IAgrE Student Awards

NOMINATION SUMMARY

IAgrE Student Project Award*		
PROPOSER: (usually Course Director/Head of Department)		
Name: Prof Paul D Brown, ALCM, BSc, PhD, PGCAP, DSc, CPhys, FInstP, FRMS		
Position: Professor of Materials Characterisation, & Director of the Nanoscale & Microscale Research Centre (nmRC) *(Final year project supervisor for Barnabas Pickford)*		
University/College: (name and address) Department of Mechanical, Materials & Manufacturing Engineering, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, UK.		
Contact details:	**Tel:** +44 (0) 115 9513748	**Email:** paul.brown@nottingham.ac.uk
DETAILS OF NOMINATION:		
Name of Student/Group of Students: Barnabas Pickford		
Personal contact details (i.e not college) to enable us to contact the student(s) once their course has ended: **Home Tel:** 01249822884 **Mob** *(preferred)*: 07876838111 **Email:** barneyrpickford@gmail.com		
Name of course studied: MEng Hons Mechanical Engineering including an Industrial Year		
Period studied	**From:** 21/09/2020	**To:** 21/06/2025
Qualification to be gained: MEng (Hons)		
Project Title: An Appraisal of Candidate Powertrains for Today's Dynamic Agricultural Vehicles		
Details of material submitted with nomination: (Project/Exec Summary/videos etc) See attached files entitled: 1 Final Project Report; 2 Project Presentation ppt; 3 Final Reflective Report; 4 Final Skills Reflection Report; 5 Interim Progress and Planning Report; & 6 Interim Skills Reflection and Ethics Report. Presented to demonstrate the academic & professional development of Barnabas throughout the duration of his final year project (40 credits equating to 1/3 of his final year mark), in accordance with IMechE principles underpinning this accredited MEng Hons Mechanical Engineering degree programme. Barnabas graduated with an extremely well-deserved 1st Class degree (including a 1st class mark gained for his final year individual project).		
SIGNED BY PROPOSER:	**DATE SUBMITTED:** 22/09/2025	

If you wish to provide any additional information to support this nomination, please do so in a covering letter. When complete, return this form, together with the supporting documents, to

The Secretariat, IAgrE, The Bullock Building (Bldg 53), University Way, Cranfield, Bedford MK43 0GH
secretary@iagre.org

NB All work submitted is treated with complete Confidentiality; no part of the paper will be published by IAgrE except for the Title and Name of the winner in each category.

To The Secretariat, IAgrE,
The Bullock Building (Bldg 53),
University Way, Cranfield, Bedford MK43 0GH
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22-09-2025

Re: Nomination for Barnabas Pickford (IAgrE Student Project Award)

To whom it may concern,

I am happy to provide a very positive letter of support for Barnabas Pickford's nomination for an IAgrE Student Project Award.

I write as project supervisor for Barnabas during the final year on his MEng Hons Mechanical Engineering (including Industrial Year) degree programme, here in the Department of Mechanical, Materials & Manufacturing Engineering at the University of Nottingham.

Barnabas was a notable project student from the outset, being thoroughly professional and proactive in the development of his research project, entitled "*An Appraisal of Candidate Powertrains for Today's Dynamic Agricultural Vehicles*." The project topic was initiated by Barnabas, based on his industrial placement experience, and his desire to develop knowledge and understanding of candidate powertrains and fuel sources for next generation agricultural vehicles, guided by concerns over climate change, the cyclic economy, and the need for long term sustainability.

The project was developed around the principles and practice of Life Cycle Analysis (LCA) modelling techniques, sensibly applied to a 155 hp tractor case study in the first instance, demonstrating appreciation of a systematic approach to LCA and the importance of associated boundary conditions. The project then progressed onto the development of LCA strategies for the appraisal of eight different candidate fuel/powertrain configurations, with use of greenhouse warming potentials (GWP) enabling effect comparisons to be made.

Taking diesel internal combustion engines (ICE) as a baseline, significant reductions in GWP were demonstrate for hydrogen fuel cell electric and hydrogen ICE vehicles, followed by strong promise for battery electric, biomethane ICE and synthetic/biodiesel vehicles. However, it was recognised that no universal solution exists, with results strongly dependent on fuel production methods (*e.g.* through comparisons of hydrogen production via electrolysis, electricity production from wind turbines and the use of low-emission biodiesel feedstocks), demonstrating need for technology selection to reflect the farming context.

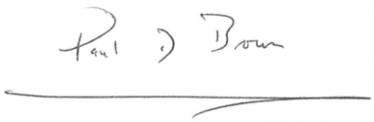
This led to several important insights, including recognition that a switch to biodiesel is viable, but may not be a long-term answer due to land-use concerns. Hence, attention should be given to combinations of on-farm solar, wind, hydrogen electrolysers or biomethane infrastructure, with hydrogen ICE, biomethane ICE and battery electric vehicles looking highly promising long-term solutions, depending on vehicle requirements and the farming sector.

Overall, the study highlighted the urgent need for agricultural specific, systems-based decarbonisation strategies, and has provided a foundation for informed decision making across the agricultural sector.

Barnabas adopted a thorough professional and remarkably logical approach to the conduct of his project throughout; testament to his character combined with recognition of his study support plans (in this case dyslexia). He recognised the importance of focusing on the more difficult challenges early on and displayed very good ability sourcing technical content and supporting information, combined with a consistent approach to gain understanding of the underpinning LCA methodology and identify reliable input data. A very strong work ethic was shown throughout, with willingness to ensure authoritative outputs were obtained. Overall, this was an excellent attempt at a very challenging, student-led project, with many interesting data sets and sensible interpretations & recommendations returned.

Barnabas has shown himself to be a very diligent and self-motivated project student, being able to embrace all challenges with dedicated interest and good humour. Hence, I am confident he is a worthy recipient of a IAgrE Student Project Award and will prove to be an excellent ambassador for IAgrE in the future. I am happy to provide the strongest recommendation.

Yours faithfully



Paul D Brown, ALCM, BSc, PhD, PGCAP, DSc, CPhys, FInstP
Professor of Materials Characterisation

M.Eng. Individual Research Paper 2024/25

An Appraisal of Candidate Powertrains for Today's Dynamic Agricultural Vehicles

B. R. Pickford, P. D. Brown
Faculty of Engineering,
University of Nottingham, UK

ABSTRACT

Agriculture contributes 17.9% of global greenhouse gas emissions. With diesel-powered tractors at the heart of the industry's energy use, transitioning to sustainable powertrains is vital; however, few studies have addressed this challenge in a practical, farm-specific context. This study aims to appraise candidate powertrains for today's agricultural vehicles using cradle-to-grave (CTG) life cycle assessment (LCA) of a 155 hp tractor. The LCA considered the vehicle's impact over a lifetime of 12 years, covering 12,000 working hours, with eight different fuel/powertrain configurations. The LCA assessed global warming potential (GWP) impact from material extraction to vehicle disposal, including fuel production and use, maintenance and manufacturing.

The hydrogen fuel cell electric vehicle achieved the lowest CTG GWP, 90% lower than the diesel baseline, closely followed by the hydrogen ICE vehicle (88% reduction). Battery electric, biomethane ICE and synthetic/biodiesel vehicles also showed strong performance with 81%, 78% and 79% reduction, respectively. However, these results depend on fuel production methods with minimal GWP impact; for instance, using hydrogen produced entirely via electrolysis, electricity produced from 100% wind turbines and low-emission biodiesel feedstocks.

These findings also show no universal solution exists, so technology selection must reflect the farm context. An immediate switch to biodiesel is viable, but is not a long-term answer due to land-use concerns. With on-farm solar, wind, hydrogen electrolysers or biomethane infrastructure, H_2 ICE, biomethane ICE and battery electric vehicles are likely long-term solutions, depending on vehicle requirements and the farm sector.

While this study provides a comprehensive CTG assessment of global warming potential, further research should expand to additional impact categories, incorporate more detailed end-of-life modelling, and evaluate hybrid powertrains to enhance the robustness and applicability of the findings.

Ultimately, this study highlights the urgent need for agricultural specific, systems based decarbonisation strategies and provides a foundation for informed decision making across the agricultural sector.

1. INTRODUCTION

1.1 Background & Context

Many of the world's most powerful economies have made commitments to be carbon neutral by 2050 [1]. Coupled with a growing world population expected to reach 9.7 billion in the same timeframe, feeding this population while meeting UN Sustainable Development Goals will be a major challenge. Currently, the agricultural industry directly contributes to 17.9% of global greenhouse gas (GHG) emissions, greater than the whole transport industry combined (16.2%) [2]. Energy use within agriculture is attributed to 1.7%, comparable to the shipping (1.7%) and aviation (1.9%) industries, which are commonly given huge focus in the global climate debate.

Sustainable agricultural practices will undoubtedly play the most crucial role in decarbonising agriculture. However, by replacing the dominant diesel internal combustion engine (ICE) in dynamic agricultural vehicles (AV) and adopting renewable electricity, 1.7% of global emissions attributed to agriculture's energy use could be significantly reduced.

The diesel ICE powertrain has been dominant in agriculture since its widespread adoption in the 1960s due to its high torque, energy density, low-cost, and ease of refuelling [3]. However, the emissions from these engines remain a significant issue that the industry has not yet tackled.

1.2 Motivation & Aim

The agricultural industry is complex and lags behind other sectors in adopting sustainable powertrains. This means there are limited alternative powertrain vehicles on the market and limited sales compared to the road transport industry.

Despite this, major AV manufacturers and research organisations are investing in alternative powertrains. Several electric tractors are on the market at the smaller end of the scale, and the New Holland T6.180 Methane Power (Figure 1) has been in production since 2022 [4]. Other potential candidate fuels and powertrains include hydrogen (H_2) ICE or fuel cell electric (FCE), biodiesel, bioethanol, LPG and battery electric (BE).

Figure 1: The first commercially available CNG tractor: New Holland T6.180 Methane Power [4].

This report aims to appraise the candidates to clarify the picture and help farmers, manufacturers, and policymakers evaluate each powertrain's viability. This will enable them to invest confidently in powertrains that will significantly reduce GHG emissions from agriculture.

1.3 Life Cycle Analysis (LCA)

To understand the potential to make an impact of each candidate's powertrain, it is essential to evaluate how each vehicle fits within the circular economy of vehicle manufacturing and our food production systems (Figure 2). Pre-mechanisation, the horses used as the primary energy sources were fed from food produced on the land; the farm was energy-independent. This could also be true for the next generation of sustainable AV powered by 'on-farm' produced green fuel/energy like methane and hydrogen [5].

Figure 2: The Circular Economy model [6].

LCA will be adopted to evaluate the impact of each powertrain across its whole life from raw material extraction, manufacturing, usage emissions and end-of-life (EoL) disposal, also known as cradle-to-grave (CTG) analysis. LCA provides a structured way to quantify the environmental effects of a product or system, but the report will also consider other factors such as infrastructure and fuel availability, cost, and the duty cycle of powertrains; it is paramount that a farming business can continue to operate with limited efficiency reductions from investing in new technology and changing fuel source.

2. BACKGROUND REVIEW

2.1 Alternative Fuels

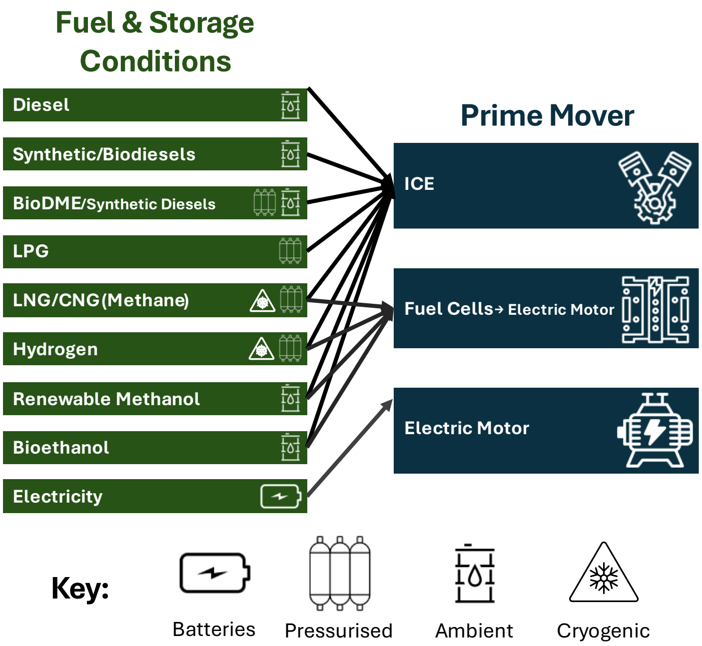


Figure 3: The key fuel options suitable for AV powertrains, the storage conditions and the prime energy transfer method.

The aviation, shipping and automotive industries are further ahead of agriculture along the decarbonisation of vehicles path, thanks in part to stricter government commitments, for example, the UK government's commitment that all new cars will be zero emission vehicles by 2035 [7]. While no commitments have been made for off-road vehicles.

The alternative powertrain landscape is unclear, with numerous fuel types and engine configurations available (Figure 3). Diesel and the ICE is the current fuel and powertrain combination of choice. Biodiesel is already available to the industry, as most tractors from the major brands are already compatible. Xing et al. [8] gives nine alternative powertrains to marine diesel oil for the shipping industry, all of which have their place in the list of candidates for AV powertrains. In other reports and LCA studies on alternative powertrains, similar lists are considered; Zincir et al. [9] considered an exhaustive list of 14 fuels, while Hill et al. [10] only considers five fuels and hybrid options. Considering these studies Figure 3 from Zing et al. [8] has been adapted to include electricity and to expand on synthetic/biodiesels.

High energy density is critical for maximising vehicle duty cycles, keeping weight low, and a small machine size to ensure the vehicle is manoeuvrable and carries a light footprint across the field, reducing soil compaction and fuel use. Figure 4 shows the energy density of fuels listed in Figure 3 by mass and volume, it shows why diesel is so suited to the AV powertrain and is the ideal candidate if purely focused on energy density. Key fuels include the excellent gravimetric density of hydrogen, but its volumetric density makes it a difficult fuel to store on a vehicle without oversized gas tanks. The only fuels close to diesel in terms of energy density performance are biodiesels, which is critical for specific uses of AVs, when vehicles are required to work remotely away from the farm and refuelling stations for long periods.

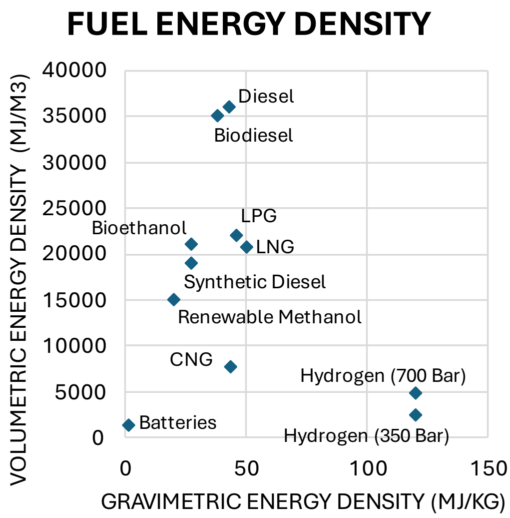


Figure 4: A scatter chart showing the energy densities of the candidate fuels. The data has been taken from several sources [11-14].

2.2 Barriers to Adoption

The barriers to adopting alternative fuels are similar to those in the transport industry, including economic concern, operational challenges, technological uncertainty and a knowledge and awareness gap, as identified by Bae et al. [15] as barriers for commercial road transport fleets. The barriers are amplified in rural areas with limited access to the extensive road network, where alternative fuel infrastructure is installed [15]. Coupled with low average profit margins on farms of 0.5% [16], making the appeal to adopt and invest in an alternative fueled fleet that does not perform as well as diesel a challenge.

2.3 Methodology

International standards for LCA methodology state that an LCA must follow the four key stages in Figure 5, with the most crucial concept being that an LCA, throughout, is an iterative process.

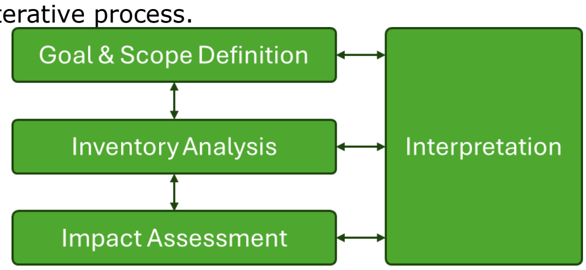


Figure 5: A schematic of LCA as set out by ISO 14040; each of the stages is an iterative process allowing refinement throughout the assessment [17].

The first stage, goal and scope definition, defines the LCA objective, functional unit, and system boundaries. The function unit sets up what product the LCA covers, and its use conditions. The system boundary is what is or isn't being included in the study; for example, is it a CTG analysis or only looking at the operational phase of a vehicle. The following stage is the inventory analysis (LCI), the data collection phase, where the raw data, such as material composition and fuel use over the system boundary, is collected. The next step in the impact assessment (LCIA) is where all the data collected is assigned an impact score against the defined impact categories, such as GWP, cumulative energy demand and abiotic resource depletion. The final stage is the interpretation, where results are analysed and validated. Each stage must be viewed as an iterative and flexible process allowing refinement throughout the assessment.

2.4 The Agricultural Powertrain

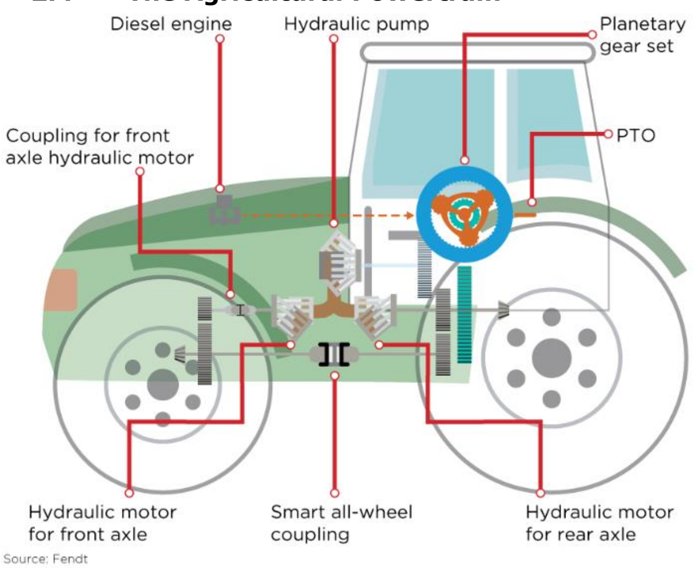


Figure 6. A modern tractor driveline uses a variable gearbox combining hydraulic and mechanical systems to deliver wheel movement with an infinite gear ratio. The engine also powers the PTO for external implements and drives hydraulic pumps for auxiliary functions.[18].

There is a considerable variation in AVs; the Agricultural Engineers Association (AEA) classifies an AV as having a power range from 51 hp, with the largest machines on the market reaching over 1000 hp. However, most of these vehicles have the same basic operating principle: the ICE powers a series of mechanical and hydraulic functions to drive the vehicle and its auxiliary functions (**Figure 6**). Most vehicles require long duty cycles; however, some machines are used as part of shift work, for example, on dairy farms. Therefore, each vehicle's requirements differ depending on the use case, so long duty cycles are not always required.

2.5 Fuel Accessibility & the Energy Independent Farm

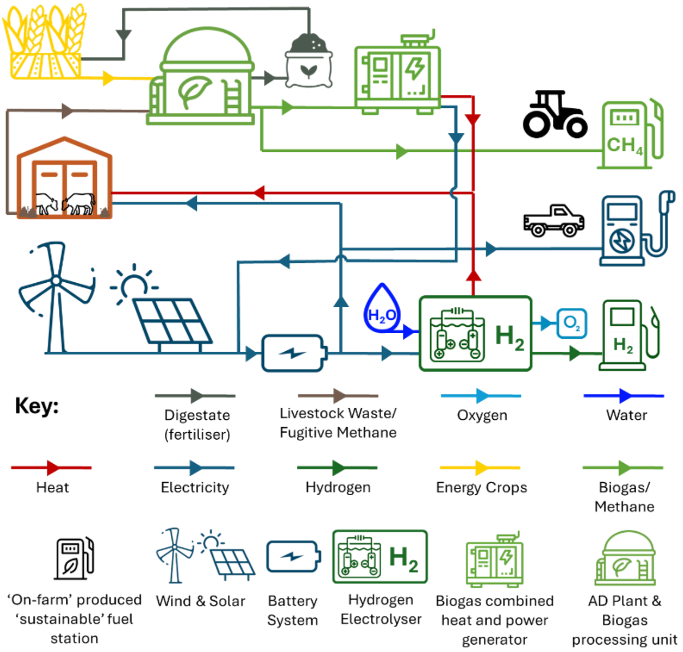


Figure 7: A schematic of the on-farm infrastructure required and energy flows that could be used to generate on-farm energy [19, 20].

For any fuel to be a viable option, it must be cost effective and have the support of a reliable supply chain, which none of the alternative fuels have yet in rural communities. However, recent technological advances could change this and make farms energy-independent. Bennamann [21], backed by the 2nd largest global AV manufacturer, CNH, are developing a solution to allow the capture of fugitive methane emissions from livestock on the farm, which would ordinarily go to the atmosphere. SY Ecofit [19] is working with several partners to combine a biogas generator system with wind and solar power to generate on-farm hydrogen using a modular electrolyser. Figure 7 shows how a combination of this developing technology with existing solar, wind, anaerobic digester (AD), biogas generator and battery technology can fuel vehicles and provide heat and electricity for buildings, from the hydrogen, biomethane or electricity produced sustainably on the farm. Not all the technology is required; farms can choose which technology to invest in, reducing the capital involved to start the journey towards energy independence. Scott and Blanchard [22] reports that AD technology alone has the potential to reduce emissions by 32-44%. Together with an alternative-fueled fleet of vehicles, there is potential to reduce the emissions from the whole business, specifically fugitive livestock emissions, which alone contribute to 5.8% of global emissions [2].

2.6 LCA Case Studies & Research Gap

Specific case studies using LCA focusing on AVs and alternative fuels are limited, but several studies have been conducted for automotive and marine focus with similar and transferable outcomes.

In 2021, Hill et al. published an LCA commissioned by the UK Government for on road vehicles [10]; the study used a complete CTG analysis addressing seven impact factors. Results showed that with the current UK energy grid mix, BEVs are already reducing lifetime emissions by 65% compared to petrol vehicles, and highlighted that H_2 FCEVs have potential but depend on the emissions from hydrogen production. The study, however, only considered a limited range of powertrains, omitting, for example, H_2 ICE, but did consider a wide range of hybrid powertrains.

Zincir et al.'s report [9] looking at marine fuels only focuses on well to wheel (WTW), which purely reports on the fuel supply chain and operating emissions, discounting production and EoL impacts from the ship. The report concludes that no single fuel solves all the problems across the eight impact factors addressed, and several fuels show promise, including H_2, LNG, synthetic fuels and biodiesel. However, like Hill's report, it did not consider some key candidates for AV powertrains, specifically BEVs and FCEVs.

Although outdated, an early AV specific example published in 2000 by Lee et al. [23] highlights that the key phase of the vehicle's lifetime impact is the use phase. In a more recent paper, Lagnelov et al. [24] compares a 5 tonne conventional diesel tractor to a similar autonomous BEV; it again shows that the operational phase of the conventional tractor dominates the lifetime impact, and that the BEV could cut GWP by 65%.

This highlights a lack of up-to-date CTG analysis for AVs that considers their unique operational challenges and powertrain requirements; this report aims to reduce this gap by using LCA to appraise and recommend powertrains for AVs that align with global climate goals.

3. METHODOLOGY

3.1 Case Study Vehicle Selection

It is not feasible to run an LCA analysis for every AV type and power; therefore, a 6-cylinder 155 hp tractor has been selected as the case study vehicle for two main reasons:

1. Recent LCI data published in 2023 by Pradel from a CLAAS ARION 630, a modern 6-cylinder 155 hp tractor [25].
2. It represents a tractor from one of the most popular power bands sold in the UK, representative of the global market [26].

3.2 LCA Methodology Design

Framework & Tools: The LCA will be designed and assessed within ISO 14040 [17] standard guidelines, using LCA Microsoft Excel analysis to compile and analyse results. The initial LCA will be for the original diesel tractor, before replacing the powertrain and completing analysis for each powertrain and fuel combination with the same 155 hp AV.

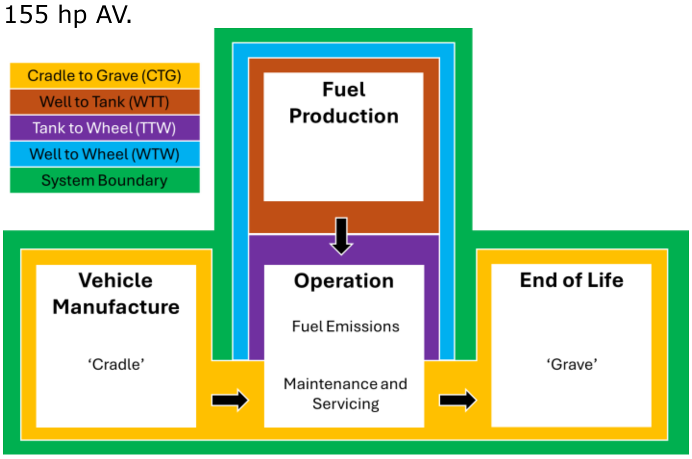


Figure 8: The LCA system boundary, with colours indicating subsystems analysed during results interpretation.

System Boundary: A complete CTG assessment is shown in Figure 8 and will be categorised by the different subsections, also shown in the figure. This will ensure the results give a complete picture of the environmental impact of AVs beyond tailpipe emissions.

Functional Unit: One 155 hp tractor operating over a lifetime of 12 years, operating for 1000 hours per year, as assumed in the LCI by Pradel, operated under typical use conditions [25].

Impact Category: GWP will be assessed, measured in kg CO_2 equivalents (kg Co2e), the major impact factor assessed in all LCA studies. Other impact categories will not be evaluated due to limited data availability and the simple analysis tool used.

3.3 Key Data Sources and Assumptions

Operating Conditions: It has been assumed that the average power output of the vehicle over its lifetime is 50%, giving a load factor of 0.5, based on data from a UK government commissioned report [27].

Vehicle Composition: The composition and LCI of each vehicle, including servicing and maintenance items, will be based initially on Pradel's LCI [25]. Component weights and material composition have been sourced from various online sources and OEM data when replacing powertrains. The significant components data sources have been summarised in Table 1.

Table 1: Component materials composition data sources.

Component	Data Source
ICE	John Deere[28]
Transmission	CLAAS UK [29]
Liquid Fuel Tank	Pradel [30]
Gas Tanks	CNH [31]
EV Battery	Emilsson et al. [32]
Motor	Nordelöf et al. [33]
EV Transmission	Bosch [34]
Invertor	Nordelöf et al. [35]
Fuel Cell	Mori et al. [36]

Raw Material Extraction & Primary Processing: CES Edupack's built-in tool, EcoAudit, will be used to gather the data, which has been assumed to be typical material processing requirements for each component.

A 2.4 scaling factor has been applied to the BE and FCE powertrain battery impacts to bring the results for these vehicles in line with peer-reviewed LCA studies that report battery emissions of 140-160 kg CO_2e/kWh [24, 37]. It corrects the underestimation of EcoAudit's reporting, which resulted in impacts of 60 kg CO_2e/kWh.

Manufacturing and Assembly: This has been ignored due to insufficient data availability. It is assumed to be similar across all vehicles; therefore, in this comparative study, its absence is expected to have had little effect on the results.

Table 2: Fuel production and emissions data sources.

Fuel	Data Source(s)
Diesel	gov.uk [38]
Synthetic/Biodiesel	gov.uk [38]
Natural Gas (NG)	gov.uk [38]
Electricity	gov.uk [38], NREL [39]
Hydrogen	gov.uk [40], GH2 [41], Verhelst and Walner. [42]
Bioethanol	gov.uk [38]
Renewable Methanol	gov.uk [38]
LPG	gov.uk [38]

Fuel Production and Emissions: Table 2 summarises the fuels and the data sources, with a majority from UK government documentation [38]. High and low values of fuel have been included for fuels with a range of primary sources, such as electricity from the UK grid or 100% solar/wind.

Powertrain Efficiency: Table 3 summarises the assumed efficiencies of each powertrain's prime mover and their data sources.

Table 3: Prime mover efficiency and data sources.

Powertrain	Efficiency	Source
Diesel ICE	0.35	Pickel [43]
NG ICE	0.32	Chen et al. [44]
BEV	0.90	Braun and Rid [45]
H_2 ICE	0.40	APCUK [46]
H_2 FCEV	0.60	energy.gov [47]
Bioethanol ICE	0.40	Brusstar et al. [48]
Renewable Methanol ICE	0.40	Zhen and Wang [49]
LPG ICE	0.31	Woo et al. [50]

Maintenance & Servicing: Replacement parts have been included in the base LCI material composition data of the tractor, for example, replacement tyres, glass and seat fabric by Pradel [25]. The material composition of service items such as filters is separately categorised in Pradel's data; EcoAudit will be used to find the impact data for these items. Table 4 summarises the data sources used to find the GWP data for the fluids and catalytic converter used over the vehicle's life cycle. Finally, Table 5 summaries for each vehicle, which fluid/service items have and have not been included in the final analysis, due to the motor replacing the ICE

Table 4: Servicing & maintenance impact data sources.

Component	Data Source
Lubricating Oil	API [51]
Anti-Freeze	Olsson [52]
AdBlue	gov.uk [53]
Catalytic Converter	Amatayakul and Ramnäs [54]

Table 5: Maintenance and servicing omissions for each vehicle.

Powertrain	Omissions
Diesel ICE	-
Other ICE	Cat. & AdBlue
FCEV & BEV	Catalytic Converter, AdBlue, Anti-Freeze & 40% of Lubrication Oil

End-of-Life: EcoAudit's default setting for EoL treatment of each material has been assumed. In reality, there would be a larger proportion of material recycled, but for this comparative study, more accurate data reporting would have little effect on results.

4. RESULTS

4.1 Material and Manufacturing Impact

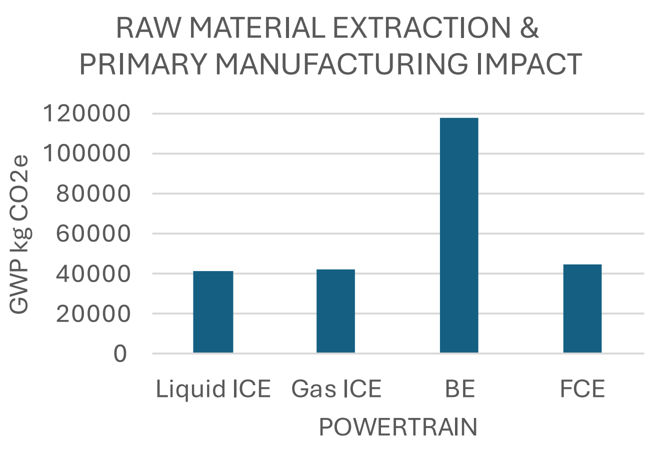


Figure 9: GWP per powertrain from raw material extraction and primary manufacturing.

Figure 9 shows the GWP contribution for each powertrain. The BE has the highest overall impact at 117,700 kg CO_2e. Over 180% higher than the ICE variants, both of which have an impact of 42,000 kg CO_2e and 41,700 kg CO_2e for the gas and liquid fuel variants, respectively. The significant, embedded impact of the BEV is primarily driven by its 500 kWh battery system, which requires a substantial proportion of rare metals and a complex cell manufacturing process [32]. The FCE AV impact is 44,300 kg CO_2e, higher than the ICE AVs due to its 30 kWh battery and the fuel cell stack materials.

These results demonstrate that BE AVs carry much greater embedded GWP impact from manufacturing before any hours of use.

4.2 Operational Phase Impact

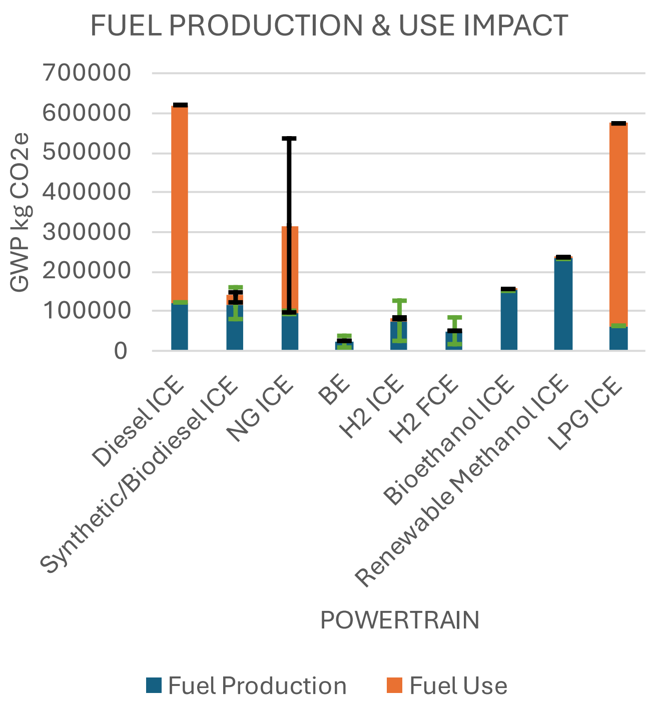


Figure 10: GWP per powertrain from fuel production and use.

Fuel Production and Use: The GWP impact of fuel production and use emissions is presented in Figure 10. Diesel ICE AVs have the highest GWP, with the fuel use contributing 497,900 kg CO_2e, and production adding 121,000 kg CO_2e, resulting in a total impact of 619,000 kg CO_2e. The LPG ICE AV follows a similar trend with similar use emissions but lower production impact.

BE and FCE powertrains have zero use emissions due to their lack of tailpipe emissions and the lowest fuel production impact. When charged from the UK's electricity grid, the BE fuel production impact would total 38,400 kg CO_2e, but this could be as low as 8,500 kg CO_2e if the vehicle were charged from 100% wind energy on-farm, highlighting BEV's overall impact sensitivity to upstream emissions and cutting WTW impact by 98.6% compared to diesel ICE AVs. FCE and H_2 ICE powertrains also exhibit wide uncertainty; 100% electrolysis-produced hydrogen (0.0042 kg CO_2e/MJ) has a lower impact than the UK government's current low-carbon hydrogen standard (0.02 kg CO_2e/MJ) [40-42]. This gives the H_2 powertrains, FCEV and ICE overall impact high of 83,200 kg CO_2e and 133,500 kg CO_2e and a low of 17,500 kg CO_2e and 29,700 kg CO_2e respectively. FCE powertrains are lower overall due to a higher efficiency of 0.6 compared to 0.4, and tailpipe emissions from the ICE [46, 47].

Synthetic/biodiesel and the other ICE powertrains show significantly reduced fuel impact compared to diesel, but also exhibit sensitivity to fuel feedstock and production method source. NG ICE has the largest possible total impact variation from 541,000 kg CO_2e to 91,800 kg CO_2e due to using fossil-based gas or on-farm produced biomethane.

The results show that these WTW impact scans are highly variable across the different powertrains, making the fuel source as critical as the powertrain choice.

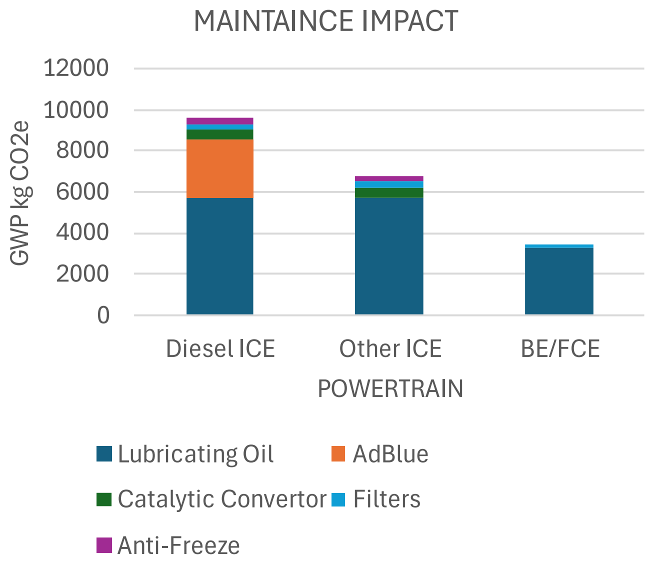


Figure 11: GWP per powertrain from maintenance.

Maintenance: Lifetime maintenance of these AVs has a smaller impact on overall GWP than fuel use, but still contributes and varies across the powertrains (Figure 11). The diesel AVs have the largest impact (9,600 kg CO_2e), driven by their consumption of AdBlue, contributing 2,800 kg CO_2e. The gas ICE AVs don't require AdBlue but still have emissions related to the anti-freeze and the catalytic converter. The BE and FCE AVs have the lowest impact of 3,400 kg CO_2e, as without an ICE, significantly less lubricating oil is required for the AV.

While the maintenance impact is a small part of the overall GWP, it is not negligible and shows how the operational simplicity of the electric powertrains has its benefits.

4.3 End-of-Life Impact

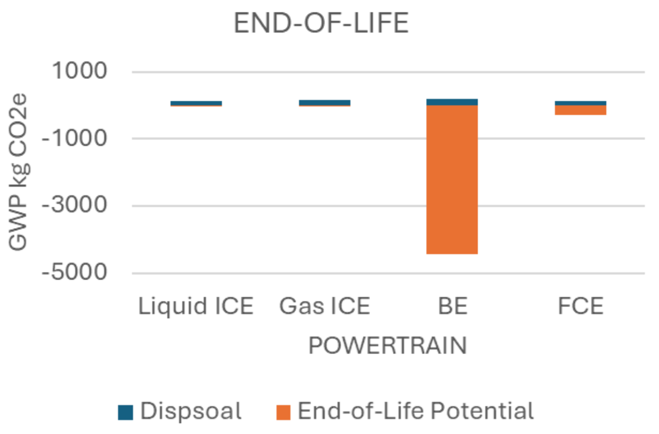


Figure 12: GWP per powertrain at EoL.

EoL impact was modelled using EcoAudit's default assumptions, the results of which can be seen in Figure 12. All components are assumed to be sent to landfill with no material recycling except for selected materials like batteries. EoL contributions are negligible in comparison to the other life cycle stages, ~100 kg CO_2e, less than 1% of the overall impact, the exception being the BEV, where the downcycling of the battery gives a negative contribution of -4,400 kg CO_2e.

4.4 Summary of Life Cycle GWP

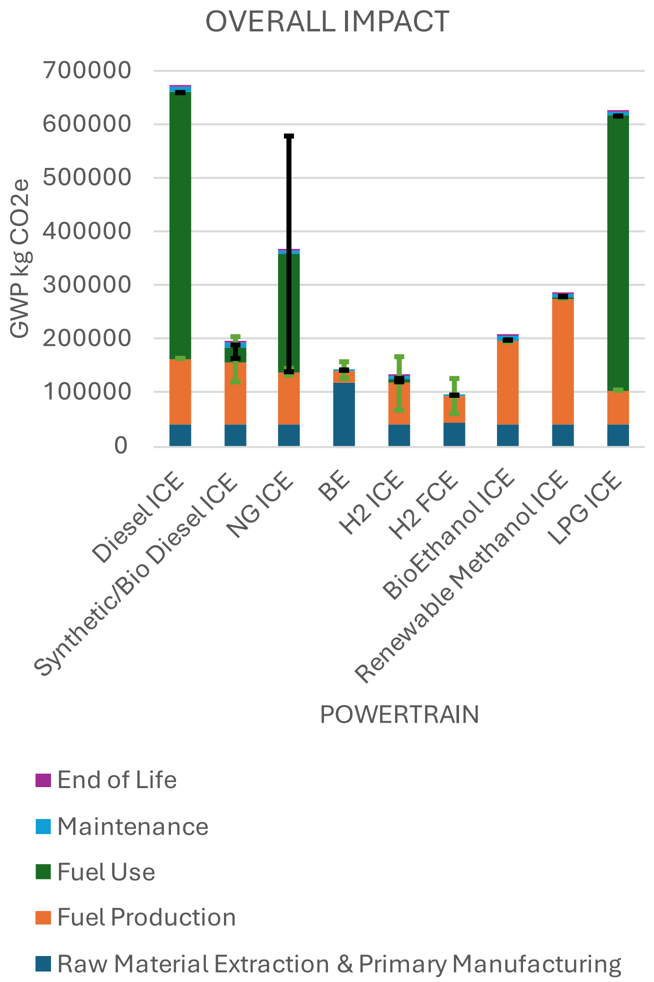


Figure 13: Overall GWP impact.

The results in Figure 13 show the dominance of fuel use and production impacts in all ICE powertrains, particularly diesel and LPG, with over 90% arising from these WTW emissions, with total CTG emissions totalling 670,300 kg CO_2e and 624,200 kg CO_2e respectively.

Despite having the highest primary impacts, the BE powertrain benefits from zero tailpipe emissions and EoL credits to give the AV a total GWP of 140,200 kg CO_2e, and an 80% reduction compared to the baseline diesel AV.

H_2 powered AVs sit at the bottom of the spectrum, with the FCE AVs overall bettering the ICE variant due to higher efficiency and zero tailpipe emissions. They each have a total CTG impact of 97,900 kg CO_2e and 130,500 kg CO_2e, respectively, cutting the impact compared to diesel ICE by 85% and 80%.

Synthetic/biodiesel and NG ICE AVs have higher emissions than the H_2 and BE powered vehicles, arising from higher WTW impact with 192,900 kg CO_2e and 365,400 kg CO_2e respectively. However, the significant error in WTW emissions gives potential for them to be as low as 137,900 kg CO_2e and 140,700 kg CO_2e, respectively. Bioethanol and renewable methanol fuel AVs have similar results, with 204,800 kg CO_2e and 284,600 kg CO_2e, respectively.

The results comprehensively compare the different powertrains' environmental CTG impacts. Still, they must be evaluated alongside broader criteria influencing real-world adoption.

5. DISCUSSION

5.1 Sensitivity and Uncertainty

As mentioned in the results, there is larger uncertainty in the use phase results due to fuel production and source validation affecting both WTT and TTW results. Despite total emissions for biodiesel and diesel ICE powertrains being similar, the quoted emission for this phase is significantly lower due to the emissions values being set at net '0' to account for the CO2 absorbed by fast-growing bioenergy sources' [38].

The study's overall limitations included underreporting of cradle impacts (no secondary manufacturing, assembly or transport impacts) and using EcoAudit default data for EoI scenarios, meaning the results are not holistic. However, with equal treatment of each powertrain, comparative conclusions can be drawn to assess each powertrain's merits and shortfalls relatively. The study also only assessed one impact factor, GWP, so conclusions can't be drawn about other LCA impact factors, such as human toxicity, depletion of abiotic resources and land use.

The selection of the 155 hp AV in the functional unit is also not representative of every AV, so consideration of factors affecting other AV classifications must be given when concluding.

5.2 Comparison to Literature

With limited LA studies focusing on AVs, comparing results directly with other studies is difficalt. Especially as AVs vary in use type and size, there is no directly comparable study; again highlighting the importance of this report, looking at this popular AV power bracket and using up-to-date AV-specific data with real-world high-use assumptions.

The UK Government report [10] across it's different scenarios considered estimates 65-81% savings for BEVs over petrol/diesel, in agreement with the results from this analysis. Lagnelöv et al reports a 65% reduction in his LCA but considers the replacement of one 335 hp diesel ICE AV with two 65 hp tractors; the variation here is likely due to the assumption made by Lagnelöv et al. that the BEVs were shipped from the factory with an additional battery each to minimise downtime waiting for battery recharge.

The relative results for diesel vehicles agree with the compared reports, that 90% of the CTG GWP comes from WTW emissions. By absolute terms, this analysis shows that the total CTG impacts for the diesel ICE AV are 61% of Lagnelöv et al.'s total, but their AV is ~46% of the size.

Hill et al. report that across their scenarios, synthetic/biodiesels can have an impact reduction of 70-50%, less than the calculated saving of 70-80% in this analysis. However, as highlighted in this report, biofuels feedstock and how biogenic CO_2 is accounted for in the analysis play a huge role in their emissions results.

Similarly, Hill et al. found that buses could save 51% in lifetime impact use biomethane, lower than found in this study (78%), but the difference could be accounted for in reporting biogenic CO_2. An ERM report commissioned by the UK Government [55] sees biomethane as a candidate, especially for the AV industry, due to on-farm fuel production; however, they did not provide insight into potential CTG impact savings.

Hill et al. briefly touch upon LNG as a potential candidate fuel, but did not consider it for complete analysis due to the poor GWP reduction potential of ~10%, agreeing with the results presented in this report.

5.3 Interpretation of Results

Assuming the best case scenario for the WTW impact of fuels gives a clear gap between the fuels regularly considered by governments, manufacturers and research organisations. Therefore, with higher CTG GWP impact and less backing from industry bioethanol, LPG and renewable methanol are unlikely to be suitable fuels for the future of AVs. Figure 14 presents the remaining fuels' best-case scenario CTG GWP impact along with diesel. This assumes that 100% biomethane, 100% electrolysis H_2, and 100% wind electricity are used to power the NG ICE, BE, and H_2 AVs, respectively. This aligns with the study's goal of GWP reduction and reflects the growing feasibility of on-farm energy generation.

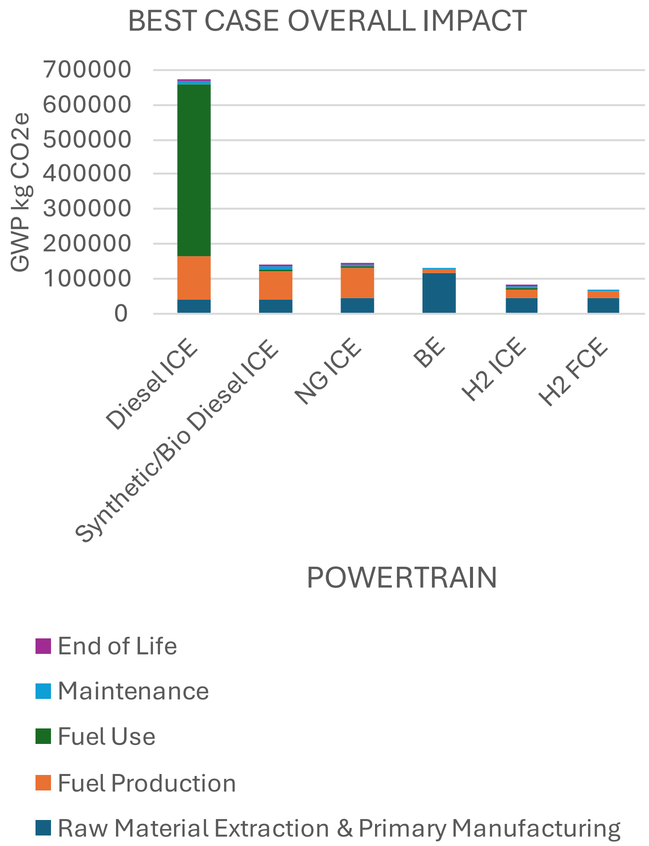


Figure 14: Overall GWP impact considering the best case WTW fuel scenarios.

H_2 FCE has the lowest CTG impact, and by investing in these AVs farmers could reduce the impact by 90% compared to the current diesel ICE AVs. Similarly, with an 88% reduction, H_2 ICE is the 2nd best powertrain, cementing the dominance of H_2 as a potential fuel for the future of AVs. Despite the lowest operating use impact, the additional impact from battery manufacturing brings the BE AV to a possible reduction of 81% compared to diesel. Closely followed by NG ICE and the synthetic/biodiesel ICE powered AVs with 78% and 79% reduction compared to diesel, respectively, due to higher WTW emissions compared to the H_2 ICE AV with the same cradle, maintenance and EoL impacts.

5.4 Practical Constraints and Trade-Offs

Environmental performance does not guarantee the suitability of the powertrains in the agricultural environment. These practical trade-offs are summarised in Table 6 enabling a balanced view of environmental and functional performance across powertrains.

Table 6: Summary of the Practical Constraints and Trade-Offs in the powertrain selection process. Key: + positive, o neutral, - negative; compared to average constraints.

Powertrain	Max Range (% of diesel)	Economics	Refueling Ease	Maintenance & Reliability
Diesel ICE	100	++	++	+
Synthetic/biodiesel	80-90	o	++	+
NG ICE	11	o	+	o
BEV	33	-	--	+
H_2 ICE	5	o	+	o
H_2 FCEV	13	--	+	--

Diesel ICE AVs continue to outperform others in range and fueling practicality, with the 367l fuel tank providing multiple days of use [56]. In comparison, the New Holland T6.180 Methane Power, without a range extender, holds 185 L of gas capacity, giving it 11% of diesel's range [4]. Assuming equivalent onboard capacity, H_2 ICE and FCE machines would provide 5% and 13% of diesel range, respectively (at 350 and 700 bar), although JCB prototype machines have been able to double capacity [57]. With a 500 kWh battery, the BE AV would achieve 33% of the range of diesel, but would weigh 2500 kg more, limiting field performance. Finally, a synthetic/biodiesel AV would have 80-90% of the range of the standard diesel AV due to lower fuel energy density [12].

Batteries remain the costliest component of the BE AV; at 500 kWh, the pack is estimated at £75000, exceeding 50% of the tractor's list price [58, 59]. FCE powertrains are complex and costly [57], while the ICE powertrains are likely to be similarly priced to the diesel AVs. Diesel maintains cost advantages due to tax exemptions, while bio/synthetic fuels can double operational costs due to premium feedstock prices [60]. Investing in on-farm energy generation of biomethane, H_2, and electricity may offer cost stability and potential savings by running these powertrains [19, 20].

From an operational standpoint, liquids are the easiest to store and refuel. Gas fuels pose safety concerns, but can be convenient and easy with the correct infrastructure [61]. BE AVs lag behind here, taking hours to refuel, unless battery swapping systems are used [61].

Lastly, reliability and user perception remain key. ICEs are long-trusted in agriculture, while BE powertrains offer mechanical simplicity proven in automotive use. FCEVs, however, are less mature and can suffer performance losses in cold climates [62].

5.5 Implications

The positive CTG GWP impact reduction potential from all powertrains in Figure 14 shows promise but highlights the importance of decarbonised fuel production. H_2 powered AVs show the most significant promise in this report, and should be the future direction of the industry, especially for arable farms with no access to biomethane generation from livestock. H_2 ICE powertrains may not reduce GWP as much as FCE, but in this industry, they are likely to be favoured due to the trust in and reliability of ICE. For the smallest vehicles (<100 hp) with short duty cycles, where large batteries will not be required, BEVs should be considered and would have the most significant impact. NG AVs powered by biomethane should be considered by livestock farms, as there is the potential to not only cut emissions from AV use but also the methane emissions from the livestock, amplifying the potential impact. All fuels except synthetic/biodiesel have duty cycle concerns; therefore, improved AV fuel storage is required for any of these fuels to be successful.

Synthetic/biodiesel offers an immediate pathway to emission reduction and, with several AVs already compatible, should be adopted where possible. However, due to land use concerns, biofuels are not a long-term solution.

6. CONCLUSION

This study set out to appraise candidate powertrains for today's dynamic agricultural vehicles through CTG LCA. It provides one of the first CTG LCA comparisons across multiple alternative powertrains for AVs, using real world tractor data and context-specific usage assumptions.

The results demonstrate that H_2 FVE AVs have the lowest CTG GWP of all the powertrains considered, a 90% saving compared to the diesel AV baseline. H_2 ICE AVs offer almost as much reduction (88%) but are limited by fuel use emissions from the ICE; however, in this industry, they are likely to be the best option due to their simpler technology and operational familiarity. BE AVs have an 81% reduction and the lowest operational impact, so are likely to be highly effective for small, short duty cycle AVs, enabling small battery packs to be used, reducing the cradle impacts. Biomethane AVs suit livestock farms with on-site production, offering 78% GWP reduction and capturing fugitive methane. Short-term synthetic/biodiesel can offer up to 79% GWP reduction depending on fuel feedstock, but with ambitious GWP reduction targets, the industry should not consider them a long-term solution. LPG, bioethanol and renewable methanol are unlikely long- or short-term solutions.

Therefore, farmers should be encouraged to adopt biodiesel and invest in on-farm energy production immediately. For livestock farms in the form of biomethane capturing technology, and on arable farms, solar and wind energy combined with H_2 electrolysers to fuel their future AV fleets.

Manufacturers should focus research and development on H_2 and CNG ICE AVs, prioritising improved gas storage packaging to ensure that long duty cycles are achievable. They should also continue to develop BE powertrains for the lower power AVs (<100 hp) and ensure compatibility of their current AVs with biodiesel in the short-term.

Government policy should support this transition by offering grants for on-farm energy and fuel production projects to incentivise farmers' investments. In the short-term, subsidies for synthetic/biofuels produced with low-impact feedstocks and manufacturing processes should be provided.

The novelty of this project and the size of the challenge to decarbonise food production shows the necessity for continued work and LCA projects into the energy use across the global agricultural industry. Future work could expand on this report to include more LCA impact factors, the modelling of hybrid powertrains and improved cradle and EoL data collection.

In conclusion, a mix of BE, biomethane, and hydrogen ICE AVs offer a clear decarbonisation path. With the technology now available, coordinated action by industry, farmers, and government is essential to unlock the full environmental potential of these powertrains and secure a more sustainable future for food production.

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LOGBOOK & ONEDRIVE

OneDrive folder: MEng Individual Project

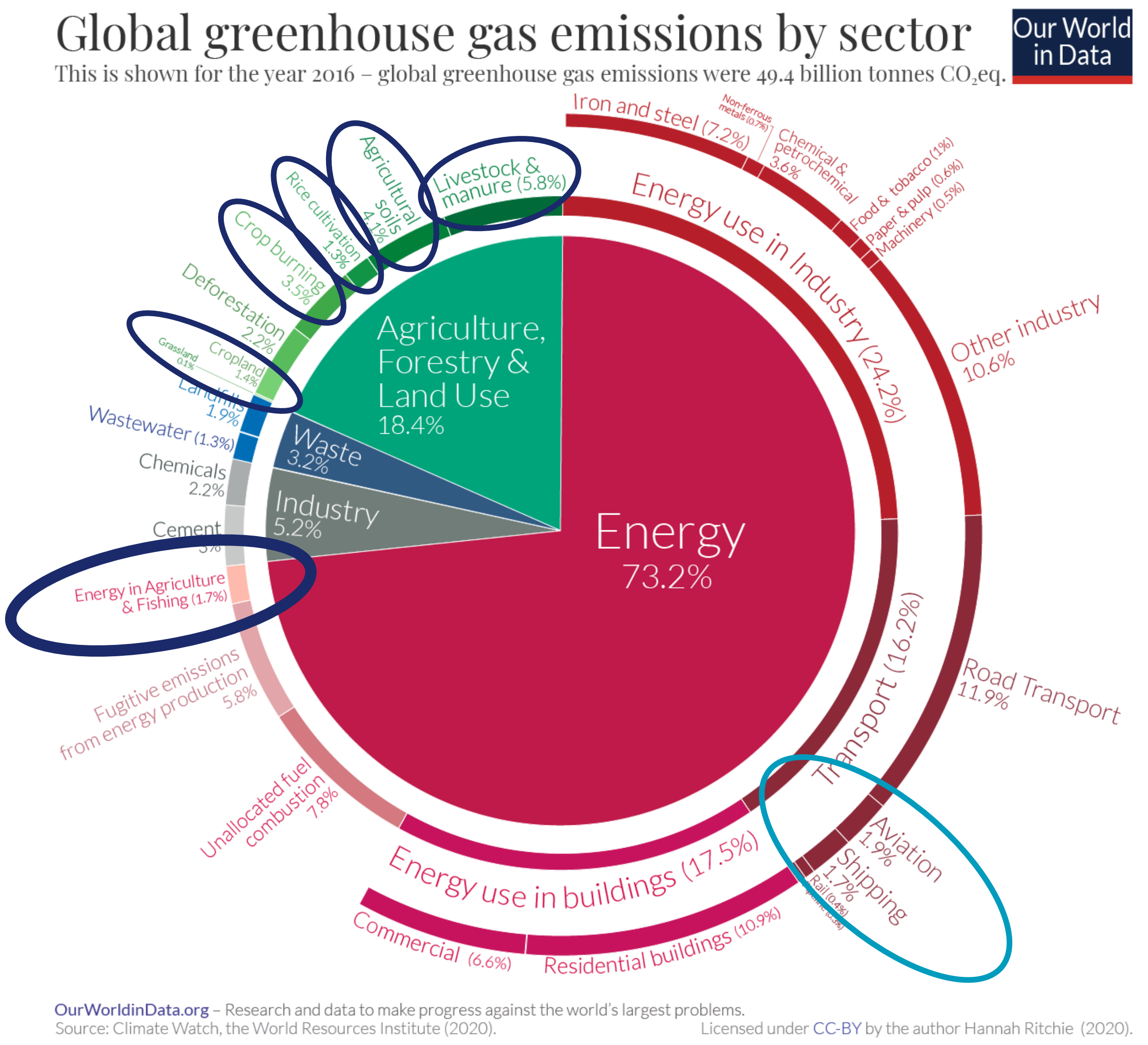
OneNote (Logbook): MEng Individual Project

University of Nottingham
UK | CHINA | MALAYSIA

An Appraisal of candidate powertrains for today's dynamic agricultural vehicles

Barnabas Pickford
20234787
Supervisor: Paul Brown

The Problem



9.7 Billion

Global population by 2050

17.9%

Of global emissions directly contributed by the agricultural industry

1.7%

Of global emissions are from the energy use in agriculture and fishing

Decarbonising Agriculture

- NFU’s 2040 Net Zero Goal
- Sustainable agricultural practices
- Clean and sustainable energy sources

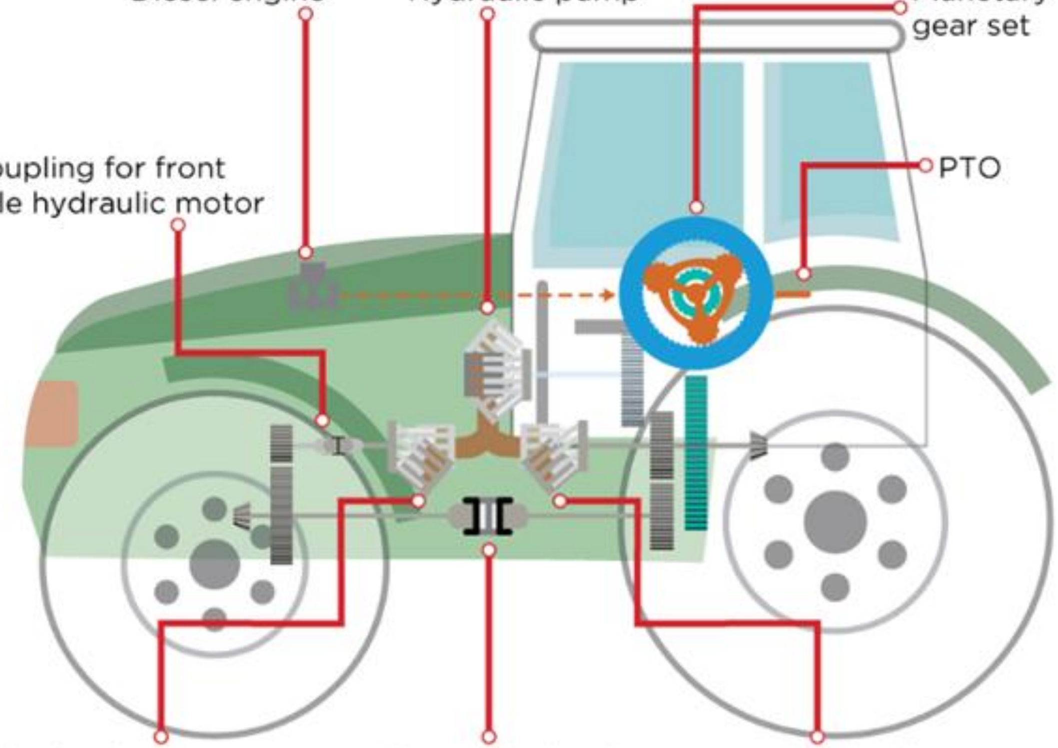
The Current Primary Energy Source

Diesel

- High torque
- Energy density
- Low cost
- Ease of refueling
- High GHG, and particulate emissions
  - Air pollution
  - Climate change

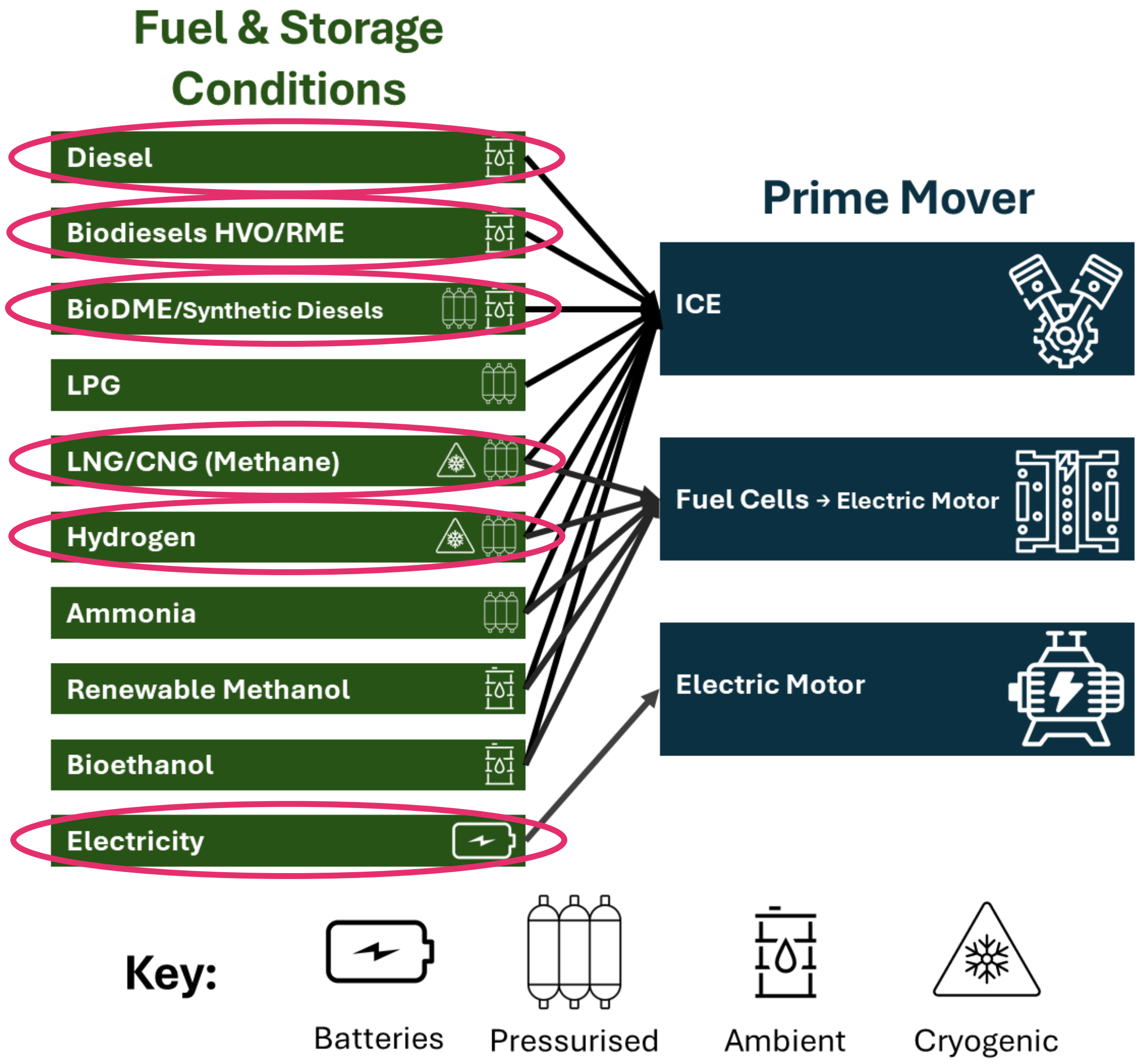
The Agricultural Powertrain

- Internal Combustion Engine
- Mechanical Power
- Hydraulic Functions
- Variation in requirements across the power range and vehicle type



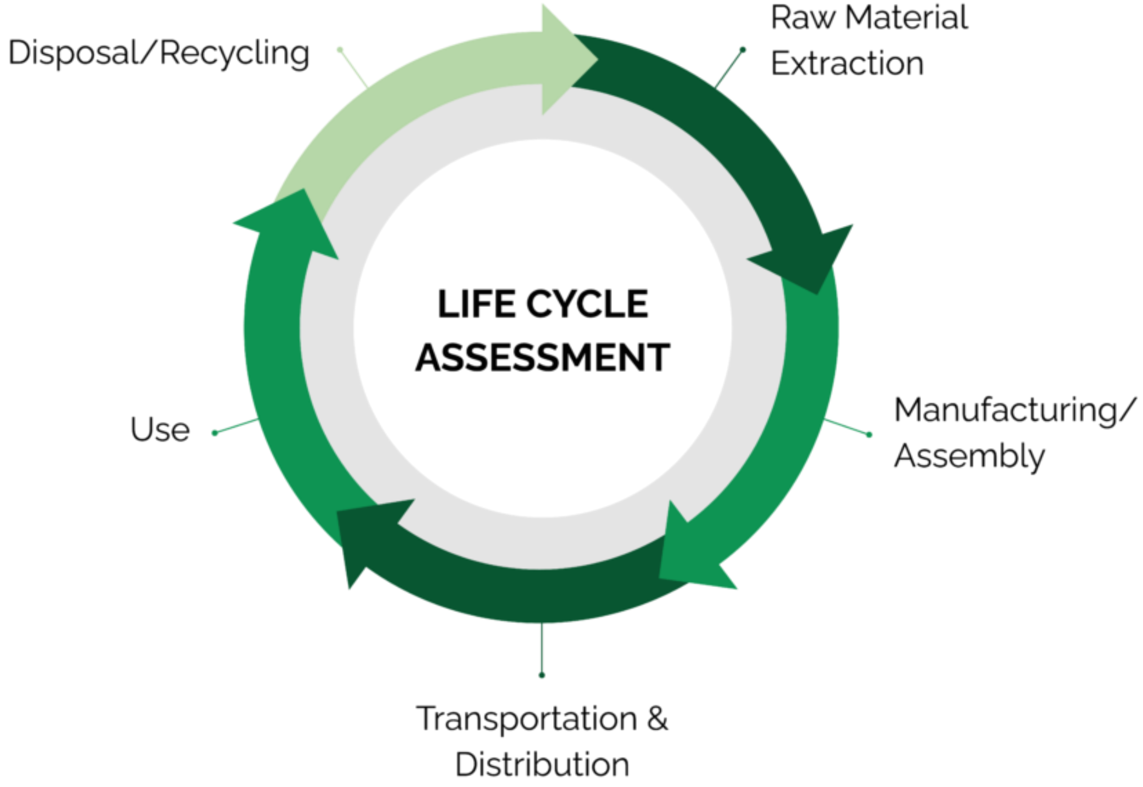
Candidate Fuels and Powertrains

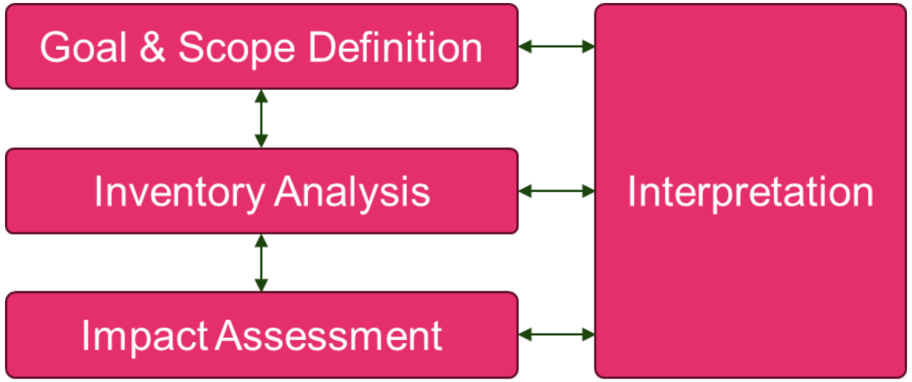
- A muddied picture
- Several candidates
- And prime movers
- Biodiesel already compatible with major brand vehicles
- Lots of investment into Hydrogen
- CNG & Battery tractors are on the market



The Life Cycle Analysis (LCA) Approach

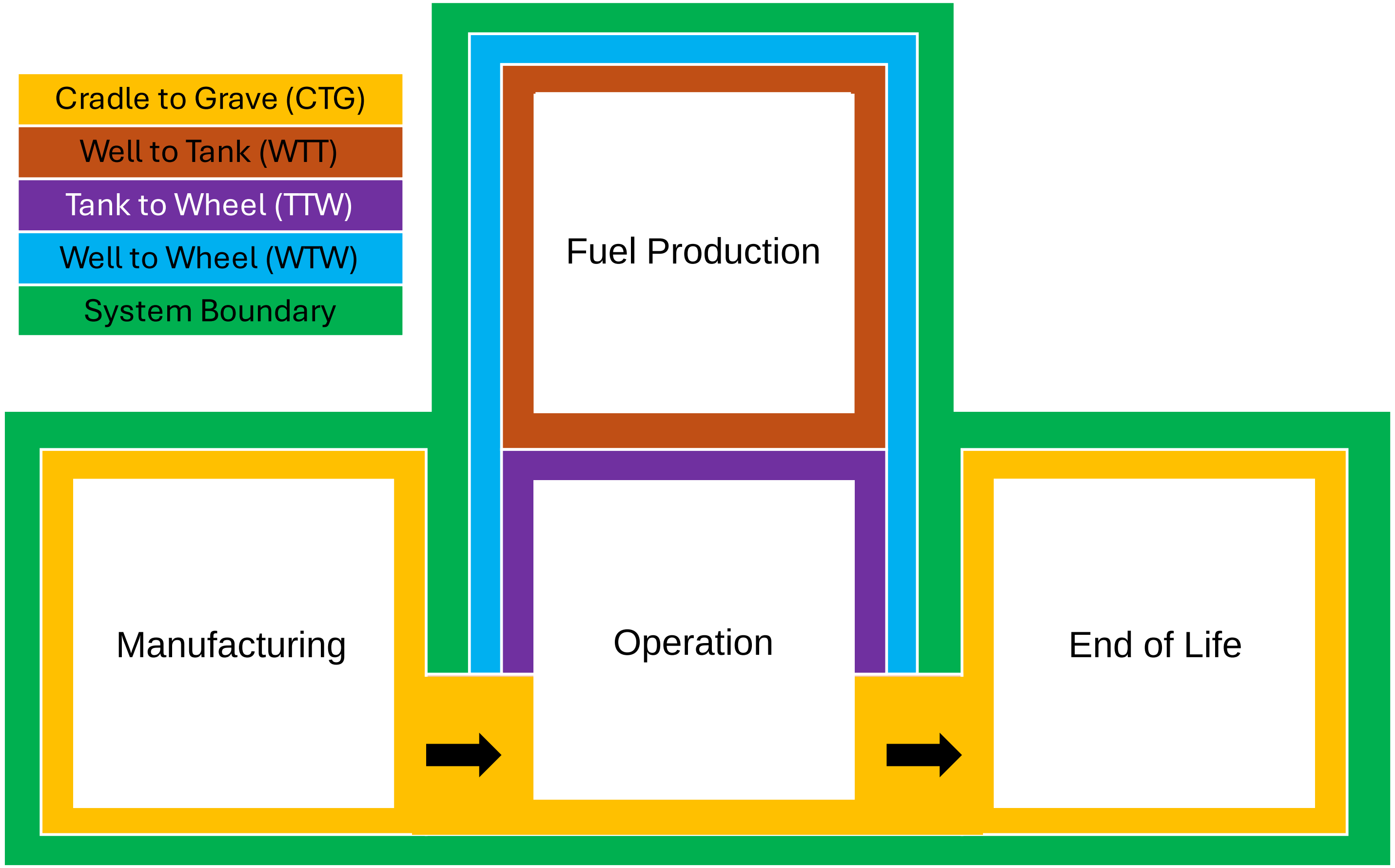
ISO 14040





The Life Cycle Analysis (LCA) Approach

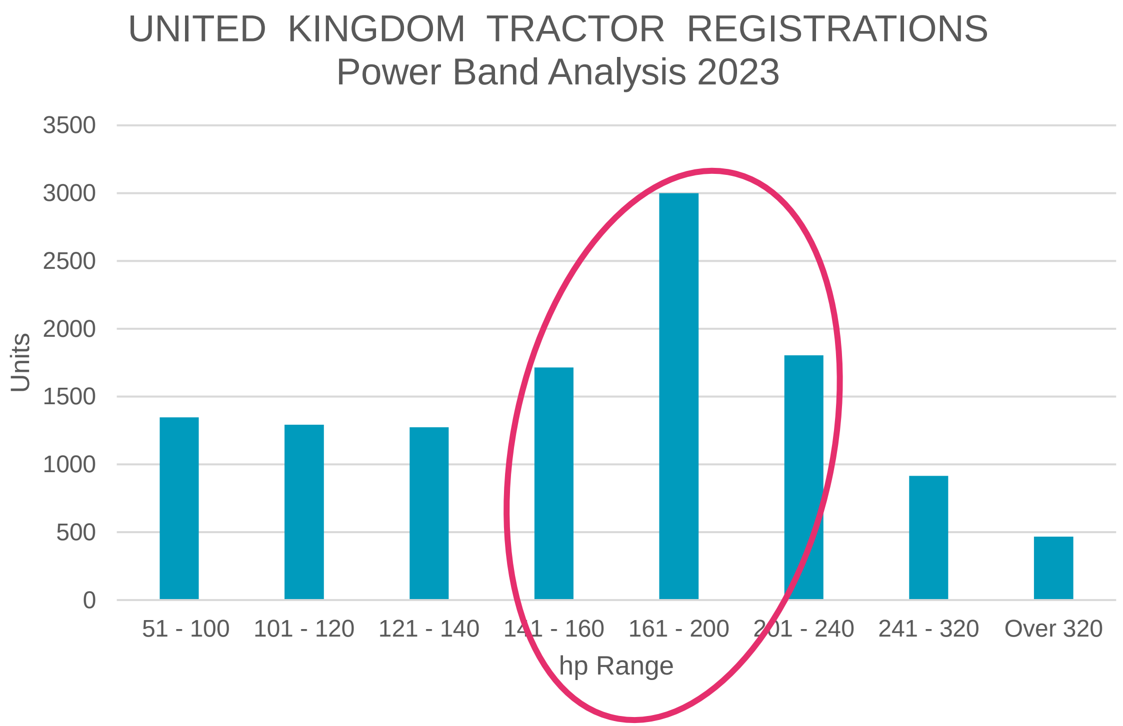
1. Goal and Scope Definition - System Boundary's



The Life Cycle Analysis (LCA) Approach

2. Inventory Analysis – Life Cycle Inventory (LCI)

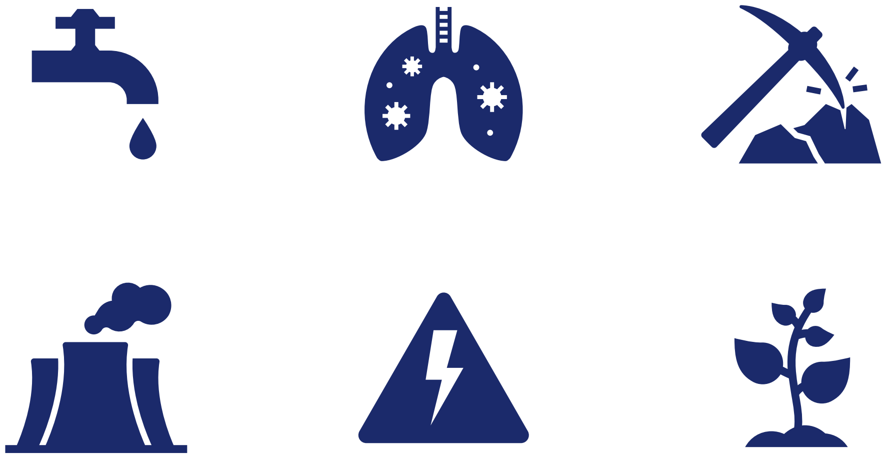
- Data Collection



The Life Cycle Analysis (LCA) Approach

3. Impact Assessment – Life Cycle Impact Assessment (LCIA)

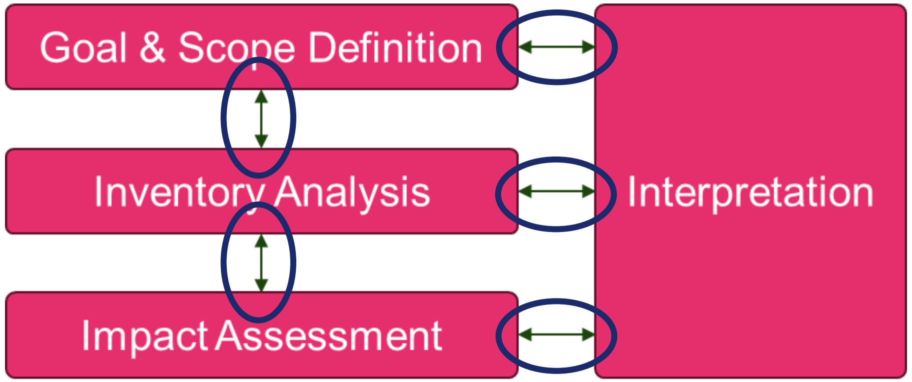
- Select impact categories
- Classify the data



4. Interpretation

- Analysis & Validation

Iterative Process:

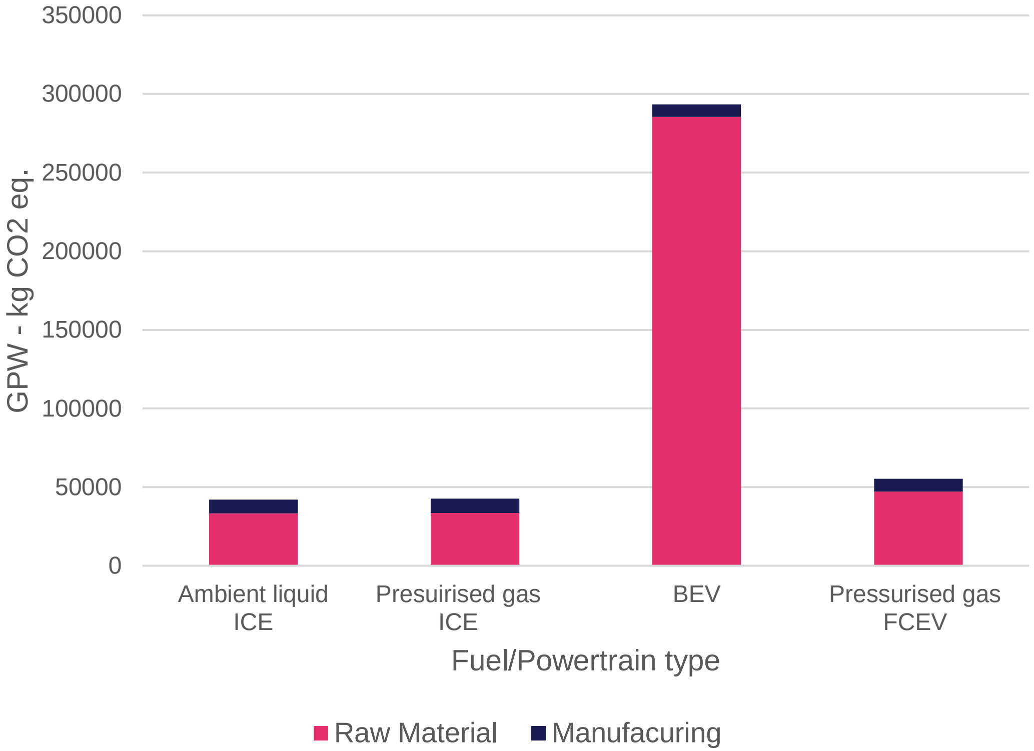


The Life Cycle Analysis

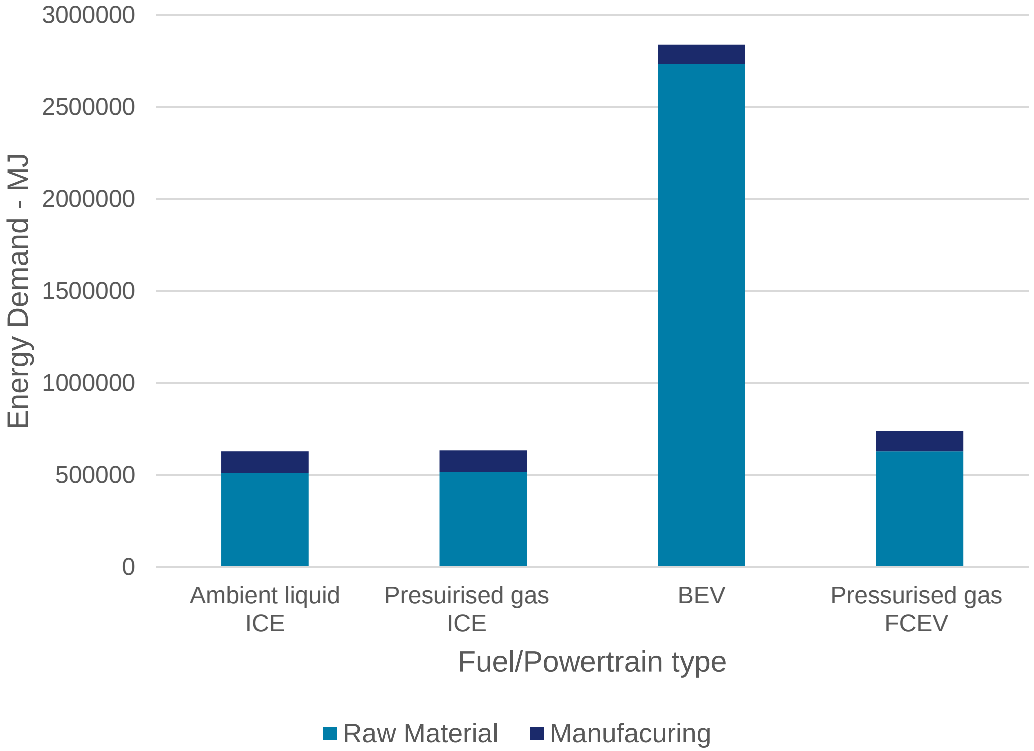
CES Edupack 2019 – Eco Audit

Raw Material Extraction and Manufacturing

Global Warming Potential

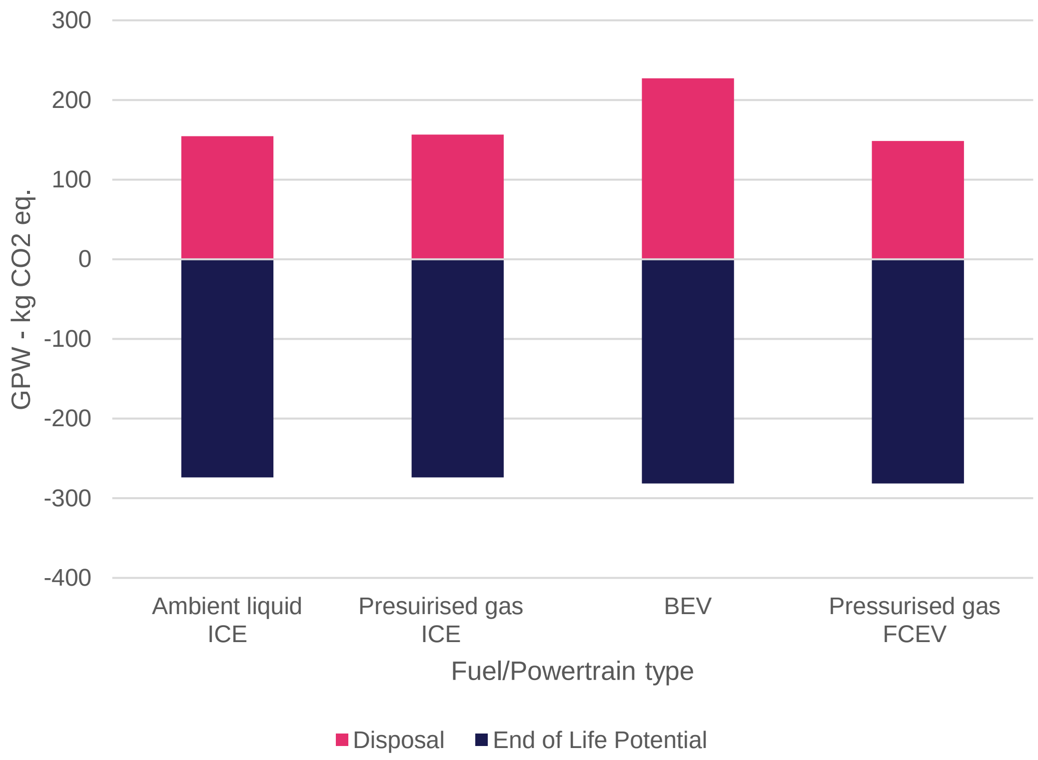


Cumulative Energy Demand

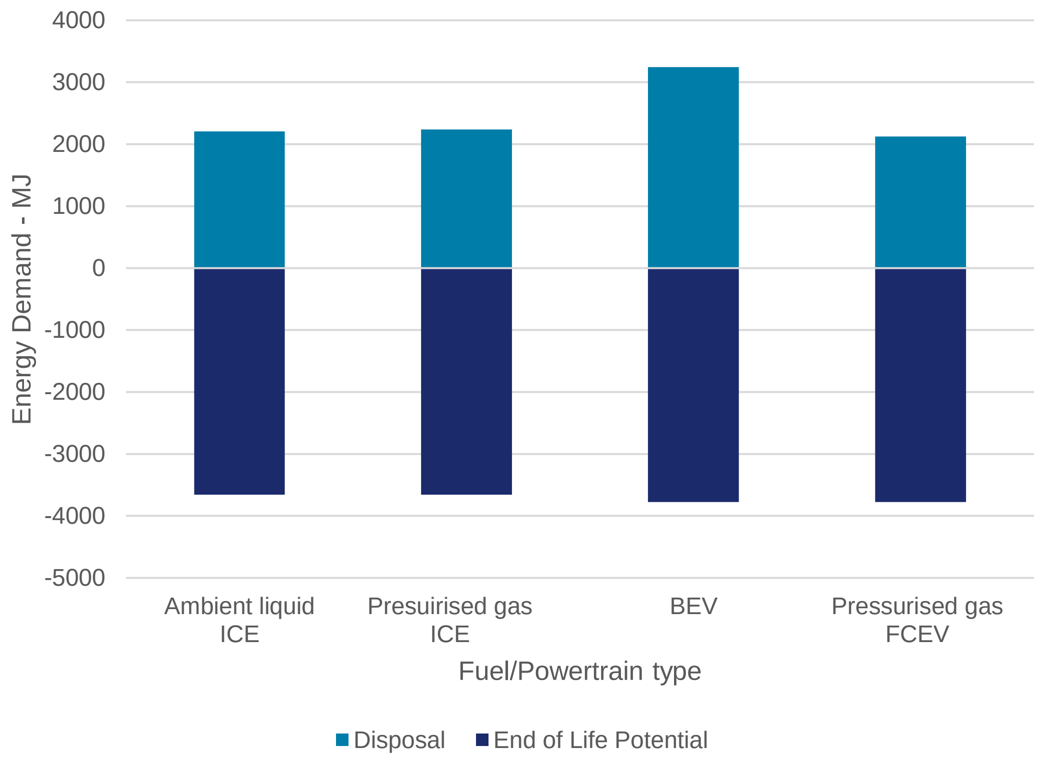


Disposal Impact & End of Life

Global Warming Potential



Cumulative Energy Demand



Operation

CNG

- ICE η≈0.38
- Huge emissions reductions compared to diesel

Electricity

- BEV η≈0.9
- No GHG from 'tank to wheel'

Diesel

- ICE η≈0.35
- Harmful emissions
- Complex after treatment required

Hydrogen

- ICE η≈0.4
- NOx emissions
- FCEV η≈0.6
- No GHG from 'tank to wheel'

Another?

- **Biodiesel**
- **Synthetic Fuels**
- Emissions reductions

Fuel Production

CNG

- Fossil fuel
- Local production?
- ‘carbon neutral’?

Electricity

- Not 100% renewable energy grid mix

Diesel

- Fossil fuel
- Finite resource

Hydrogen

- Needs to be 100% ‘green’ for any overall benefit
- Local production?

Another?

- **Biodiesel**
- **Synthetic Fuels**
- ‘carbon neutral’?

Practical Reality

On Vehicle Storage

- Liquid Fuel ICE – 367l

Range:

- 100%
- (several days)

- Pressurised Gas ICE – 185l

Range:

- CNG ≈13%
- H2 ≈5%

- BEV – 500kWh

Range

- ≈35%

- Pressurised Gas H2 FCEV – 185l

Range

- ≈13%

Practical Reality

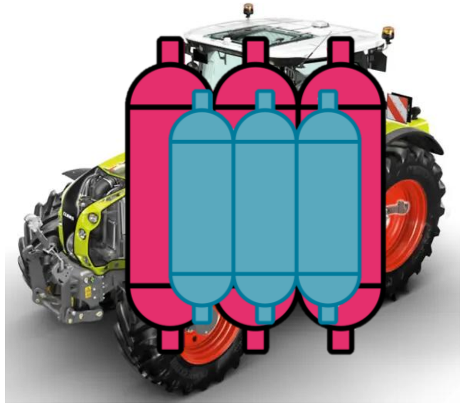
On Vehicle Storage

- Liquid Fuel ICE – 367l

Range:

- 100%
- (several days)

- Pressurised Gas ICE – 1450l/3500l



Range:

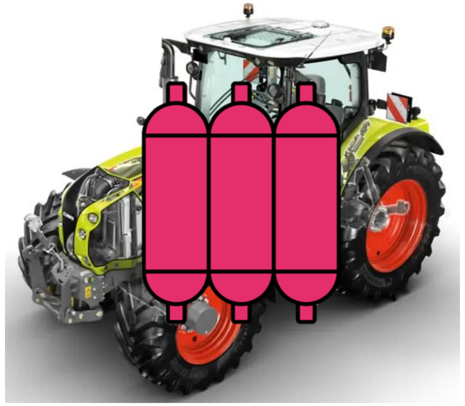
- CNG ≈100%
- H_2 ≈100%

- BEV – 1430kWh

Range

- ≈100%

- Pressurised Gas H_2 FCEV – 1370l



Range

- ≈100%

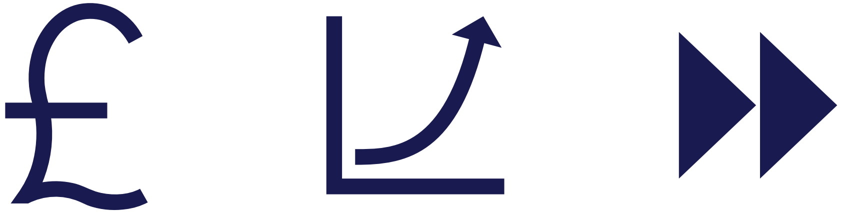
Practical Reality

Fuel Delivery/Storage

- Liquid Fuels – The perfect scenario
- BEV – charging time concerns
    - Battery swapping?
    - Shift work?
- H2/CNG – Rapid refuelling, but storage safety concerns and difficult/costly to transport/store

Cost

- Biodiesel/Synthetic fuel/CNG – higher fuel cost
- H2 – Very high fuel cost, unless on farm production
- H2/CNG ICE – higher vehicle cost
- H2 FCEV & BEV – Very high vehicle cost



Practical Reality

Other Considerations

- BEV’s
  - Battery life
  - Reduced maintenance cost
  - Vehicle weight
- Government Backing
  - H2 highway network likely to become a reality
  - On-farm energy production and small-scale AD plant grants expected

Preliminary Recommendations

- No one-size-fits-all approach
- Different solutions will fit different farms and different working environments/shifts
- The overall goal and potential to make an impact must not be overlooked

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Thank you
Any questions?

Final Reflective Report

BARNABAS PICKFORD | 20234787

PROJECT TITLE: AN APPRAISAL OF CANDIDATE POWERTRAINS FOR TODAY'S DYNAMIC AGRICULTURAL VEHICLES

Introduction

The project's aim was to appraise candidate powertrains for agricultural vehicles to guide the industry in its transition from diesel-powered vehicles to truly sustainable powertrain that will make a genuine difference to decarbonising food production. By clearly identifying the merits and pitfalls of the candidates, especially focusing on the environmental performance. This was enabled by a cradle-to-grave (CTG) life cycle analysis (LCA) assessment of each powertrain, reviewing global warming potential (GWP) and a review of external trade and other factors such as economics and fuel infrastructure.

Skills Development and Knowledge Application

Critical thinking is a key skill in an LCA, as results must be cross-checked with other similar analyses to ensure the results are both reasonable and defendable. I identified results under reporting issues with the battery electric vehicles and, using my critical thinking skills, developed a strategy to rectify the issue, ensuring the LCA was reflective of the vehicle.

I had some initial skills from 2nd year modules with the CES EcoAudit tool, but I developed these so I could proficiently use the software for my analysis. I also had basic knowledge of LCA but was unsure of the full process; my skills in this have drastically developed during the 1st semester when I was developing the LCA methodology and my project workflow. I would like to have, if time and budget constraints allowed, used professional LCA tools, like GREET or OpenLCA, enabling me to gain an even higher level of LCA understanding and achieve a higher level of accuracy in my analysis.

Data visualisation was a key skill, I was hoping to develop more, and had I been given more time would have liked to have made the results figures in my report more interesting and accessible to the reader.

Project Management and Problem-Solving

My approach to project management has been strong from the start; I effectively used tools such as Microsoft To-Do to plan and schedule weekly tasks, ensuring I continued to make consistent progress. Where deadlines were far away, I sometimes struggled to keep focus and maintain motivation on the project, but in times where deadlines clashed with other modules, I utilised my support plan to space them out, ensuring I could complete each piece of work for every module to the best of my ability.

A significant challenge I faced was the collection of use phase data, fluids, as CES EcoAudit bases its data purely on materials. After researching multiple options, I came across the UK Government's GHG conversion factor for the combustion of different fuels that reported emissions factors for both scope 1 & 3 fuel emissions, including electricity.

Personal Growth and Future Outlook

I was excited to start this project, and that my project idea was initially accepted by my supervisor, as this field is of personal interest and where I want to take my career. Throughout the project, I have gained confidence in independent research, having started with little idea about how I would build up the LCA and gather the relevant data. I have developed the ability to defend my methodical choices based on evidence and how to integrate them into technical report writing. Other skills I have developed are systems thinking, LCA workflow and the ability to work iteratively and reflectively in technical contexts, which will all be transferable and invaluable to my future career.

I plan to use the professional learning and skills development from this project to build my career around the decarbonisation of the agricultural industry, specifically the industry's energy use. Playing whatever role I can in helping to change food production for the better, so we can continue to sustainably feed the world's growing population.

At the end of the semester review your 5 important skills and reflect on their development.

Skill	**Starting confidence:**	**Concluding confidence**	**Reflection on how successful the plan has been with a reflection on how it could have been improved.**
Critical thinking	☑ L ☐ M ☐ H	☐ L ☐ M ☑ H	I took pride in my work and used a wide range of data sources to generate my LCA of each agricultural vehicle. I then cross-checked my results with existing studies from the automotive, marine and agricultural sectors, critically analysing my work, showing that the development plan in this area worked and helped me develop this skill to a high standard. To improve this further, I could have been more prepared and sought more feedback from my supervisor on my initial results before submission.
Technical writing	☐ L ☑ M ☐ H	☐ L ☐ M ☑ H	Having achieved good results in my interim report, I wanted to build upon those skills acquired to improve my technical writing skills further, making my final report easy to follow and read, keeping the reader engaged and interested. I continued to use the reference manager EndNote, and took on board feedback from my supervisor to introduce a summary table for the constraints and trade-offs section, to keep a good balance between visual aids and technical writing content. I enjoyed writing the final report and am happy with the level of my technical writing skills.
Project management	☐ L ☑ M ☐ H	☐ L ☐ M ☑ H	Microsoft To-Do was an excellent tool that helped me to effectively manage the project, in combination with my other coursework and deadlines. With the help of my support plan, I hit all deadlines in this module whilst achieving excellent marks in group and individual assessments in my other modules, proving successful project management.
CES Eco Audit & LCA Proficiency	☑ L ☐ M ☐ H	☐ L ☑ M ☐ H	In the first term, I quickly learned the basics of EcoAudit, which became the key tool in my final LCA. In the 2nd semester, I quickly found further limitations (under-reporting of battery impact) and, with my critical thinking skills, overcame the issues. I tried and tested other LCA methods like GREET and OpenLCA, but ultimately found that for this agricultural-specific LCA, under the time constraints available and without the budget to purchase large LCIA datasets, simple Excel LCA analysis with EcoAudit was the best option.
Data visualization	☑ L ☐ M ☐ H	☐ L ☑ M ☐ H	I would have liked to develop these skills further to improve the accessibility of my report, so my data was put into a wider context, but still, I enjoyed using PowerPoint to create schematics and present my graphs in a clean way, so the data was easily understood.
Workflow/Methodology Development	☑ L ☐ M ☐ H	☐ L ☐ M ☑ H	I was pleased with the methodology and workflow I had developed for the project, having successfully followed ISO14040 standards for the LCA, with clear project boundaries and a well-defined functional unit. Where necessary, I adapted my methodology throughout, ultimately resulting in a successful project, showing my skills development in this area.

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Department of Mechanical, Materials and Manufacturing Engineering

A STUDY TO IDENTIFY THE OPTIMUM POWERTRAINS FOR AGRICULTURAL VEHICLES IN THE UK

MEng PROJECT PROGRESS AND PLANNING REPORT

Royal Agricultural Society of England, "FARM OF THE FUTURE: JOURNEY TO NET ZERO," 2022.

Author: Barnabas Pickford

Student ID: 20234787

Date of report: 19/12/24

Supervisor: Paul Brown

Word count: 5998/6000 - Page count: 22

Summary

Global efforts to achieve net-zero emissions by 2050 coincide with the challenge of sustainably feeding an estimated 9.7 billion people. The agricultural sector significantly contributes to global greenhouse gas (GHG) emissions and relies heavily on diesel-powered machinery. Diesel dominates the industry for its ability to deliver high torque and excellent energy density, but its poor environmental impact needs to be addressed. Therefore, a shift to sustainable powertrains is essential; machinery manufacturers are developing a range of technologies, but no clear solution has emerged. Life Cycle Analysis (LCA) provides a robust methodology to assess these alternative powertrains.

This project aims to identify the optimal powertrains for UK agricultural vehicles using LCA and an assessment of other factors to ensure the feasibility of the powertrains in the farming business. A case study 155hp vehicle will be used for the LCA to evaluate alternative powertrains, including hydrogen fuel cells, batteries, biodiesel and methane. The conclusions will guide policymakers, farmers and manufacturers to develop and invest in optimal technology that significantly reduces the environmental impact of the agricultural industry's energy use, contributing to a greener future for us all.

Table of Contents

Introduction

1.1. Background & Context

The world's leading economies have committed to being carbon neutral by 2050 [1]. Coupled with a growing population expected to reach 9.7 billion by 2050 [2]; sustainably feeding the world, ensuring alignment with the United Nations (UN) Sustainable Development Goals (SDGs) [3], will pose significant challenges. The agricultural industry contributes a significant proportion of the world's greenhouse gas (GHG) emissions (Figure 1), and specifically, its related energy use accounts for 1.7%, comparable to aviation (1.9%) and marine (1.7%) [4].

There is an extremely heavy reliance on diesel-powered vehicles for their ability to deliver the high torque required to pull increasingly large machines through the fields, their high energy density, low cost, and ease of refuelling. However, emissions from these engines remain a significant issue, despite the latest Tier VI after-treatment systems.

Major agricultural machinery manufacturers are investing in alternative fuels, releasing prototypes and commercially available solutions such as New Holland's T6.180 Methane Power [5]. And the Fendt has the e100 Vario [6]. Research organisations have developed other prototype powertrains, such as Amogy's ammonia Fuel Cell (FC) tractor [7]

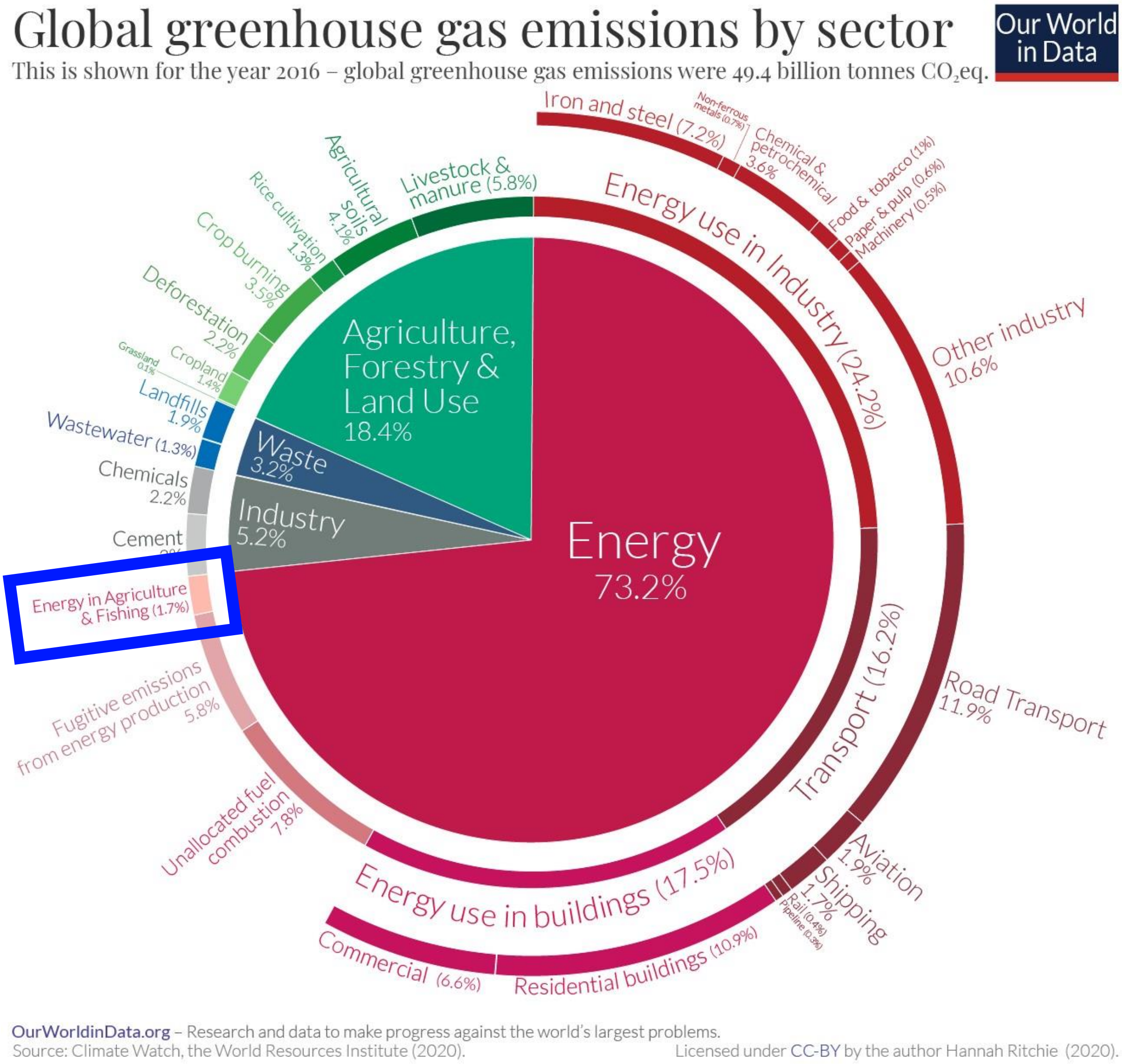

Figure 1: A pie chart from Our World in Data [4] highlighting the GHG emissions by sector. The 1.7% of emissions contributed to the energy use in Agriculture and Fishing are highlighted.

All these discussed powertrains and machines are labelled as green or sustainable; however, is there an option that will enable more progress to eliminate GHG emissions from agricultural energy use than others?

This project aims to identify the optimum powertrain for today's agricultural vehicles so farmers, specifically in the UK, can quickly make a difference in combatting climate change. The project audience is policymakers and machinery manufacturers, so they can direct investment into the development of these optimum powertrains and also the farmers so they can invest with confidence in machinery for their farms, which genuinely has an impact on reducing the GHG emissions from their business.[8]

To consider the whole picture from cradle to grave of these machines, not just their use emissions, Life Cycle Analysis (LCA) has been selected. LCA is a primary process and methodology used to assess the environmental impacts associated with all stages of the product life and is formed of 4 key stages according to the international LCA standard ISO 14040 [9] shown in Figure 2: A schematic of LCA as set out by ISO 14040; each of the stages is an iterative process allowing refinement throughout the assessment [9]Figure 2.

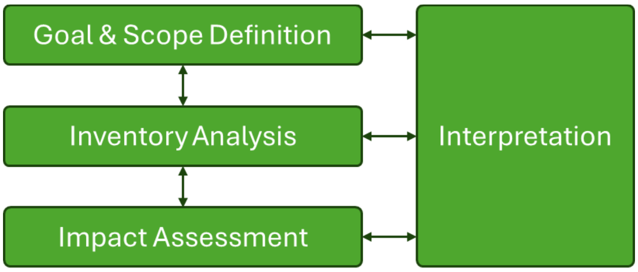

Figure 2: A schematic of LCA as set out by ISO 14040; each of the stages is an iterative process allowing refinement throughout the assessment [9]

The focus will be on the LCA, specifically GHG emissions, but the project will also consider other factors such as infrastructure and fuel availability, cost, reliability, safety, and the duty cycle of powertrains; it is paramount that a farming business can continue to operate with limited efficiency reductions due to a change in fuel for the machinery fleet.

A complete LCA allows a proper understanding of the 'cyclic economy' involved in our food production systems. Pre-mechanisation, the horses used as the main energy sources were fed from food produced on the land; the farm was energy-independent [10]. This could also be true for the next generation of sustainable agricultural vehicles powered by 'on-farm' produced green fuel/energy like methane [11] and hydrogen [12].

1.2. Aim and Objectives

Aim

'Identify the optimum powertrains for agricultural vehicles in the UK.'

Objectives

1. Conduct a literature review of the candidate powertrains and their environmental impact; by the end of 2024.
2. Define and design/construct a robust LCA methodology; by the end of 2024.
3. Complete a full LCA of a case study vehicle, excluding powertrain and fuel; within the next month.
4. Complete an 'Tank-to-Wheel' LCA for each powertrain; within the next 2 months.
5. Review and complete an LCA of 'Well-to-Tank' emissions for all candidate fuels; within the next 3 months.
6. Conduct a context comparison of all the candidate fuels and powertrains; within the next 4 months.

2. Literature review

2.1. The Drive Towards Sustainable Fuels

The aviation, marine and automotive industries are also travelling along the path to net-zero and in these sectors, more research has been conducted on the topic of ‘sustainable fuels’ due to more stringent pressure from government commitments, for example, the UK government's commitment for all cars new cars to be fossil fuel-free by 2035 [13], but there is no legal deadline for agricultural vehicles.

2.2. Barriers to Adoption

The major barriers to adoption are also similar across all industries; for heavy-duty commercial vehicle fleets, Y. Bae et al. [14] say the key barriers were economic concerns, operational challenges & technological uncertainty. L. Mohammed et al. [15] identified similar challenges, adding that a knowledge and awareness gap was also a barrier. If these barriers to adoption are stopping large commercial transport fleets from switching to alternative fuels, these barriers are only amplified in the agricultural industry; the average return on capital for farm business is only 0.5% [16], which the BBC commented is ‘low compared to other businesses’ [17]. Operational challenges are also amplified; tractors rarely leave a farm, so they don’t have access to transport hubs where an increasing number of alternative fuelling stations have been installed across the UK [18].

2.3. LCA

An LCA must follow the four iterative steps set out by ISO 14040 [9]. The stage goal and scope definition are where the LCA objective is defined along the functional unit and system boundaries. The functional unit is the product, the period the LCA is being carried out over, and its use conditions. An example of a system boundary for an automotive study can be found in Figure 3; it sets out what and what’s not being included, for example, production and end-of-life impacts and sets out sub-system boundaries like Well-to-tank (WTT) or Well-to-wheel (WTW) that can be studied independently within the system boundary. The following stage, inventory analysis (LCI), is the data collection phase, the raw material composition of the product, manufacturing impacts, known as the ‘cradle’, use phase, for example, fuel consumption, and the end-of-life impacts, known as the ‘grave’. A full LCA of a vehicle, like in Figure 3 is often known as a ‘cradle-to-grave’ analysis. The first step of the impact assessment (LCIA) is to select impact factors which are described in EN 15804 [19], then classify the LCI data to each of the selected impact categories. The final stage is the interpretation, where results are analysed and validated. It is that each stage is viewed as an iterative and flexible process allowing refinement throughout the assessment of each stage; M. Liu et al. [20] underlines that LCA is a ‘dynamic’ process.

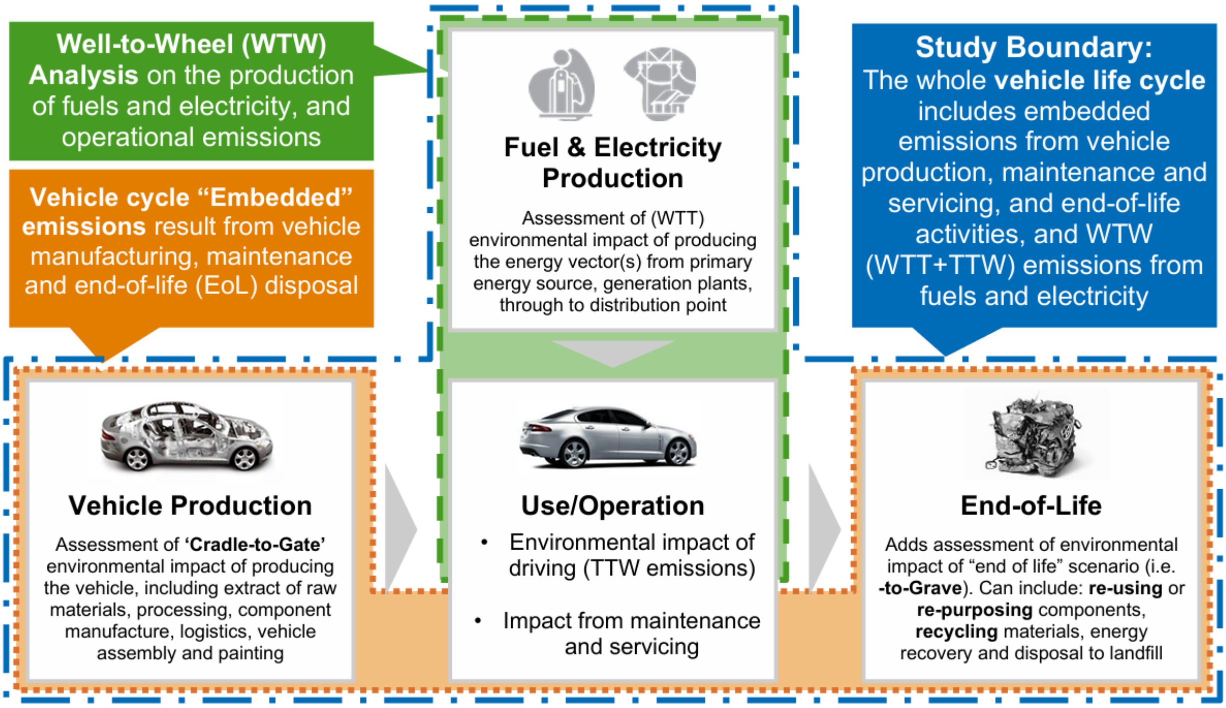

Figure 3: The example system boundary of an LCA study [21].

2.4. LCA Case Studies

In 2021, authors N. Hill and S. Amaral completed an LCA for a wide range of on-road vehicles in the UK and a wide range of fuel types. The system boundary in Figure 3 is a cradle-to-grave analysis and assesses seven emissions-focused impact factors. The results show that with the clean energy mix from the UK grid, BEVs are already reducing GPW by 65% compared to petrol vehicles and highlight that Hydrogen Fuel Cell Vehicles (HFCVs) have promise but depend on future decarbonised hydrogen production.

An LCA case study from the marine industry used a different approach using WTW analysis, purely looking at the fuel supply chain and ship operation emissions, discounting production and end-of-life analysis on the ship [22]. B. A. Zincir and Y. Arslanoglu [22] studied eight impact factors, many of which were the same, but there was more focus on impacts on life, for example, eutrophication and human toxicity. The results show that no single fuel solves all environmental problems but that a number of fuels show promise, including Hydrogen, LNG, synthetic fuels and biofuels.

Vehicle production and end-of-life impacts in N. Hill and S. Amaral report [21], account for a major part of the cradle-to-grave analysis, so results would not be majorly different if they used the same WTW approach as B. A. Zincir and Y. Arslanoglu [22]. The other major difference in their analysis was in the tool LCA tools used, N. Hill and S. Amaral [21] used a bespoke Ricardo LCA model with specific UK data compared to B. A. Zincir and Y. Arslanoglu [22] who used an open-sourced tool, OpenLCA, and GREET.

Specific LCA systems for agricultural vehicles are hard to come by; a simple example of a conventional tractor LCA was published in 2000 by J. Lee et al. [23]. Although outdated, it shows that the working use phase of a tractor's life has the biggest impact. In 2021, O. Lagnelov et al. [24] published a comparative LCA, comparing a 5-tonne conventional diesel tractor to a similar autonomous electric tractor; they again showed that the operational phase of the LCA dominates and that the electric tractor could cut the GWP by 65% despite higher production impacts.

2.5. The Agricultural Powertrain

There is huge power variation in agricultural vehicles, but nearly all vehicles sold today are diesel-powered and have the same basic operating principle: the Internal Combustion Engine (ICE) powers a mechanical and or a series of hydraulic functions (Figure 4).

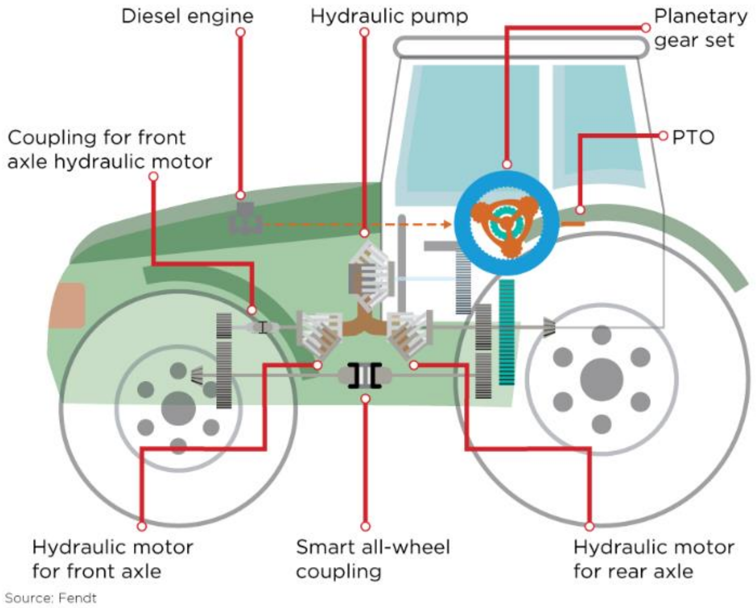

Figure 4: A typical modern tractor driveline with a CVT, where a combination of hydraulic and mechanical functions provides the wheel movement with an infinite gear ratio. The PTO is a mechanical power coupling that provides power to external implements; the engine also powers separate hydraulic pumps to provide power to hydraulic functions. [25]

Most vehicles also require long-duty cycles so they can operate remotely away from the farm for several days at a time. However, smaller machinery used on dairy farm shifts are used continuously for up to 4 hours and then are parked up, ready for the next shift. For all machines, energy density and volumetric energy density are important; modern tractors are very tightly packaged to give maximum power for a light, nimble footprint.

2.6. Candidate Powertrains & Fuels

The alternative powertrains landscape is not a clear picture; there is a magnitude of fuels and several ways of extracting power from the fuel through fuel cells (FCs), ICEs, battery systems or hybrid-electric systems.

Diesel is the current fuel of choice because it can perfectly deliver the requirements for the agricultural powertrain. Most tractors from the major manufacturers can also use biodiesel, which can deliver environmental benefits. H. Zing et al. [26] give nine alternatives to marine diesel oil for the shipping industry; along with electricity, they are all plausible candidates fuels for future agricultural powertrains. In other & reports, LCA studies looking at alternative fuels consider similar options; B. A. Zincir et al. [22] considered 14 fuels in their LCA of marine fuels, but N. Hill and S. Amaral just considered a list of 5 fuels along with hybrid options. Taking into account serval studies, Figure 5 has been adapted from H. Zing et al. [26] to include electricity as an option and expand on biodiesels to include HVO, RME, and other synthetic diesels, of which BioDME is one.

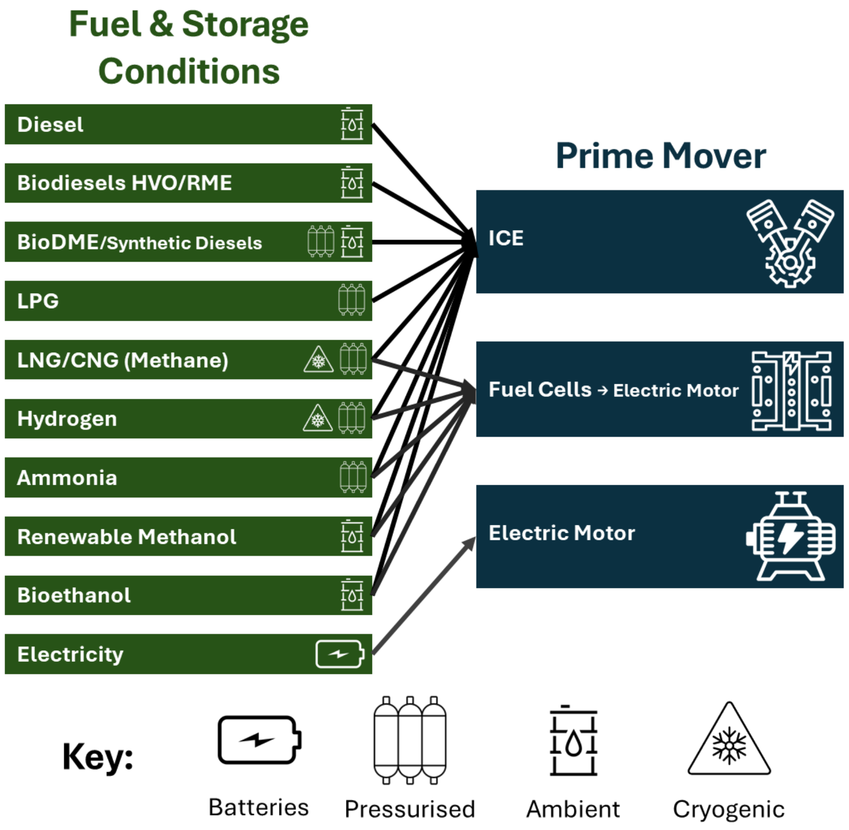

Figure 5: The key fuel options suitable for agricultural powertrains, the storage conditions and the prime energy transfer method.

High energy density is critical for maximised vehicle duty cycles, which are a key factor in assessing the optimal fuel for agricultural powertrains, to keep the machine's weight down and its dimensions small.

Table 1 shows energy density data of the candidate fuels, and it is easy to see why diesel has been the dominant fuel source; it has good gravimetric density and leading volumetric density compared to all other candidates. Hydrogen has over double the gravimetric density but lags significantly by volumetric density. The only fuel close to diesel in volumetric density is the Biodiesels/HVO/RME fuels.

Table 1: Energy density values for a selection of the candidate fuels from several sources. Average dt in the far-right columns for both gravimetric and volumetric density. Average density is in the far-right columns for both gravimetric and volumetric density. The colours represent the data source: Engineering Toolbox [27],World Nuclear Association [28], Department for Energy Security and Net Zero [29], US Department of Energy [30], J. Benajes et al. [31], Wikipedia [32]

	Energy Density									
Fuel	**Gravimetric Density MJ/kg**					Average	**Volumetric Density MJ/m3**			Average
Diesel	42.6	42.6	42		42.45	42.4	36000			36000
CNG	47.1	36.7	42	46.8		43.1	7697			7700
LNG	50			49.4		49.7	20800			20800
Methane	48.6					48.6	7697			7700
Hydrogen *700 Bar*	120		120	120		120.0	4770			4800
Hydrogen *350 Bar*	120		120	120		120.0	2400			2400
Ammonia	25.2					25.2				
Renewable Methanol	19.9					19.9	15800	13287		15000
Bioethanol	26.7	26.8			26.9	26.8	21100			21000
BioDME/Synthetic Diesel/OME	28.9		29		23.4	27.1	19200			19000
Biodiesels/HVO/RME	37.8	37.2			38	37.6	34800			35000
LPG	45.7	46	46			45.9	24400	19553		22000
Lithium-ion Batteries				0.927		0.9			2490	2500

2.7. Fuel Availability and the 'Energy Independent Farm'

For any of these candidate fuels to be viable options, the fuel must be cost-effective and support a reliable supply chain. However, recent technological advancements could make on-farm fuel and energy production a reality, creating 'energy independent farms'. Companies such as Bennamann [33] are developing solutions that allow the creation of a green fuel on-farm; they capture the methane from the livestock waste that ordinarily goes to the atmosphere, turning it into a sustainable fuel. SY Ecofit is working with several partners to combine a biogas generator system with wind and solar power to generate on-farm hydrogen [12] to power farm vehicles. Figure 6 shows how a combination of wind/solar and AD/fugitive methane can be used to generate on-farm electricity or methane, which can be used to fuel/power vehicles, provide heat and electricity to farm buildings, and generate hydrogen for fueling vehicles. Not all this infrastructure needs to be installed; for example, the farm could just install AD/fugitive methane technology for methane production to power farm vehicles [34]; the infrastructure requires significant capital investment and can be built in several stages. Combining this with an alternative-fueled vehicle fleet has the potential to reduce the GWP of the whole farm business.

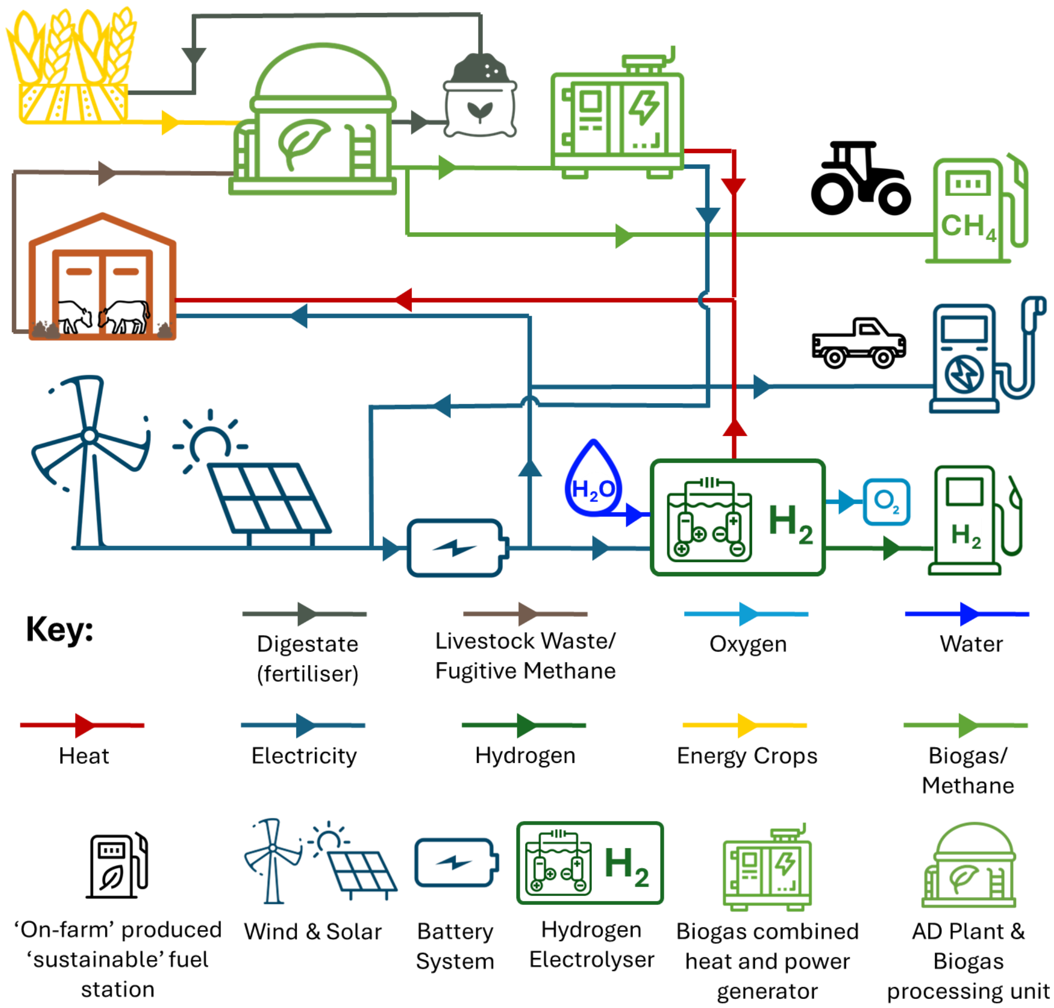

Figure 6: A schematic of the on-farm infrastructure required and energy flows that could be used to generate on-farm energy [12, 34].

2.8. Summary and Research Gap Identification

Research into alternative powertrains for agricultural vehicles lags behind efforts in the automotive and marine industries. Studies highlight the barriers to adoption, such as costs and lack of infrastructure, which will be further pronounced in agriculture due to lower profit margins, remote operation and long duty cycles. LCA is an established methodology that has been used regularly in studies to assess automotive and marine fuels, but agricultural-specific examples are few and far between, with limited scope or are now outdated and not relevant to modern-day machinery. The automotive and marine studies indicate that hydrogen, biodiesel, synthetic fuels, CNG/LNG and BEVs show promise but have trade-offs against diesel, specifically poor energy density. Additionally, on farm energy production created further opportunity for GHG emissions reduction from the whole farm business and combined with an alternative fuelled vehicle fleet.

The literature review highlights that there is a lack of up-to-date cradle-to-gave analysis for agriculture vehicles that considers their unique operational challenges and powertrain requirements; this study aims to reduce this gap by using LCA to identify the optimum powertrains for agricultural vehicles in the UK.

3. Project Methodology

As identified by the research gap, the proposed methodology will use LCA to analyse the candidate powertrains allowing recommendations to be used. However, it is not feasible to run an LCA analysis for every agricultural vehicle type and power; to reduce workload and ensure the feasibility of the project, LCA will be completed for 1 case study vehicle, a 6-cylinder 155hp tractor. This vehicle has been chosen for two reasons:

1. Recent LCI data was published in 2023 by Recherche Data Gouv for a modern 6-cylinder 155hp tractor [35]. This data will be incredibly useful and save lots of project resources in collecting data for the LCI. The tractor has been identified as a CLAAS ARION 630 (Figure 7).

Figure 7: A render of a CLAAS ARION 630 showing its internal powertrain and driveline [36].

2. It represents one of the most popular power bands in the AEA yearly tractor registration analysis (Figure 8) [37]. Furthermore, a 6-cylinder tractor at this power bracket is a large vehicle for its power; the 175hp CLAAS ARION 660 is a similar tractor with the same 6-cylinder engine.

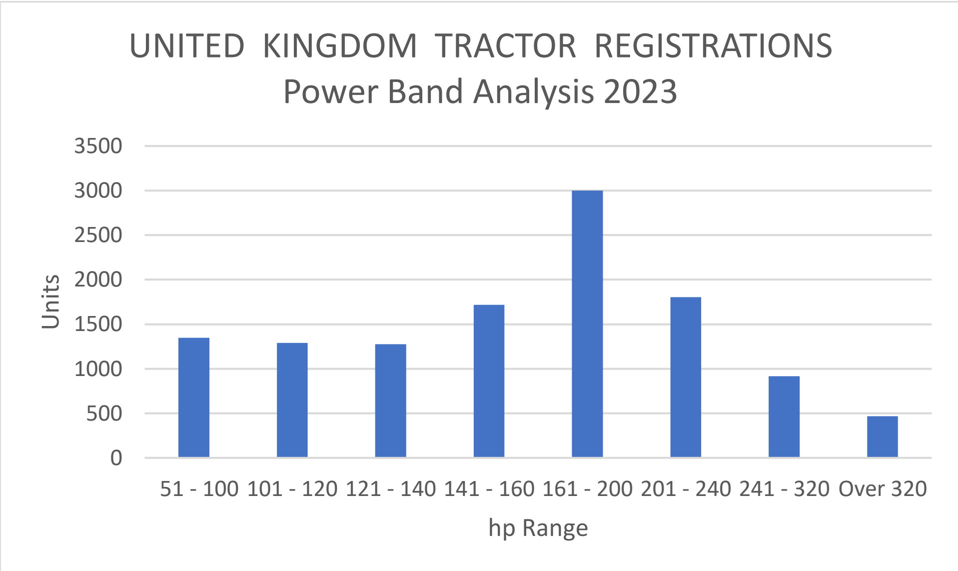

Figure 8: The total 2023 tractor registrations in the UK by power range

The LCA will be carried out to ISO 14040 [9] standards and the impact factors assessed will be chosen to ensure relevance to the study, focusing on the factors outlined in EN15804 [19]. A review of LCA tools will be carried out for the analysis. However, the first pass LCA to gather basic data will come from CES Eco Audit; other tools for detailed analysis which is being considered include OpenLCA and GREET as well as simple Excel LCA models.

Using the results from this case study, vehicle LCA and other data on machine duty cycles, fuel characteristics, like energy density, powertrain feasibility, and other context powertrain recommendations can be made to cover the whole spectrum of agricultural vehicles.

The project's success will be measured on clear and detailed LCA results from the case study vehicle and a clear set of identifiable recommendations for the optimal powertrains.

4. Project Progress

Work Package 1 (WP1) has been completed at this midway point of the project, and work is progressing with WP2 and WP3. Appendix 1 contains the detailed Gantt Chart outlining tasks, milestones and WPs.

For WP2, the candidates have been identified, along with the energy transfer schematic found Figure 5; the first principles energy review, Milestone 1 (M1), has yet to be completed, so none of the powertrain options have been ruled out.

The LCA methodology (M2) that forms WP3 can be found in the *LCA Methodology* the section below has been completed to an acceptable standard for this stage of the project but will need reviewing and refinement in the next few months. Specific details missing include data sources for some LCI data, and the LCAI tool has not been selected.

The first pass LCA of the case study vehicle has been completed using CES Eco Audit (M3), producing the following results shown in Figure 9 and Figure 10. The material and manufacturing data relied on several assumptions from the LCI data to ensure its compliance with the Eco Audit software, including specific material types and the makeup of electronic components listed in the LCI database and a 100% landfill assumption for vehicles' end-of-life [35]. Omissions of the LCI data included the use of oils and lubricants, as Eco Audit doesn't have inbuilt data for this. The operational emissions have come from a feature built into the software that outputs generic data from a 'fossil fuels' ICE input, a power value, and a use time over the vehicle's life; this is likely to be higher than in reality as the tractor is not run at 100% load for its whole life. The results demonstrate that the use phase dominated the impact of the vehicle, but further work needs to be done to address the basic assumptions and omissions to improve the accuracy of this data.

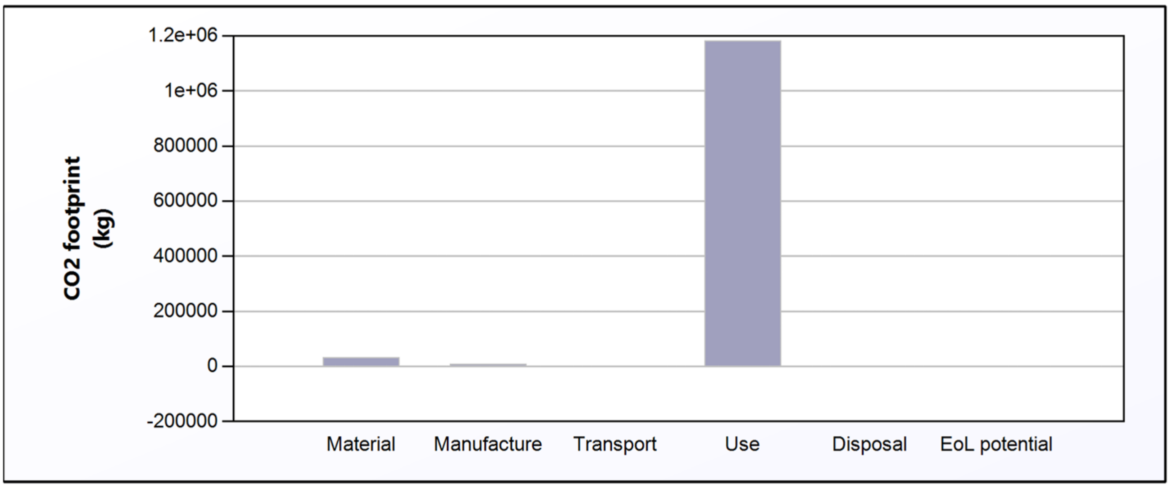

Figure 9: GPW measured in kgCO2e for the 155 hp tractor from the first pass of the LCA.

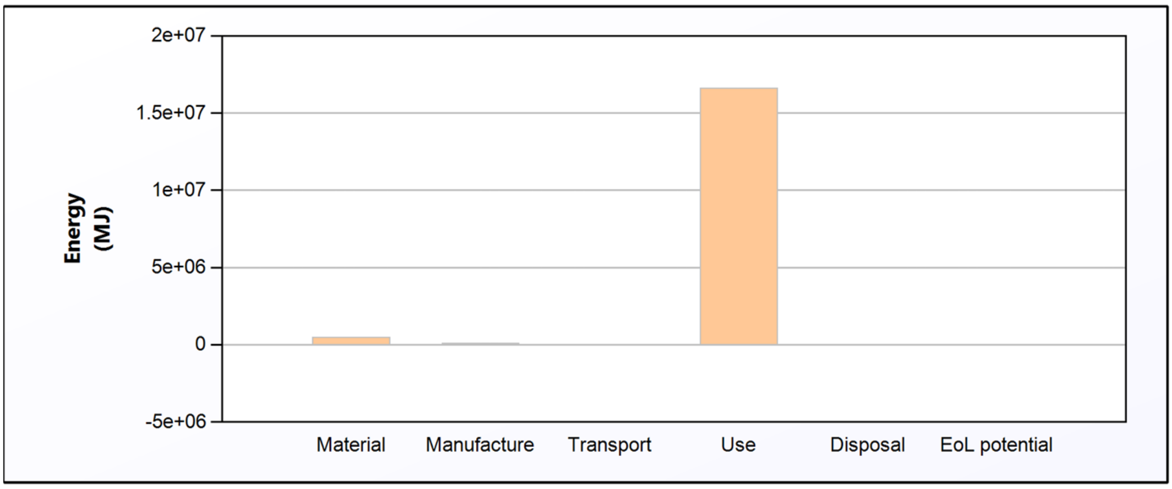

Figure 10: Cumulative Energy Demand in MJ for the 155 hp tractor from the first pass of the LCA.

Microsoft OneNote and OneDrive (Appendix 2) have been key resources used in the project to date for collating and organising information; they have helped keep meetings productive and work efficiently as every file and note related to the project has been recorded using or within these shared libraries.

To date, significant and relevant progress has been made on this project, and it is a good place to start detailed LCA early in 2025. Delays or lack of detail in some tasks and M1 within WP2 and WP3 should not significantly impact the project's completion, as LCA is an iterative process that will be continuously refined throughout the project completion.

4.1. LCA Methodology

Phase 1 – Goal and Scope Definition

- LCA Objective:
  - ‘Evaluate the environmental impacts of a 155hp agricultural vehicle in the UK market with its current diesel powertrain and compare it to alternative powertrains to identify an optimal option.’
- Functional Unit:
  - ‘One 6 cylinder 155hp agricultural vehicle operated over its lifetime of 12000 hours under typical use conditions in the UK market.’
- System Boundaries:
  - Figure 11; the LCA will be a full ‘cradle-to-grave’ analysis, including fuel production impacts.
- Assumptions and Limitations:
  - Expected lifetime usage of 1200h in line with the manufacturers data from the LCI data [35]. Others to be identified as the project progresses.
- In line with the project objectives, complete the LCA in 3 key stages:
  - Cradle-to-Grave LCA of vehicle excluding powertrain and fuel.
  - Tank-to-Wheel (TTW) LCA of candidate powertrains and fuel.
  - Well-to-Tank (WTT) LCA of fuels.

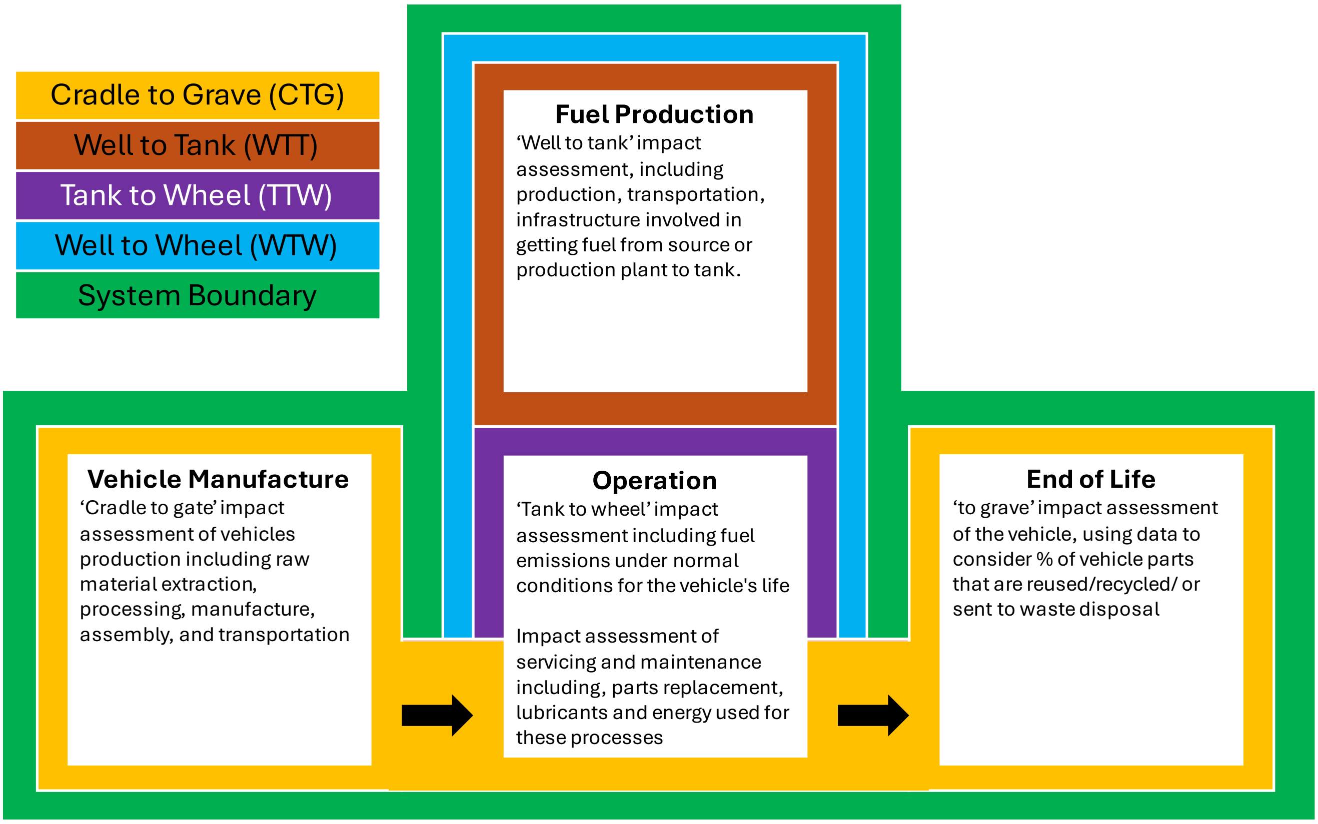

Figure 11: The System boundary for the LCA study, the colours represent the different subsystems involved that can be separately analysed during the results interpretation phase.

Phase 2 – LCI

- Data Collection:
  - Vehicle raw material composition from LCI data [35].
  - Manufacturing data by energy use from LCI data [35].
  - Operation use phase; fuel emissions data and maintenance intervals from manufacturing specifications and the LCI data [35].
  - Fuel production impacts: data source to be confirmed.
  - End-of-life impacts: data source to be confirmed.

Phase 3 – LCIA

- Impact categories:
  - Global Warming Potential (GWP) - kg CO2 equivalent
  - Cumulative Energy Demand (CED) - MJ
  - Abiotic Resource Depletion
    - Non-renewable resources - kg Sb equivalent
    - Fossil resources - MJ
  - Acidification Potential (AP) - mol H^+ equivalent
- Data Classification:
  - Mapping LCI outputs to the impact factors using selected LCA tools which are to be confirmed.

Phase 4 – Interpretation

- Results analysis to identify major contributors to impacts.
- Results validation by comparison with similar studies for automotive, marine and agricultural LCA studies.

5. Future plan

5.1. Milestones and Objectives

At the commencement of the spring semester, the first task will be to complete the '1st principles energy review' of the fuels and powertrains (Gantt chart in Appendix 1, Figure 13). The next steps will be to review and select the LCA tools allowing work to progress through the project's LCA stages. Table 2 shows a summary of the milestones and deliverables from the project's Gantt chart; with a reduced number of credits being taken in the spring semester, the current delays in the project will be recoverable.

WP4 is the major stage of this project, which includes M2-5, and in combination with WP5 and M6, is the full LCA stage of the project. WP4 is due to be completed 20/02/25, the results of which will feed into the WP5, due for completion on 13/03/25 (M6). WP4 completion also feeds into the 'Other influencing factors review', which, along with the first stage of WP5 and WP2-4, will form the content in the presentation due to be started on 03/03/25 for delivery on 17/03/25 (D3). Once WP5 has been completed and the presentation delivered, the final report write-up will commence on 25/03/25, with a first draft due on 28/04/25 (M7) and final submission on 06/05/25 (D4).

Table 2: Milestones & Deliverables summary table from the Gannt Chart (Appendix 1)

Work Package	Milestone/Deliverable	Description	Completion Date	Progress
WP1	D1	Submit Proposal Review	06/11/24	Completed
WP2	M1	Energy transfer schematic completed	12/11/24	Started
WP3	M2	Methodology completed and vehicle selected	21/11/24	Completed
WP4	M3	Vehicle LCA completed	05/12/24	Started
	D2	Submit PPR	19/12/24	Completed
	M4	Diesel powertrain LCA completed	30/01/25	
	M5	Candidate powertrains LCA completed	20/02/25	
WP5	M6	'Well to tank' emissions LCA completed	13/03/25	
WP6	D3	Presentation	17/03/25	
	M7	Final report draft complete	28/04/25	
	D4	Final report submitted	06/05/25	
WP7	M8	Complete audit and put in portfolio	22/10/24	
	M9	Complete reflection	28/01/25	Started
	D5	Submit portfolio for marking	13/05/25	

5.2. Risks and Mitigations

To ensure successful project completion, key risks have been identified in Appendix 1, Table 3, where appropriate mitigation measures have also been outlined. The risks have been assessed by probability and impact, enabling the prioritising of risk mitigation measures; Figure 12 shows that there are no outstanding high risks.

These risks do not pose a significant risk to the project's critical path, as seen in the Gantt chart (Appendix 1, Figure 13), which demonstrates that the timeline is achievable. Very low probability risks include the availability of CES/Virtual Desktop and (R2) over-ambitious project objectives (R1), which are mitigated through regular data backups and discussions with the project supervisor. R3-5 have a low probability, the most likely of which is poor data availability R3; mitigation involves adherence to ISO14040 for the LCA, ensuring responsible assumptions and estimations are used in place of missing data and that they are all explained as part of the interpretation phase of the LCA. The highest impact risk is a potential misunderstanding of the LCA and project methodology (R5), which could seriously hinder the project's success, but through the development of the project methodology under the guidance of the project supervisor, this risk has been effectively mitigated. The risk of illness/injury setting the project back is low; it is mitigated through the built-in contingency to the project planning and, if necessary, can be further mitigated through the Support Plan to extend deadlines.

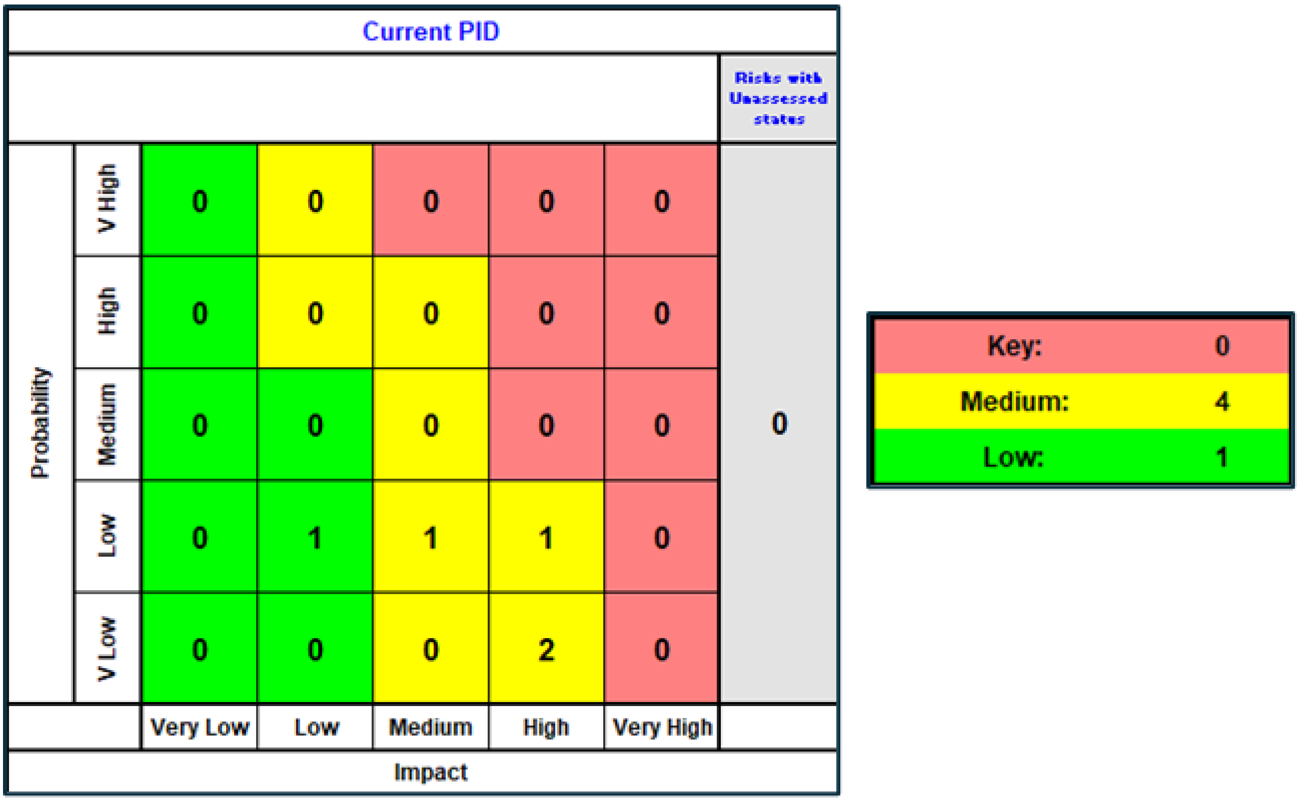

Figure 12: The PID chart from the project Risk and Mitigation table Appendix 1, Table 3.

6. Conclusions

The agricultural industry sector is facing immense pressure to cut its carbon footprint to zero, necessitating a shift from conventional diesel-powered vehicles to sustainable alternative fuels. The project has identified the candidate powertrains and fuels that could provide this answer and plans to leverage LCA to evaluate the environmental performance of the powertrains. As a case study vehicle, a 6-cylinder, 155hp tractor has been chosen as it represents a significant proportion of the market, and recent, reliable LCI data has been published for this vehicle.

The project has identified nine fuel alternatives, including hydrogen, ammonia, CNG/LNG, biodiesel, electricity and synthetic diesel, which show potential for reducing GHG emissions significantly; however, trade-offs from energy from reduced density will have to be made. These fuels can deliver power through either ICE, FCs or electric motor powertrains, with each one needing a separate confederation of its suitability for agricultural vehicles. Initial findings for a preliminary LCA study using CES Eco Audit have highlighted that a majority of the environmental footprint for a diesel tractor's lifetime is during its operational phase, validating the need for an alternative sustainable powertrain and fuel.

On-farm energy independence could offer an innovative approach to integrating new vehicle fleets onto the farm, enabling the production of methane, hydrogen and electricity. This circular model could also further help reduce the farming business's environmental footprint by capturing biogas from livestock waste, stopping this from entering the atmosphere.

Suitable project management and risk strategies have been utilised to ensure the project is successful in fulfilling its aims and objectives. The next steps involve refining the LCA model and completing the first principles energy review to enable focus LCA of the most promising powertrains. Together with a feasibility review and external context study, the project will conclude and offer policymakers, farmers, and machinery manufacturers actionable insight into the optimal power train for agricultural vehicles in the UK, which will enable the sector to lead the drive toward net zero emissions so we can continue to feed the worlds growing population sustainably.

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Appendix 1 – Gantt Chart and Risk Table

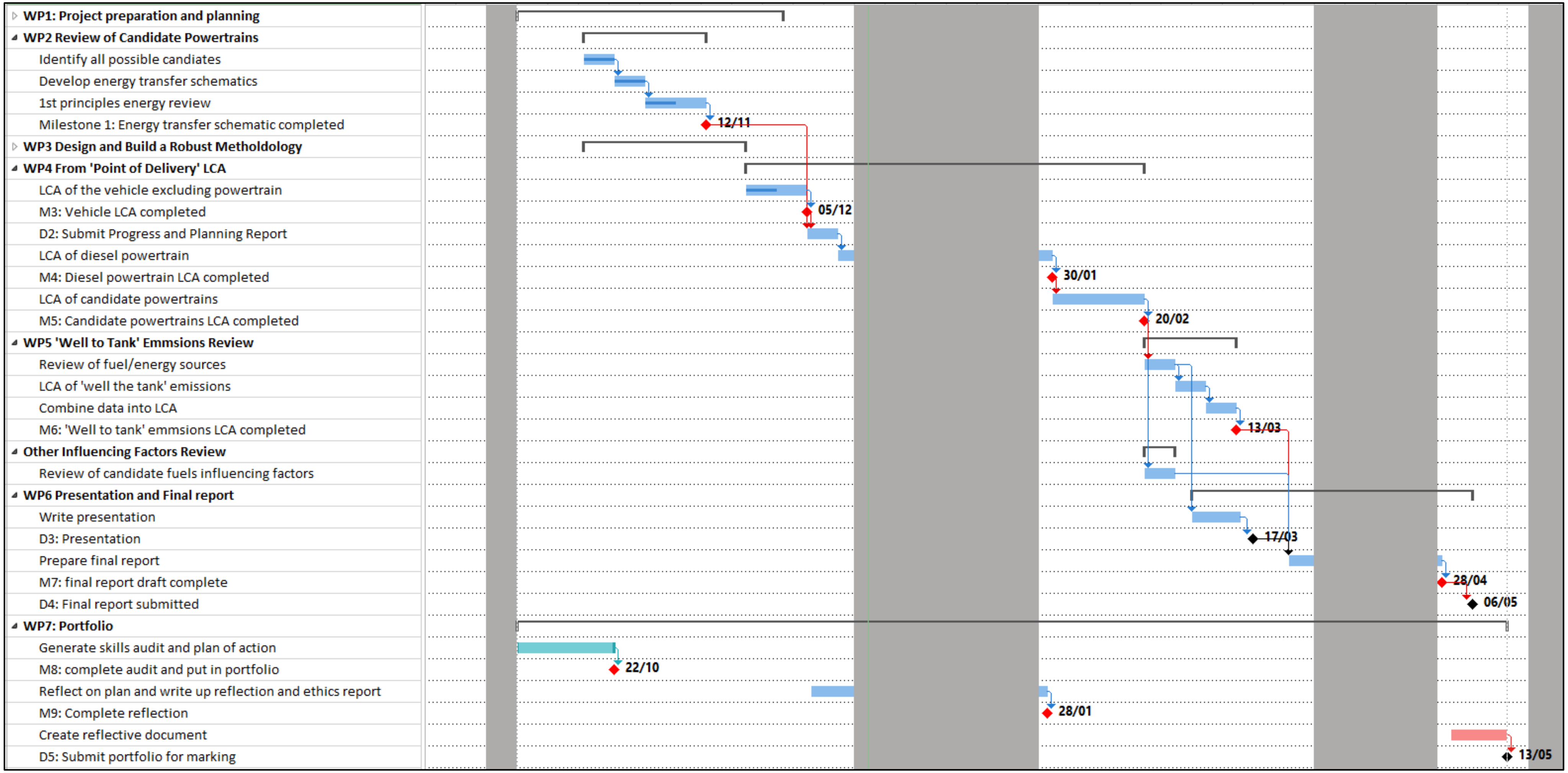

Figure 13: The project Gantt chart showing vacations, dependencies, substantial tasks, milestones and deliverables. Completed WP1 & WP3 have been collapsed to ensuing visibility of the future work schedule.

Table 3: The Project Risk Table

Risk ID	Initiation Date	Work Package	Risk Title	Cause "If…"	Effect "Then……"	Proposed Mitigation	P	I	Ranking
R1	5-Nov-24	All	Over ambitious objectives, not all LCA or reviews completed	project changes direction	Objectives might change	Regularly review progress with supervisor and, when and where necessary, make slight adjustments to aims, objectives and title.	VL	H	VLH
R2	5-Nov-24	WP4, WP5	CES/Virtual Desktop unavailable	CES/Virtual Desktop becomes unavailable	Completion of LCA study might not be possible	Ensure work is always backed up to OneDrive In case of unavailability, use Coates computer rooms to access CES.	VL	H	VLH
R3	5-Nov-24	WP4, WP5	Poor data availability	Data is poor or unavailable for alternative powertrains in agricultural vehicles	Then LCA for the alternative powertrains will be difficult	Follow ISO 14040 so LCA methodology, where required, estimates data in a responsible manner from other industry applications or sources. Being sure to report these assumptions in the final LCA report.	L	M	LM
R4	5-Nov-24	All	Illness/injury/other factors out of my control	Work is prevented	Project may fall behind	Build in contingency to the project planning timetable If necessary make us of Support Plan by contacting the M3 DLO	L	L	LL
R5	5-Nov-24	WP4, WP5,WP6, WP7	Ability to apply the methodology	I miss understand the methodology of LCA	I won't have the ability to undertake the project	Work with supervisor to ensure the correct direction of methodology development and dedicate significant time to developing LCA expertise.	L	H	LH

Appendix 2 – Logbook

For the project OneNote logbook and OneDrive folders please use the links below:
OneNote: MEng Individual Project Logbook
OneDrive: MEng Individual Project MMME4086

Reflection on your initial skills assessment and plan, and reflection of how your project links to the four ethical principles of engineering.

As the first semester of your project draws to a close, you will revisit your initial skills assessment. You will select up to five key skills and reflect on how they have evolved throughout the course of your work. This reflection enables you to track your progress, evaluate the effectiveness of your action plan, and contemplate future development strategies.

Ethical Principles Review

Throughout your project, you will consider four fundamental ethical principles:

- **Honesty and Integrity**
- **Respect for life, law, the environment, and public good**
- **Accuracy and Rigour**
- **Leadership and Communication**

For each principle, you will identify 1-2 aspects pertinent to your specific project. This review encourages critical thinking about the ethical implications of your work and enhances your awareness of professional responsibility within the field of engineering.

At the end of the semester review your 5 important skills and reflect on their development.

Skill	**Starting confidence:**	**Concluding confidence**	**Reflection on how successful the plan has been with a reflection on how it could have been improved.**
Critical thinking	☑ L ☐ M ☐ H	☐ L ☐ M ☑ H	During the 1st half of the project, I used the library resources and the skills taught in Advanced Technology Review (MMME4052) to develop my critical thinking skills. I achieved good feedback across the board for my coursework for MMME4052, showing that I have successfully developed these skills. Going forward into the final project stages, I will use these skills to critically assess my results against publicly available data.
Technical writing	☐ L ☑ M ☐ H	☐ L ☐ M ☑ H	I took pride in my technical writing ability and successfully used these skills when writing and formatting my Project and Planning Review. I especially developed skills in line with using a reference manager to assist with organising and formatting my references in the report. I'm looking forward to continuing to develop these skills to ensure that my final report is of the highest quality.
Project management	☐ L ☑ M ☐ H	☐ L ☐ M ☑ H	I successfully developed skills in Microsoft Projects to build the project Gannt Chart. This was especially useful in the final few weeks before the Project and Planning Review deadline as it allowed me to clearly see where I was behind on task deadlines so I could plan ahead and use my Support Plan to extend the deadline. I also heavily utilised Microsoft To-Do during the term, enabling weekly and daily focus on tasks. I will continue to use these skills over the 2nd half of the project to enable successful task prioritisation and completion.
CES Eco Audit & LCA Proficiency	☑ L ☐ M ☐ H	☐ L ☑ M ☐ H	Early in the project timeline, I used lecture resources provided by my project supervisor, and simple example projects to familiarise myself with CES Eco Audit. I did this successfully, but I do not feel my proficiency in LCA has reached a high enough level to complete the project to a high standard. Limitations within CES Eco Audit mean I will urgently, at the start of the 2nd semester I will, identify additional LCA tools and methods that allow complete a holistic LCA needed for this project.
Data visualization	☑ L ☐ M ☐ H	☐ L ☑ M ☐ H	Limited data visualisation skills have been required so far as only first pass initialise LCA has been completed, so no results need comparing and visualising. I have, however, begun using skills to help visualise project methodology and key themes in the project by creating schematics using Microsoft PowerPoint. When the data is ready, I am confident that my plan outlined in the previous submission and my graphic design skills will enable clear data visualisation and results interpretation.
Workflow/Methodology Development	☑ L ☐ M ☐ H	☐ L ☑ M ☐ H	I used the library's online resources to gain proficiency in the EndNote suit of tools, which I used successfully to manage the resources used for the Project and Planning Review. I have also developed, using the research, an LCA methodology that will yield reliable and useful results in line with my project aims and objectives. I need to spend time early next semester finalising this methodology, in tandem with selecting additional LCA tools, to further develop these skills to a higher standard.

Ethics reflection

Please identify one to two areas that link to each of the four fundamental themes of ethical practise. Ensure that you put in complete paragraphs and you can expand onto more pages if necessary, but is not required.

Theme	How does your project link to these.
Honesty and Integrity	Honest and Integrity will be upheld by presenting a unbiased, data led evaluation of all the candidate powertrains though LCA. It will not use opinions to inform any decision during the LCA to ensure results are solely evidence based and can be robustly defended. The methodology, assumptions & limitations will be document to ensure transparency in the project and enable the stakeholders to trust the findings. By maintaining ethical practice throughout the project upholding honesty and integrity the project will be able to contribute credible insight to the engineering and agricultural industries.
Respect for life, law, the environment and public good	The project holistically aligns with the principle of respecting life and the environment by identifying sustainable powertrain options that reduce greenhouse gas emissions and resource consumption in agricultural vehicles use and manufacturing. By firstly addressing the issues relating to the currently preferred diesel powertrain it will identify where improvement can be made support industry compliance with its own and the world's climate goals, emissions legislation, enabling wider public good mitigating the effect of climate change and protecting our environment. Compliance with these legal and regulatory standards ensure the results are ethically and legally sound contributing to broader industry goal of responsible engineering.
Accuracy and Rigour	The project links to accuracy and rigor, through ensuring the LCA adheres to the relevant ISO standards, ISO14044 and ISO14040. The project will be formed from detailed reliable data to ensure compliance with the engineering this principle. Carful consideration will be given to ensure sensible informed decisions are made when designed the methodology, and system boundaries so the results can be sued to make informed critical decisions. The level of rigor will ensure objective criteria will be used to guide the project conclusions for reducing the industries greenhouse gas emissions.
Leadership and communication	Leadership and Communication is essential to the project success. The project demonstrates leadership by proactively addressing issues and challenges in the agricultural machinery industry, which is often overlooked by government and green technology advocates. Clear and effective communication of the LCA findings is vital so the readers and stakeholders can clearly make informed decision about the direction in which to drive change and adopt/develop genuinely sustainable technology, ensuring positive impact across the whole industry.