting

Year	Amount planted Number of farms	Amount planted Total area (ha)	Amount harvested Number of farms	Amount harvested Total area (ha)
2015	4	55	8	125
2016	6	64	10	155
2017	7	87	11	143
2018	6	115	9	137
2019	5	83	12	184
2020	3	46	7	107
2021	3	33	11	129
2022	2	11	9	107
2023	3	7	8	95
2024	1	6	6	88
2025	1	1	5	87

Annex 7: Potential applications & end-users for willow biomass

Willow chips present a versatile material that can be used in many disciplines both in a raw form or processed into a refined material. There are several potential end users of willow chip including:

Bioenergy:

- Biomass Boilers: Willow chips can be used as a fuel source for biomass boilers, providing heat and electricity for domestic and commercial buildings.
- Biogas Production: Willow chips can be used in anaerobic digestion to produce biogas, which can be used for electricity generation or heat production.
- Biofuels: Willow can be used as a feedstock for advanced biofuels, such as cellulosic ethanol

Biomaterials:

- Bio-based materials, such as bioplastics and biocomposites reducing reliance on fossil fuel-based products.

Biochar:

- Biochar, a carbon-rich material derived from biomass, offers numerous applications, including soil amendment, water filtration, and carbon sequestration.

Soil Amendment and Compost:

- Soil Conditioner: Farmers and gardeners can use willow chips as a soil amendment, mulch and soil conditioner to improve soil structure and fertility.
- Compost: Willow chips can be composted to produce a high-quality organic fertiliser.
- Bioactive bedding for animals.

Animal Feed and Supplements:

- Ruminant Feed: Initial scientific results suggest that the use of willow as a feed additive or supplement for ruminant animals can significantly reduce methane emissions from burping.
- Pharmaceutical and Cosmetic Applications: valuable compounds from willow (such as salicins and salicortins) can be extracted for use in pharmaceutical and beauty products.

Solutions to environmental problems

- Flood mitigation: hydraulic roughness offered by SRC can reduce velocity of water and provide more time for people to react to flooding events whilst also stopping floating objects causing damage to properties and blocking culverts and bridges.
- Water quality: SRC can be used as a means of pollution control for point sources of effluent and diffuse run off from agricultural land.

- Agroforestry and buffer strips: SRC can be deployed to offer the above applications whilst also providing wildlife corridors, shelter and fodder for animals or sources of wood chip for animal bedding.
- Ecosystem services: SRC willow supports a biodiverse flora and fauna and provides many feeding opportunities for invertebrates, birds and mammals. Many of the insects supported provide additional benefits e.g. willow catkins provide an early source of pollen and nectar and attract pollinators which are beneficial to local food crops. Also, willow crops support predatory arthropods that are useful as natural pest control measures.

Annex 8: Net Zero Willow commercialisation scenarios

Circumstance	Type	Scenario	What this means	Outcome for NZW
Head wind	Policy	Policy turns against biomass crop planting; Environmental NGOs remain opposed to biomass crops; Existing rules are tightened - for instance summer harvesting is prohibited and/or winter/spring machinery activities restricted due to damage to soils	More difficult to persuade farmers to plant due to incentives for Regen agriculture and woodlands and no grants for biomass; Existing growers pull out their crops;	Bot machine in current form is not useful and either remains redundant or needs a lot more additional investment to be adapted for other uses (e.g. tree planting); Very limited potential for scaling up manufacture without further investment; Harvesting machinery is useful for a period but mainly to harvest for growers who are pulling out their crops; Very expensive kit to maintain but fewer skilled individuals capable of doing this; Need to find funding to adapt bot to other, more easy to penetrate, broader uses e.g. strip tillage, weeding, tree planting etc; Need to concentrate existing machines on export market in countries where SRC willow cultivation is encouraged and/or remains a suitable crop option.
Head wind	Markets	Markets remain small and niche	No chance of achieving economies of scale where expensive machinery can be justified	
Head wind	Infrastructure	No call for additional infrastructure or machinery	Existing contractors withdraw; No new entrants;	No interest in SRC machinery development leading to brain drain to other disciplines; Current contractors take on other work

Circumstance	Type	Scenario	What this means	Outcome for NZW
Head wind	Versus alternative biomass crops	Biomass Connect trials indicate that other biomass crops are better suited to the UK climate; Farmer preference drawn to alternative options that are easier to grow; easier to harvest; easier to make money from or have more markets	Even lower interest in willow	Only option is to adapt machinery to other uses or leave industry; No point in trying to continue with SRC willow as a business venture leading to exit of leading innovator in this sphere
Head wind	Climate	UK winter climate continues to worsen making it even more difficult to get on the land during dormant season; Impossible to plant/harvest at correct time of year	Ever narrowing window of opportunity for getting on the land; Existing growers have to wait and may get their crops planted/harvested at the wrong times leading to poor results and disgruntled growers; Grubbing out existing crops will lead to release of C from soil; Reversion to food crops on the land will lead to further increases in C emissions as a low input option will be replaced by a high input option	If contractors pull out, then so will farmers;

Circumstance	Type	Scenario	What this means	Outcome for NZW
Status quo	Policy	No new policy instruments for planting biomass crops; Or, policy and incentives don't come on line until 2027-28: Or, policy comes on line but is still not lucrative enough to attract sufficient farmers to plant	Small amount of planting stimulated	Very little opportunity to use NZW innovations; No immediate need to build additional machines
Status quo	Markets	Some markets open up but organic growth providing very specific, niche opportunities for well placed, experienced or well-resourced companies	Lack of growers equals lack of biomass material produced. A chicken and egg scenario remains in place as farmers are persuaded to plant, and big companies are not attracted by the investment opportunity into an immature market.	NZW is well placed to harness limited opportunities, but small markets will never provide a return on investment to UK Plc from the £4 million investment.
Status quo	Infrastructure	There is just about enough work to keep 1-3 companies in the game	Machinery is only available in certain parts of the country, and it is very expensive to move to and prevents the industry developing outside of key existing areas	NZW is unlikely to expand operations beyond north west. This will limit opportunities for would be growers across the UK; No net expansion in the market means that existing but less efficient machinery such as the Step Planter remain a viable option.
Status quo	Versus alternative biomass crops	SRC willow remains a part of the potential crop options but is not particularly favoured (Miscanthus remains the main choice for farmers)	Insignificant increase in planting. Very little upscale. Probably as much planted as removed so no growth.	Very few opportunities for commercialisation in the UK; Hard to justify commercialising varieties and multiplying.

Circumstance	Type	Scenario	What this means	Outcome for NZW
Status quo	Climate	The winter conditions remain very challenging, but the NZW machinery is shown to cope well with these conditions	Machinery demonstrates promise, but cost is generally prohibitive because without financial and policy support for the crop.	The concept is proven but there is no space to commercialise into.
Tail wind	Policy	Policy instruments fall into place for biomass crops - either blanket SFI options or specifically targeted regional schemes to meet a specific need;	Encouragement to growers to plant and gives the industry the right signals for major investment;	[redacted]

Circumstance	Type	Scenario	What this means	Outcome for NZW
Tail wind	Markets	Markets develop for the biomass material produced; Biomass crops considered as a good crop option to reduce a farm's GHG footprint; SRC willow considered a go to choice for flood mitigation projects, buffer strips and agroforestry planting	The push provided by incentives will bust the chicken and egg issue and encourage major investors into the sphere; This will lead to new market entrants at all part of the supply chain who will aim to compete with each other providing better services and better prices for farmers; Additional investment will lead to more innovations; increased best practice; higher yields and improved quality; This will lead to a snowball effect leading to more momentum and greater expansion of the industry and enable environmental protection and biodiversity benefits to be achieved and Net Zero targets to be met; Rising revenues lead to more innovations and better outcomes for in all parts of supply chain	A major expansion in the planted area of SRC willow would make the bot much more necessary as older equipment requiring manual labour would not be able to meet demand. This would lead to a full order book for UK plantings:

Circumstance	Type	Scenario	What this means	Outcome for NZW
Tail wind	Infrastructure	Demand for infrastructure and machinery increases due to incentive push and market pull	Machinery will become commonplace and more widely available across the country; A skills base will be created encouraging training opportunities and new jobs	Positive growth forecasts and company expansion will encourage major investors which will enable even bigger scale up and fund innovations that allow the bot to be used for lots of other uses; Such cash injection would be transformative and allow the bot to become part of mainstream land management activities with even wider possibilities for worldwide deployment
Tail wind	Versus alternative biomass crops	SRC willow becomes the main choice of farmers based on yields, incentives, markets, environmental protection and biodiversity benefits	The biomass crop with the most "native" credentials is adopted as the best option for the UKs challenging, temperate climate. The adoption of a biodiversity gold standard approach to planting allows trends in biodiversity to be monitored over a longer term.	
Tail wind	Climate	The winter climate conditions remain very challenging, but the NZW machinery is shown to cope well with these conditions;	Difficult farming conditions for all crops especially conventional food crops. SRC willow is better equipped than most to thrive and allow farmers to produce ecosystem services and profit from difficult land. SRCs wider benefits enable it to be part of a mosaic farming system that allows adaptation to climate change.	Incentives and market pull enable investment to continue to develop, refine and improve machinery so that operations lead to even lower impact on the soil and reduced LCA GHG emissions

Circumstance	Type	Scenario	What this means	Outcome for NZW
Strong tail wind	Policy	Working biomass crops policy attracts attention from other countries who wish to replicate the success	More SRC willow planted in other countries	Great opportunity to benefit from upsurge in demand for planting and harvesting machinery and new varieties
Strong tail wind	Markets	A strong (world leading) UK market leads to opportunities for this to be replicated in temperate climates across the world	An industry that is the envy of the world; expansion opportunities for UK companies to export and build partnerships abroad; Opportunities for UK academic organisations to train overseas students in this area	The mass take up of NZW technology in the UK would lead to enormous potential for export opportunities transforming the products from a niche/bespoke manufacturing enterprise into a much larger enterprise generating economic benefits to the north west and creating many technical, well-paid jobs.
Strong tail wind	Infrastructure	Development of more machinery that is smaller, more efficient, cheaper and not requiring manual labour but high skilled individuals;	Potential wholesale change to the way farming is conducted;	
Strong tail wind	Versus alternative biomass crops	A large industry surrounds SRC willow; This is accompanied by more academic funding which will enable more unknowns to be researched (particularly pharmaceuticals and high value products);	A potential return on investment from over 50 years of UK R&D support for SRC willow; Development of the biorefinery approach will lead to greater returns to growers and people involved in the supply chain making willow a cash crop	

Circumstance	Type	Scenario	What this means	Outcome for NZW
Strong tail wind	Climate	The winter climate conditions remain very challenging, but the NZW machinery is shown to cope well with these conditions;	Impact of agricultural production methods on GHG emissions significantly reduced	

Annex 9: [redacted].

Annex 10: [redacted]