Red Diesel Replacement Competition

Phase 1 - Final Project Report

Publishable

Project Code	**RDR/P1/L2/9504**
Project Lead Organisation	Terex
Project Title	Development of Electric-Driven Mobile Aggregate Crushers and Development of Net Zero Road Map for Mobile Aggregate Processing
Project Start Date	5th April 2022
Project End Date	31st March 2023

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1. Project Summary

Currently, track mobile aggregate crushers are predominately powered by diesel engines driving either a hydraulic, mechanical clutch or electrical drive system. This project was designed to develop and build a working prototype of a track mobile aggregate crusher with a next generation permanent magnet motor and DC (Direct Current) bus drive system. As part of the project, the lead organisation (Terex) collaborated with Queen's University and other organisations (with knowledge of this technology) to assist with its application in a track mobile aggregate crusher. As part of the technical design, analysis was carried out on the operation of the crusher to understand duty cycles and how the technology will work in them. Additionally, as part of the overall project, research was conducted into alternative power sources that can provide net zero electrical energy that would be suitable to power machinery in locations that do not have access to mains supplied power.

The main goal of this project was to develop a track mobile aggregate crusher with improved efficiency that will reduce the consumption of diesel fuel by 20%, with future potential to reduce fuel consumption further by up to 90% when an electrical power source is available. The technology developed as part of this project is also applicable to other semi-mobile applications, for example environmental processing equipment (such as a Terex Ecotec Shredder).

1.1 Project Organisations

Terex

Terex is a global manufacturer of materials processing machinery and aerial work platforms. The company designs, builds and supports products used in construction, maintenance, manufacturing, energy, recycling, minerals, and materials management applications. Certain Terex products and solutions enable customers to reduce their environmental impact including electric and hybrid offerings that deliver quiet and emission-free performance, products that support renewable energy, and products that aid in the recovery of useful materials from various types of waste. The products are manufactured in North America, Europe, Australia and Asia and sold worldwide.

Terex sites across the United Kingdom predominantly belong to the Terex Materials Processing (MP) segment. Terex MP is a substantial portfolio of businesses that manufacture equipment for the Aggregates, Environmental, Concrete, Material

Handling and Lifting industries. Terex MP brands include Powerscreen, Finlay, EvoQuip, Terex MPS and Terex Washing Systems, MDS and ProStack. These brands design and manufacture mobile, modular, portable, and static solutions to support crushing, screening, washing, recycling, and conveying applications for the world's minerals, aggregates, and construction industries.

Queens University Belfast

Queen's University Belfast, a Russell Group university and member of leading Research-intensive UK universities, will lead the vehicle modelling and simulation research aspects of the project. Queen's University has an extensive history of vehicle modelling and electrification of heavy-duty powertrain experience.

Wrightbus

Wrightbus based in Ballymena, Northern Ireland, have over 20 years' experience in producing low and zero tail pipe emission vehicles, including micro, mild and full hybrid electric powertrain topologies, alongside full battery electric and fuel cell technology deployment. They have extensive experience both in modelling, design, and manufacture of advanced powertrain configurations.

AJ Power

AJ Power Ltd (www.ajpower.net) is based in Craigavon, Northern Ireland, and specialise in the design and manufacture of generator sets, with access to accredited advanced testing facilities, assembly, with genset manufactured for a wide range of specialist applications from 10 kVA to 4376 kVA. They have a specialist knowledge of the power demand profiles and previous track record of collaboration with Terex on delivery of crushing and screening equipment power solutions.

2. Technical Report

2.1 Drive Topologies of Track Mobile Aggregate Crushers

Track mobile aggregate crushers can be powered by a range of drive line topologies. The majority of tracked mobile aggregate crushers sold by Terex are powered by diesel engines—the crushing chamber is powered either by hydrostatic drive or via a clutch, while all other functions on the machine are powered by hydraulic pumps and motors. In this Phase 1 project, the new technology was compared to an existing Terex mobile jaw crusher, which has a crushing chamber that is driven by a dry plate clutch powered by a diesel engine, while the other functions on the machine are powered by variable displacement hydraulic pumps and motors. Figure 1 shows drive topology of the Terex mobile jaw crusher.

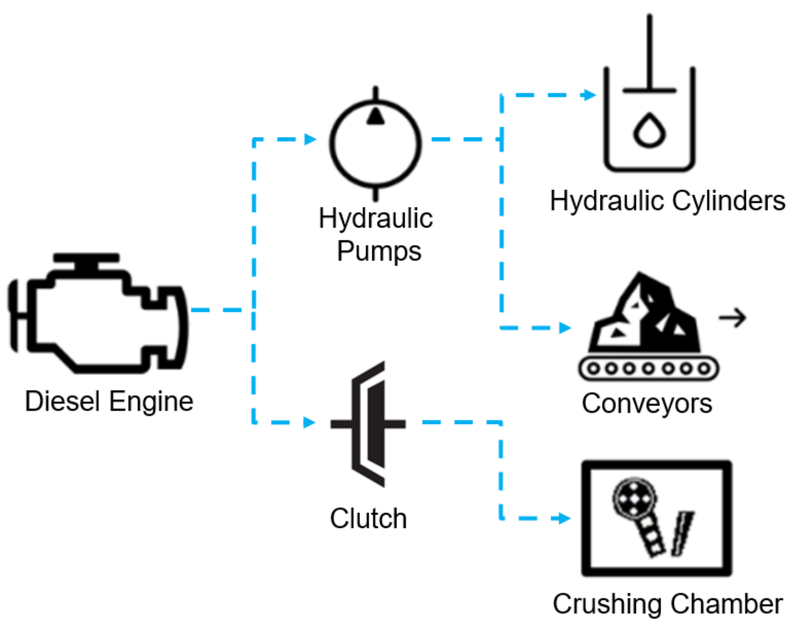

Figure 1 – Terex Mobile Jaw Crusher Drive Topology

Terex also produces hybrid crushers. All functions on this type of machine are powered by induction electric motors, meaning that the machine can either be powered by an on-board diesel engine or plugged into a mains electrical power source. Compared to a diesel/clutch/hydraulic machine, this drive topology will significantly increase machine cost. Most hybrid/electric drive track mobile aggregate crushers available on market today have drive topology similar in concept, which is illustrated in Figure 2.

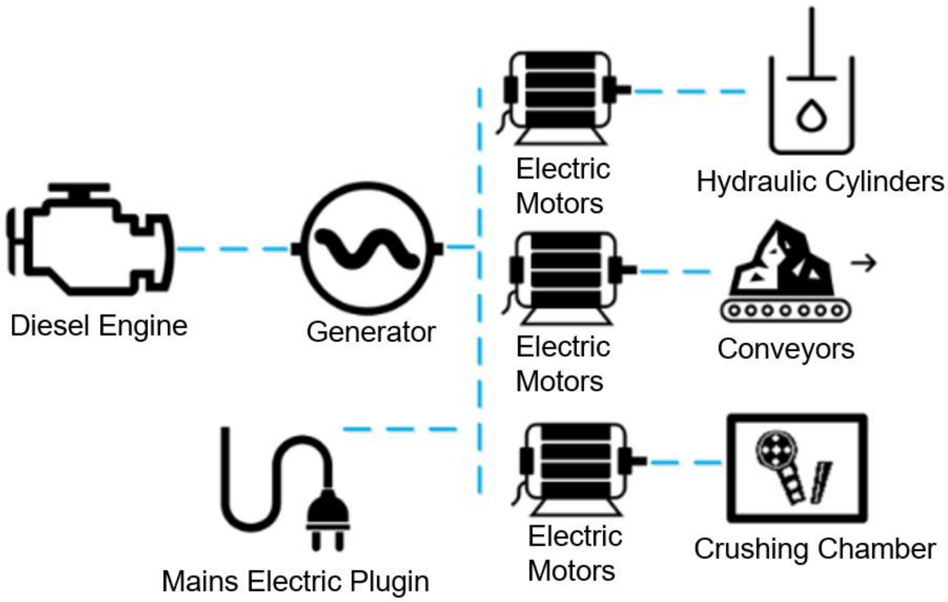

Figure 2: Electric Drive Track Mobile Aggregate Crusher Drive Topology

2.2 Project Design Concept

As part of this Phase 1 project, a working prototype of a Terex mobile jaw crusher was developed with a diesel engine driven by a permanent magnet motor generator. The main crusher drive was powered by a permanent magnet motor. The system also included super capacitors integrated into the DC bus control system of the power electronics. The remaining drives on the machine were powered by an open loop variable displacement hydraulic pump, which was driven by the through drive function of the motor generator.

While this Phase 1 prototype machine is powered solely by a diesel engine, the system was designed so that a future development would allow the system to be connected to an electricity supply to power the machine with the engine switched off. This would be achieved by adding a clutch between the engine and motor generator, along with an additional DC/AC converter and transformer filter.

The drive topology that was developed for the Terex mobile jaw crusher as part of this Phase 1 project has several benefits over both the existing diesel/clutch/hydraulic machine and electric powered/hybrid machines that are currently available:

- **Drive line efficiency** – with the increasing cost of energy, one of the key goals of this Phase 1 project was to develop a more efficient drive line, to improve the overall efficiency of the machine. This concept uses several technologies to achieve this.
- **Permanent magnet motor technology** - there are several advantages to a permanent magnet motor/generator over an AC induction motor in a crushing and screening application. In a high-power application such as a crusher, it is important that torque variation is reduced to maintain drive speed. Variations in drive speed can have undesirable effects such as stalling (due to reduced inertia in flywheels), variance in aggregate shape, and reduction of throughput. A permanent magnet motor can overcome this by generating a more constant torque, with full torque available from low speeds. Additionally, a permanent magnet motor has a higher efficiency due to lower losses. In comparison to a wound coil rotor in an AC induction, motor losses due to heat generation are also lower. This reduces the cooling requirement as well as the supply power demand. Finally, the permanent magnet design also allows for a smaller rotor. This, combined with water cooling technology facilitates a smaller size, giving a higher power density, which leaves the motor easier to package on a mobile application (where space and weight are at a premium due to transport constraints).
- **Energy storage and engine sizing** - in a conventional diesel/clutch/hydraulic or electric drive crusher, the diesel engine must be sized to be able to power the peak load of the machine. In a track mobile jaw crusher, the average load when crushing can in some applications be as low as 40%. This means the engine is sized much larger than required. A supercapacitor was also fitted to the system to store energy when the machine is running at lower load, and then provide additional power to the crushing motor when machine comes under full load. This ensures the smaller engine is running at higher percentage load and in more efficient part of the power curve of the engine.
- **Manufacturability** – reengineering a diesel hydraulic machine to be powered by diesel genset with electric drive functions would involve considerable

changes to the machine design. A significant number of the machine sub-assemblies would need to be redesigned and optimised for the electrical drive system. With the selected drive concept for this Phase 1 project, most of the machine sub-assemblies are the same as used by the diesel hydraulic version of the machine, with the Powerunit and crushing chamber drive being the only sub-assemblies with significant changes. This commonality of components improves the manufacturability of the machine, ensuring that both the hybrid and diesel hydraulic machine can be produced on the same final assembly production line, with a similar production cycle time.

- **Machine dimension** – reengineering a diesel clutch hydraulic machine to full electric drive using industrial electrical technology can often involve increasing machine size—the drive components are generally larger and heavier than equivalent powered hydraulic components. This increase in size and weight means the overall machine weight and dimensions increase. The compact dimensions of the permanent magnet technology, as well as the smaller engine means that the overall machine weight and dimensions can be kept the same as the conventional diesel/clutch/hydraulic machine.
- **System durability** – the majority of electric hybrid track mobile aggregate crushers available on the market today are manufactured using industrial electrical components. These components are not best suited to mobile machines and are often required to be mounted in vibration isolated cabinets and cooled with either forced air cooling or air refrigeration systems. The technology used in the drive system for this Phase 1 project has been developed for the off-highway market. All components are suitable for wet and dusty environments with a rating of IP67, a vibration rating of up to 5.9g RMS, and mechanical shock rating of up to 50g. Any of the components that require cooling are fitted with a liquid cooling system, similar in design to systems already utilised on track mobile crushers for hydraulic oil and engine cooling.
- **Flexible power source** – as the construction and quarrying sectors work to decarbonise equipment there is currently a range of technologies being evaluated by both major OEM (original equipment manufacturer) and industry. Some of the technologies being considered are battery electric, hydrogen fuel cell, hydrogen combustion, and E-Fuels to mains umbilical plugin. As yet, no one clear winner has been chosen by the industry and it is unlikely that there will be one best technology that will work for all machine types or even

application that the machines are used in. As the industry transitions, it is important that technology developed can be used across the industry and not be focused on a niche power source that is either limited in supply or may become obsolete (hence leaving the product unusable with new power sources). The concept selected as part of this Phase 1 project leaves the machine design flexible so that it can be run on currently available diesel, or with the future plug-in option that can be plugged into a mains power source or alternative power source (for example hydrogen powered generator or Ammonia powered generator). With track mobile aggregate crusher concepts, where a machine is designed to be used in many different applications and locations, it is important that the machine can operate using the power sources that are available and suitable for the location and application.

3. Drive Cycle Simulation

3.1 Introduction

Within the W-Tech Centre at Queen's University Belfast, significant research has been conducted over a period of almost 10 years in the development of simulation models for the electrification of diesel powertrains, primarily for the bus industry. W-Tech have produced vehicle models for both electric and hydrogen fuel cell powertrains which can predict the energy consumption of specified vehicles over a given drive cycle (time/velocity/elevation profile). These models are used by Wrightbus both in the development of new vehicle configurations and to assist in the demonstration of vehicle capabilities for bus operators during the sales process. In this project, QUB/W-Tech have brought this expertise in zero emission powertrain simulation to develop a simulation model representing a Terex mobile jaw crusher hybrid prototype machine. The machine model was developed within MATLAB Simulink to be used for the following cases:

- Feasibility study of overall design
- Component sizing
- Estimating performance and fuel consumption
- Inform control system design
- Predict system states to help inform system level design choices (eg. cooling required based on heat loss from electrical components)

3.2 Simulink Model

The Simulink model developed for the Terex mobile jaw crusher hybrid prototype crusher is broadly analogous to a series hybrid fuel cell bus model, in which W-Tech have vast experience developing in the past. The main difference for this application is that the crusher has an engine/generator that replaces the fuel cell, and supercapacitors that replace the battery. The model is a backwards-facing, power-flow, drive cycle model, built within MATLAB Simulink. Figure 3.1 shows the top level of the model as represented within Simulink. The powertrain model is contained within the "Model" block. The "Control" block contains the model control system, while "Data Out" is simply for logging and organising results signals into a hierarchy for display in the Simulink Data Inspector and simulation output object. Outputs include a range of telematics traces, as well as predicted fuel consumption.

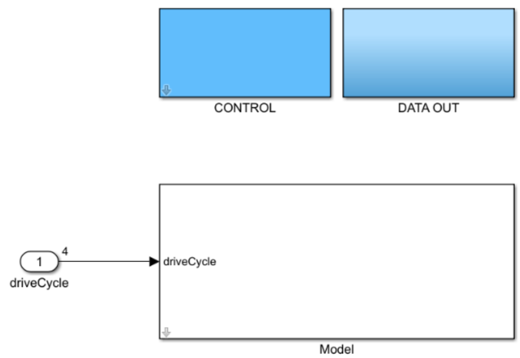

Figure 3.1 – Simulink top level model page

The key input into the Simulink model is the drive cycle (a series of data points which describe the typical operation of the powertrain). For the crusher powertrain, the drive cycle is composed of the following components: time, crusher RPM, crusher power (kW), hydraulic pump power (kW). In the backwards-facing model, the drive cycle splits between the crusher power and the pump power. Power flows backwards from the drive cycle input at the crusher mechanism, through the motor, and then into the supercapacitor bank. The engine/generator is disconnected from the load at the crusher; thus, the control system determines the power requested from the generator, effectively making this portion of the model forward-facing. The pumps, which are required to operate the conveyors, are directly driven by the engine.

In the initial stages of the project, Terex provided drive cycles that were logged from a similar direct drive crusher machine. The drive cycles were each of 15-minute (900 second) duration, at various engine speeds. These drive cycles were used as input into the simulation model to assess design feasibility and for sizing of components.

The initial simulations showed that there was not enough overall system energy in the concept design available to complete the required cycles at any of the engine speeds. Following these simulations, the capacity of the energy storage system was increased to allow the simulation model to complete the required cycles.

For motor and generator selection the simulation model included the coolant and efficiency maps for the components. The simulations recommended that these components should be used, as they are representative of both worst case and nominal conditions.

Another issue that was identified from the simulations was related to the control of the generator power limits. A maximum power demand parameter from the generator is specified within the model. The purpose of which is to prevent the generator power demand from overloading the engine.

Simulations were used to analyse the energy storage system power and current requirements during the 900 second drive cycles to ensure the system stayed within the manufacture recommended temperature limits. The simulations show that the energy storage system currents and power requirements are well within the safe limits.

3.3 Conclusions

During this project, a simulation model has been developed within MATLAB Simulink which describes the operation of the Terex mobile jaw crusher powertrain. The model has been used to show that the design is feasible for all drive cycles considered, and has helped to inform energy storage system, motor and generator sizing and selection. The model has also been used to inform control logic.

4. Results from Testing

The main goal of this Phase 1 project was to design and build a prototype machine with next generation electrical drive system. Due to the short duration of the project, only limited testing was planned. Delays in the build of the prototype (caused by ongoing supply chain issues) resulted in the project deadline being extended by one month, to allow for additional testing to be carried out.

The testing was completed in two phases—an initial phase that included commissioning of all machine functions and a second phase of load testing.

The initial testing involved electrical insulation testing, electrical continuity testing, electrical discharge testing, machine and power electronics software functionality and safety testing. Following the initial testing, the power electronics system was calibrated to ensure correct parameters for each of the system components. As part of this initial testing the machine was run with no load for a period of 57 hours to ensure that the system performed as designed.

For the second phase of testing the machine was moved to a test site, where it could be loaded with limestone. During this test, further calibration was carried out on the power electronics. Using a data logger fitted to the engines, ECU fuel consumption figures were taken from the engine. The figures obtained were compared to consumption figures taken from similar machines with both clutch driven crushing chambers and hydrostatic crushing chambers.

When comparing energy consumption of crushing equipment, it is difficult to get direct comparison between machines. This is due to the variability of rock and the crushing reduction rate the machines achieves, which results in variability in the overall energy consumption of the machines. There is no standardised test that can be used to ensure comparable results. Due to the limited test time in this project, data from comparative machines in similar applications was selected to compare in this test.

The testing carried out to date has found a 12% reduction in fuel consumption based on a typical duty cycle for a mobile jaw crusher. During ‘no load and idle’, the fuel saving increases to 20 and 36% respectively. The testing carried out has been done at a fixed engine speed of 1700 RPM. The fuel saving features that would match the engine speed and machine function speeds to the load have not yet been set up or tested. Given the significant fuel saving at 'no load and idle', the target of 20% fuel saving over conventional machine should be achievable when the fuel save function on the machine is tested.

5. Summary of Net Zero Report

As part of this Phase 1 project, a study was carried out on possible technologies that could deliver a net zero powertrain for typical track mobile crushing and screening range of equipment. The report focused on the technical feasibility of various technology but did not consider the commercial feasibility, capital cost of the technology, or the running costs.

It is somewhat debatable if the use of synthetic and alternative fuels (including hydrogen combustion) in an internal combustion engine can be classified as zero emissions. Internal combustion engines will typically require and consume some lubricating oil, resulting in some CO2 emissions. Additionally, combustion in a predominately nitrogen atmosphere will result in the production of NOx, which can be abated by the use of after-treatment technologies. However, there is no doubt that many of the synthetic or alternative fuels have their contribution to make in terms of reduction of gaseous or particulate emissions when compared to conventional fossil fuel diesel.

- Biodiesel (FAME) fuel is not ideally suited other than as a component of a blended fuel without compromise of fuel quality, engine operation or exhaust emissions. Additionally, storage of this fuel presents some difficulties for anything other than short term.
- Dimethyl Either (DME), because of its gaseous nature at atmospheric conditions and lower calorific value per unit volume, requires significant modification to the engine’s fuel delivery systems and to fuel storage facilities. Its major advantage is the virtual elimination of particulate emissions.
- Methane and other hydrogen carrier technologies offer the advantage of fuel storage and transportability, in comparison to hydrogen. However, these technologies are very much in the early stages of development.
- e-Diesel, like methane, is a fuel technology that is in the early stages of development.
- HVO can be used as a ‘drop-in’ replacement for conventional diesel, without significant modification of the fuel delivery system. The fuel is stable in storage, and it reduces CO and HC emissions, but little or no reduction in NOx emissions. HVO has the advantage that it is approved by virtually all major industrial engine manufacturers for use in the engines without modification.

The options that appear to offer the greatest potential for ‘net zero’ at the point of delivery are the battery supply or the hydrogen fuel cell. Both options require the complete conversion of the machinery to an all-electric drive train, which involves significant redesign of the existing machinery. It should be noted that both options negate the CO_2 and other emissions associated with the off-site conversion of the primary source of energy, the electric power generation in the case of the battery solution and the hydrogen production in the case of the fuel cell option.

Both the battery and the fuel cell solution present significant logistical challenges that would need to be overcome for implementation to be realised. In the case of the battery solution, the size and weight of the battery is considerable, as is the capacity of the electricity supply required to recharge. In the case of a hydrogen fuel cell solution, while the size and weight are somewhat more manageable, there is again the challenge of providing a high-pressure hydrogen refilling system. In both these cases electricity of hydrogen must be brought to the machine as they are not sufficiently mobile to facilitate traversing to a fuelling point.

6. Financial Review

The financial review summarises project costs, machine costs and operating costs associated with the machine developed as part of this project.

6.1 Project Costs

The project was split into four work packages with total of 19 deliverables. The total project cost at application was £649,447, with a claim amount of £434,907.

6.2 Machine Costs

One of the key blockers for the adoption of electric drive machines in industry today is the additional capital cost of electric drive machines. When reviewing the cost of the machine produced as part of this Phase 1 project, it is important to compare them to current drive topologies in production today.

For this review, the manufacturing costs of the machine developed as part of this project were compared to the similar machine with clutch driven crushing chamber and also a hydrostatic driven chamber. To compare the solution with a conventional hybrid drive, the cost differential between a Terex hybrid mobile jaw crusher and hydrostatic version of the same machine was used.

During the cost review of the machine developed as part of this project, the Bill of Material for the prototype machine was reviewed to ensure the cost reflected a realistic production cost of the machine. As production volumes of this product would increase, there would be further opportunity to reduce component costs due to technology maturing and increased component volume.

For this review, costs were used that would be achievable in line with the route to market plans in this report. While the cost of this technology is higher than a conventional diesel hydraulic machine and comparable to a conventional hybrid machine, this project has proved that it is a commercially viable drive technology.

6.3 Operating costs

The machine that was developed as part of this project is powered by a diesel engine, with the goal of developing a more efficient drive train. As shown in the section on testing, there is currently a 12% saving in fuel consumption, with the projected 20% achievable with additional fuel save options on machine.

A future development of this design is to include a mains electric plug-in option, which would allow the machine to operate without the diesel engine running, with the engine only being required when the machine is to be transported to different locations. With current electricity prices in the UK there would be negligible savings by running the machine on mains electricity. More work would need to be carried out in a future phase of the project to determine the actual electrical power requirements to understand the exact running cost on mains electricity.

7. Route to Market

The specific goal of this Phase 1 project was to produce a working prototype of a Terex track mobile aggregate crusher and perform initial testing. On successful completion of this project, Terex aims to further develop the technology introduced in this project to fully commercialise it.

This Phase 1 project does not have the ability to be powered from alternative power source. A plug-in option was considered as part of the concept phase—this option would need to be developed before commercialisation.

Terex is currently submitting a funding application to the second phase of the red diesel replacement (RDR) fund. The activities listed above are planned to be completed as part of this application, with a full-on site demonstration of the technology in December 2024.

From the work carried out in this project the plan to commercialise the product in 2025 is deemed to be achievable. Below are some of the possible risks that could encounter:

- **Reliability of the technology** – the technology developed as part of this project is still relatively new and not widely used in the aggregates processing or construction industry. There could be reliability issues with the technology limiting the machine performance or service life. This risk will be mitigated by implementing a rigorous test plan as part of the next phase of this project.
- **Fuel consumption** – as shown in the test results, this technology is more efficient than typical diesel/clutch/hydraulic machines. There is more work to be carried out to ensure that the target of 20% fuel saving is achieved. To demonstrate this saving, the machine will need to be tested in a variety of real-world applications. If the target fuel saving cannot be reached, then it would weaken the commercial proposition for this product for operators currently running on diesel. With the addition of the plug-in option there would still be a significant benefit as the machine can be plugged into a mains electric or other form of lower carbon electricity source.
- **Energy costs** – with the UK current diesel and electricity costs this solution would have comparable running costs when plugged into mains electricity as running on diesel. Without some other incentive to encourage operators to invest in this technology, there is a risk that increased electricity costs could make the plugin operation of the machine more costly that diesel.
- **Market acceptance of technology** - the technology developed in this project could operate across all applications that the existing diesel/clutch/hydraulic

machine operates in. With the development of the plug-in option, it would be possible to take advantage of mains power when available. Some operators may however be reluctant to move away from existing mechanical and hydraulic technology. Terex would mitigate this risk by providing both sales and technical service training to dealers and operators on the technology, to ensure the products could be operated and maintained safely and efficiently.

8. Lessons learned

Below is a summary of the lessons learned as part of this project.

8.1 Shared Learning

Bamford Bus Company Ltd. trading as Wrightbus ("Wrightbus") and Queen's University, Belfast ("QUB") have been in active collaboration for over 25 years, resulting in several high impact outputs, most notably the development of the driveline architecture for the hybrid electric New Bus for London (Routemaster) and more recently, the zero-emission driveline architecture for the Streetdeck Electroliner, certified as the world's most efficient double-deck battery-electric bus.

Wrightbus is the UK's leading independent supplier of accessible buses. Founded in 1946, Wrightbus has over 20 years' experience in producing low and zero-emissions vehicles and is uniquely positioned to provide UK manufacturers with insight into the challenges and opportunities of adopting a blend of vehicle technologies (due to their breadth of experience in the development of diesel, hybrid, electric and hydrogen powertrain platforms).

Queen's University Belfast is a member of the Russell Group of 24 leading research-intensive universities in the UK. QUB was ranked 8th in the UK for research intensity in the Research Excellent Framework (REF) assessment in 2014. For Aeronautical, Mechanical, Chemical and Manufacturing engineering QUB was ranked 15th in the UK with 88% of the research output was classified as being world-class or internationally excellent.

Wrightbus and Queen's University Belfast have a long history of collaboration with Innovate UK, Advanced Propulsion Centre (APC) and EPSRC joint funding initiatives. Notable recent collaborations have included:

- APC3 Modular Architecture for Ultra Low Emission Buses (£8.6m) 2017 → 2018 investigated ultra-low and zero-emissions technologies sector such as hydrogen powertrain development.

- IDP13-103361 NextGenHybridBus 2018 → 2021, set out to develop a Next Generation Hybrid (NGH) as a 'mild', fuel-efficient vehicle leveraging three generations of Wrightbus “micro-hybrid” diesel product.
- IDP14-7850 NextGenEV 2017 → 2022, project developed next generation electric bus powertrain that will be suitable for both single and double deck buses between 10 and 18 ton GVW.
- EPSRC Prosperity Partnerships EP/S004971/1 StreetZero - QUB and Wrightbus secured EPSRC funding through the Prosperity Partnership programme to advance the roadmap to zero-net emissions in the urban public transport sector, leveraging their joint experience in low and zero emission bus development.
- ARMD20-1016 BEV/FCEV Single-deck Demo 2020 → 2021 Next Generation New Energy Single Deck Bus Technology Demonstrator Project delivered a zero-emission EV single-deck concept bus that will offer both BEV and FCEV variants.
- APC17-92503 NextGenFCEV 2020 → 2024 aims to produce next-generation fuel-cell electric buses to accelerate the development of a long-term sustainable, low-emission hydrogen supply-chain in the UK.

Wrightbus and QUB agreed to further deepen their partnership in 2015 with the establishment of the (now-titled) Wright Technology and Research Centre at Queens University Belfast (“W-Tech”) with seed funding for a number of postdoctoral research fellows and PhD studentships, and an agreement in 2016 for a 5-year £8.7m Research and Advanced Engineering Centre. In 2022, the contract was renewed and a further 5-year £5m agreement to extend the term to 2027.

One of the core research themes for W-Tech is the development of low and zero-emission vehicle drive-cycle models and associated energy management systems for the bus industry. These organisations are, therefore, well positioned to provide expert insights into the development of a suitable simulation tool to guide initial design and component selection for the design of a Terex hybrid crusher, as part of this RDR project.

Through model definition and development, component performance analysis and parameter refinements, W-Tech researchers in collaboration with Wrightbus and Terex engineers were able to identify areas of further refinement of on-board energy storage and recommend areas for control system optimization, in order to reduce fuel consumption. The unique expertise of W-Tech was also utilized to inform inputs and scenarios included in AJ Power's "Net-Zero road map report", particularly around battery-electric and hydrogen pathways.

Given close synergies between the future low and eventually, zero-emission demands of both bus and off-highway industries, close collaboration between sectors is essential to drive further technological innovation and make Northern Ireland a centre of excellence for low/zero-emission powertrain research and development. Wrightbus and W-Tech are currently investigating potential partnerships for RDR Phase 2 to further this agenda.

8.2 Project management

This RDR project was the first competitive funding project Terex was involved in and required significantly more project management and administration than anticipated. During the project, the monitoring officer for the project changed, and the transition was handled efficiently. When questions would arise, both the monitoring officers and Department of Business Energy and Industrial Strategy team were easy to contact and responded promptly to questions. Project meetings ran monthly and were well attended by all teams on project. This regular cadence kept all sides well informed of the status of the project and any changes or issues that arose.

8.3 Project duration

The first phase of the RDR project was planned to be 11 months, which is a very short time frame to deliver a major project. On reflection at the end of project, if any issues arose that required redesign at the concept stage of the project, it would not have been possible to deliver the project on time.

8.4 Project finance

With projects that involve concept design, detailed design, and prototype build, it is very difficult at project application to fully plan all costs involved with the project. The flexibility shown throughout this project in approving the required changes helped the team focus on the areas of the project that required the additional support when required.

9. Conclusions

This project set out to deliver a working prototype of a Terex mobile aggregate crusher with a next generation electric drive system. This was achieved and in addition, with the further month extension to project, testing on site was also included.

To date there is no one clear technology that will be the solution to replace diesel fuel in the construction mining and quarrying sector. As can be seen from the report on net zero, there are many potential technologies that are being investigated. At this point in time, for Terex to select a given technology (such as battery electric or hydrogen) and engineer it into all future products, it would be difficult to penetrate the market in any meaningful way unless the rest of the sector selected that technology choice. The solution developed as part of this project is a more flexible option, allowing operators to purchase equipment that can still be run on diesel. As alternative net zero sources of power become available, the machine can be powered from them. This gives operators the confidence to invest in the technology, knowing that it can be utilised regardless of how the journey to net zero develops over the coming years. With the mobile nature of the product, it can be used across multiple locations during its lifetime, the machine can be connected to the power source that is available in any given location.

This application of the drive technology is not just applicable to crushers. Terex is currently reviewing the potential to use the learning on this project to introduce it on mobile environmental equipment used in the waste processing recycling industry.

Dissemination is an important part of this project. As the industry looks for products that can eliminate the use of diesel—it is critical that industry players are aware of technology that is technically feasible.

The collaboration supported by this funding has helped build stronger relationships with local partners that are working in same area. An RDR Phase 2 funding application is being planned between Terex, WrightBus and Catagen. Without this funding, it is unlikely that collaboration would have been undertaken to this extent. Terex now also has a stronger relationship with Queen’s University and are also part of the industry advisory board of Advanced Manufacturing and Innovation Centre.

Terex is committed to continually developing new products to meet customer demand and increasing Environmental Social and Governance goals and objectives. Full details can be found in the compan'y ESG report. As the industry works to develop net zero solutions, it is critical that government provides funding to focus the industry on areas that require innovation and that is aligned to overall net zero objectives. Funding of this nature helps bring together industry partners who can collaborate to develop technology, ultimately commercialise the solutions and make real-world impact in reducing carbon footprint.

10. Glossary of Terms

DC	Direct Current
Aggregate Crusher	A machine to crush various rock types into smaller pieces
Screener / Screening	A machine to separate rocks into different sized products
Tracked mobile	A self-propelled machine fitted with continuous track system
IP (IP67)	Ingress Protection standard for dust and water
OEM	Original Equipment Manufacture
Plug-in	Connecting of machine to external power source
ESG	Environmental Social and Governance
E-Fuels	A class of synthetic fuels
ECU	Engine Electronic Control Unit