POWERING TOWARDS NET ZERO
BATTERY AND HYDROGEN FUEL CELL TECHNOLOGY FOR AUSTRALIA'S HEAVY HAUL FREIGHT INDUSTRY

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SUMMARY

Decarbonisation of heavy haul rail is an essential contributor to a zero-emissions future. This paper provides an overview of the energy modelling being conducted at Aurizon, Australia's largest rail freight operator, to define the energy demands and onboard storage capacities and to define the requirements for battery and hydrogen fuel cell technology to replace current diesel-electric systems. The energy modelling uses event recorder data from existing diesel-electric locomotives for 150 round trips across Aurizon's operations. Detailed analysis of the haul between Moura and Gladstone shows that, on average, 6.6 MWh of energy is required per locomotive per round trip and that 1.7 MWh or 29% is currently lost through the dynamic braking system. Capturing and reusing the dynamic braking energy or "regenerative braking" (RB) in the Moura haul can reduce the net energy demands by 29%, leaving a net energy requirement of 4.9 MWh.

Applying the analysis across a sample of 13 Aurizon operational corridors ranging in length from 100 to 2,800 km shows Aurizon has energy requirements of 2.5 to 68 MWh with a regenerative braking potential of 17 to 39% with an average of 29%, leaving a net energy requirement of 1.5 to 54 MWh per locomotive. Assuming the net energy requirements must be provided once per trip, this requires a large onboard storage capacity. In contrast, the regenerative braking storage component is much smaller because the energy is stored and used multiple times per trip. Hence even though the regenerative braking energy represents 29% of the total energy, the storage capacity is only a fraction of the total (0.4 to 2.0 MWh).

This demonstrates the importance of RB batteries as a critical aspect of decarbonisation. Based on these significant onboard storage requirements, a future 2030+ Battery Electric Locomotive (with a usable capacity of 6.7 MWh (twice that which would be currently available) would be able to service hauls up to 400 km. Beyond this range-extenders in the form of battery electric or hydrogen fuel cell electric tenders would be required to plug into the back of the BEL to extend their range to efficiently meet the haulage requirements.

1 INTRODUCTION

Heavy haul rail transportation plays a critical role in the global economy as it is a crucial mode of transportation for a range of goods and commodities, accounting for 7% of all freight [1]. However, rail transport accounted for 3% of carbon dioxide emissions in 2020 [2]. The need to transition towards a more sustainable and decarbonised heavy haul rail transportation system has never been greater. Analysis by Aurizon based on our own deployment and operational experience and by others [3] has found that overhead electrification is a high-cost solution and not economically viable for relatively low utilisation and long range operations. Through our analysis and supported by others [3], [4], the lowest cost solutions for heavy haul rail are expected to be battery and hydrogen fuel cell technology. To assess the viability of these technologies, Aurizon has conducted energy modelling across a wide range of its operational hauls to define the onboard energy requirements and hence the suitability of these technologies.

2 NOMENCLATURE

ER – Event Recorder

DB – Dynamic Brake

LFP – Lithium Iron Phosphate

LTO – Lithium Titanium Oxide

NMC – Nickel Manganese Cobalt

RB – Regenerative Braking

CoP – Coefficient of Power

$H_{external}$ – External Heat Generation

$H_{internal}$ – Internal Heat Generation

$W_{cooling}$ – Cooling Power

3 METHODOLOGY

The energy requirements for each route determine which platforms will be viable and the required recharging or refuelling infrastructure. Aurizon has been collaborating with Central Queensland University and University of Queensland to better understand our energy demands for rail haulage. Through this research, we have developed and validated our own tools that allow us to analyse various rail haulage tasks across our fleet. We used these tools to analyse event recorder data from locomotives operating in 13 corridors across Aurizon's operational footprint. Figure 1 shows an overview of this process.

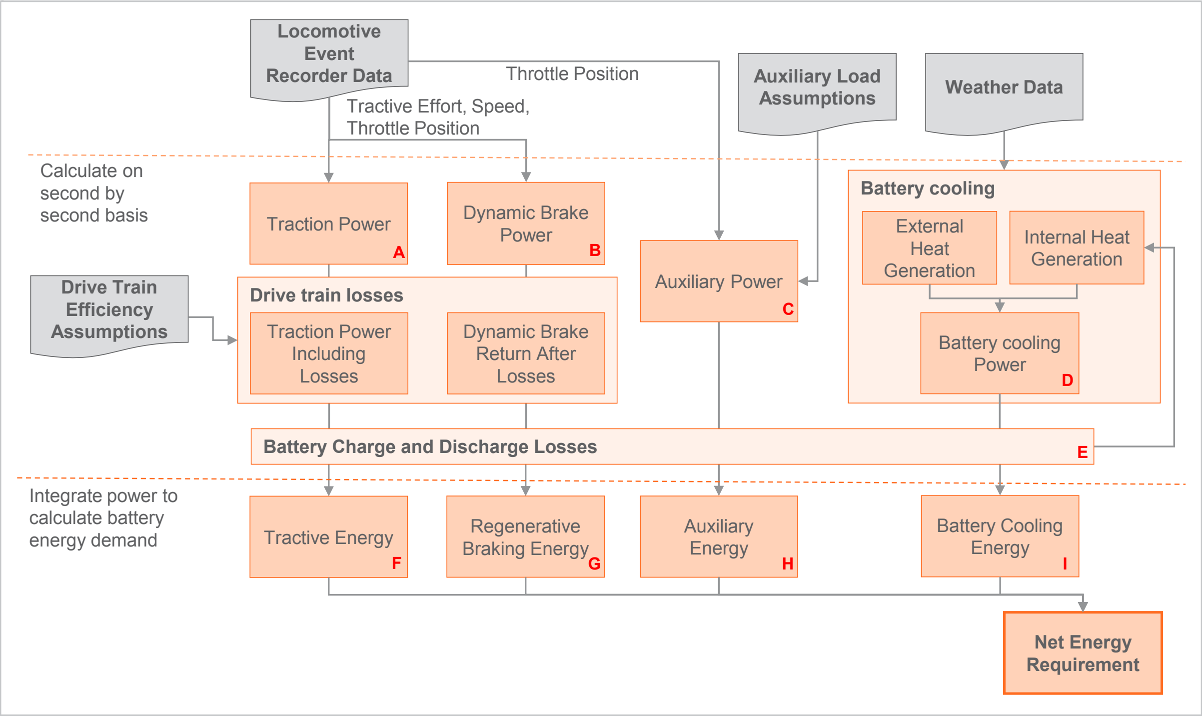

Figure 1: Route Energy Modelling Process

Locomotive event recorder (ER) data from various classes of locomotive was collected either by direct download from the on-board event recorder, or for more modern locomotives through remote download capabilities. Raw data extracts were split into round trips using train schedule information and location from the ER data, resulting in multiple trips per corridor. As shown in Figure 1, power for traction, dynamic braking, and auxiliaries were calculated from the ER data on a second-by-second basis and used to model energy demands.

Tractive Effort in the ER data gives the force at the wheel. Depending on the throttle position, this is either a tractive force or a dynamic braking (DB) force. Traction power (A) and DB power (B) were calculated by multiplying the force by the locomotive speed from the ER data. Auxiliary power (C) was calculated using auxiliary load assumptions based on the throttle position from published or measured data. Battery charge and discharge losses (E) were calculated based on power demands and battery efficiency assumptions. Battery cooling power (D) was calculated from external heat loads based on weather data and internal heat generation based on battery charge and discharge losses. Power was then integrated on a second-by-second basis to calculate the tractive energy (F), RB energy (G), auxiliary energy (H), and battery cooling energy (I). The net energy requirement for the trip was calculated from the total energy demand (tractive, auxiliary, and cooling) less the RB energy.

The auxiliary load assumptions are shown in Figure 2. Auxiliary power is required for air compressors and other services on the train. As described in our previous work with Knibbe et al. [5], auxiliary load was estimated at each throttle position. Based on measurements conducted by Aurizon, auxiliary load for a 2800 class locomotive varies between 16 kW at idle with the compressor off and 177 kW at notch 8 with the compressor on. Assuming the compressor runs 50% of the time, this results in a range of 20 kW to 140 kW depending on throttle position. For non-idle running, the percentage of tractive power was calculated and applied to all other loco classes.

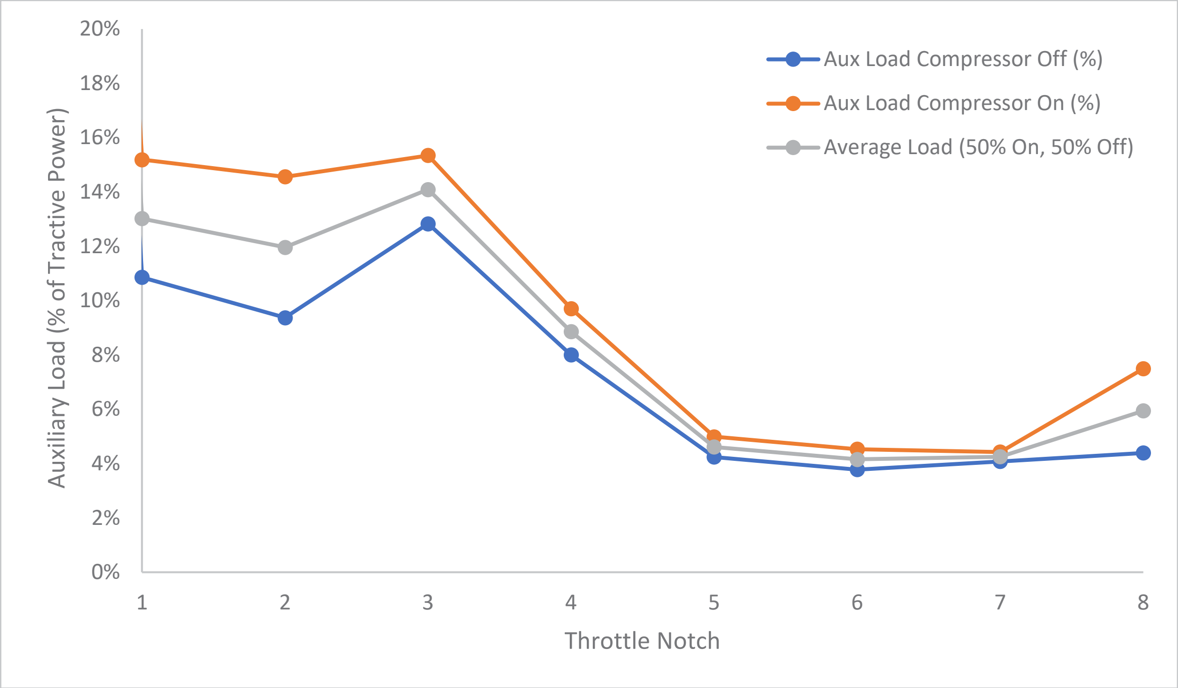

Figure 2: Auxiliary Load vs Throttle Position

In our prior work with Knibbe et al. [5], we examined three different battery chemistries, LFP, NMC and LTO. We compared the lifetime cost and pack energy density of each battery chemistry and found LFP to be the most suitable option for heavy haul rail, which agrees with the conclusions from [4]. LTO has excellent cycling stability, resulting in a longer life, but has high upfront cost and low energy density. NMC has the highest pack energy density, but has the highest lifetime cost due to relatively high upfront cost and low cycle life. The pack energy density of LFP is between that of NMC and LTO, and it has the lowest lifetime cost due to low upfront cost and good cycling stability leading to longer life.

Battery charge and discharge losses depend on the total power flowing to or from the battery and the battery efficiency. Power to the battery comes from DB return after losses. Power from the battery includes traction power including drive train losses, auxiliary power, and battery cooling power. Based on Krause et al. [6], an overall battery efficiency of 95% was used, and charge and discharge losses were assumed to be the same, so 2.5% each.

Good battery thermal management is important for safety as well as cell performance and lifespan. During charging and heavy cycling, significant heat is generated in the battery. Poor battery thermal management results in performance degradation but in severe cases can result in thermal runaway and battery fires. In Australia during summer, many regions experience temperatures over 35 ◦C. Given the size of the batteries required in heavy haul rail, and the high-power requirements for both traction and dynamic braking, liquid cooling systems are preferred.

Battery cooling power was estimated using a battery cooling model developed in conjunction with University of Queensland and is described in detail in [5]. Battery cooling power depends on heat generated by the battery and heat from the external environment. Heat generated by the battery was estimated from the charge and discharge losses, assuming all losses are due to internal resistance and result in heat generation. Heat from the environment was estimated using the solar radiation and the roof area of the locomotive. Cooling power is given by:

$$W_{cooling} = (H_{internal} + H_{external})/CoP$$

Where *CoP* is the Coefficient of Power depends on the cooling system and is a function of the difference between the external temperature and the temperature of the controlled environment housing the battery [7]. Solar radiation and temperature data were sourced from the Bureau of Meteorology. A worst-case was based on 90th percentile days for solar radiation and temperature and was used for battery size calculations. An average case was used for energy and charging requirement calculations.

To calculate drive train losses a model of locomotive efficiency developed in conjunction with Central Queensland University was used. Figure 3 shows the assumptions and the resulting energy use calculated for a 340km round-trip between Moura and Gladstone. Using the process shown in Figure 1, traction motor power and the resulting energy use at the wheel (A), is adjusted by the efficiency of the final drive, traction motor, inverter, and battery discharge to derive the total energy from the battery (N). Added to the Auxiliaries and Battery Cooling this gives the total energy provided from the battery. Dynamic braking power calculated from the ER data (B) is reduced by the Final Drive, Traction Motor, Regen Control and Battery Charge efficiency to calculate the potential power from RB. The net energy from the battery is the total energy less the saving from RB.

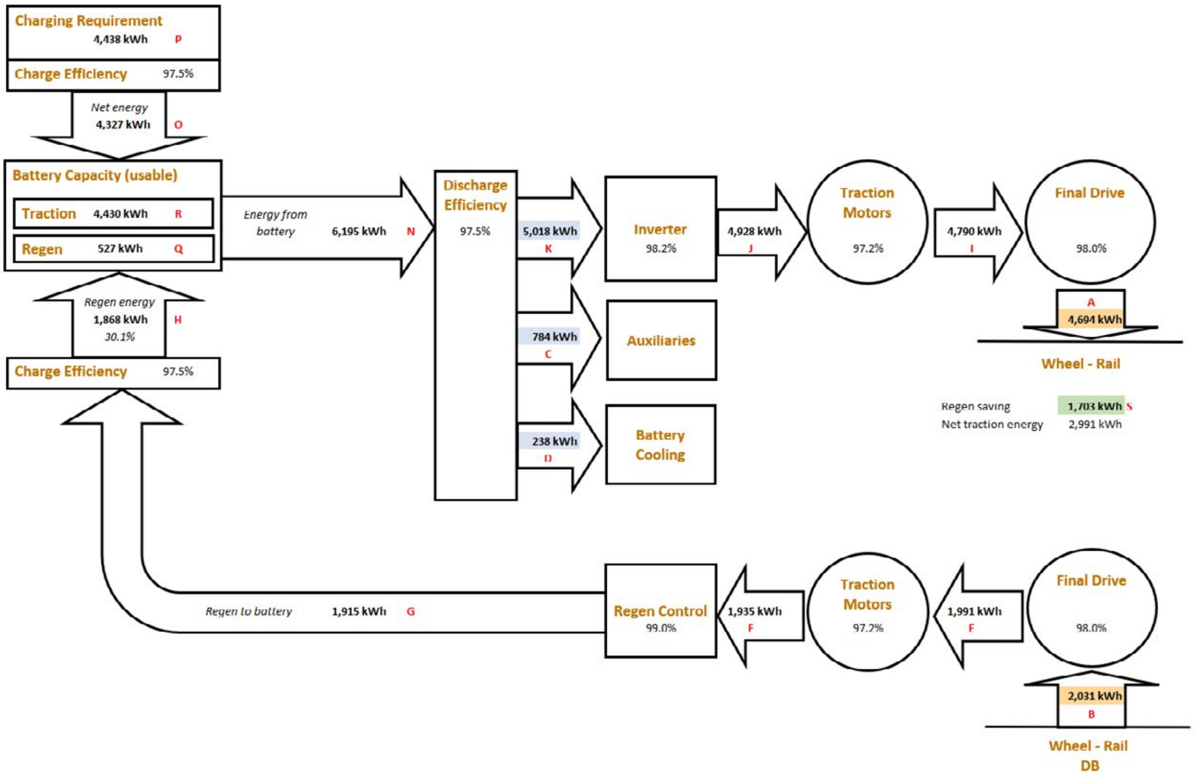

Figure 3: Drive Train and Battery Efficiency Calculations

To size the required battery capacity, independent batteries for RB and traction were modelled. The RB battery undergoes several charge/discharge cycles during a trip and is charged from the DB return. The traction battery is charged externally and has only one cycle per trip. In general, the batteries could be combined into a single battery, or the different usage patterns may make it more economic to use different battery chemistries or alternative technology such as hydrogen fuel cells for different energy demands. In the model, any power requirements of the locomotive are first met by the RB battery. If the RB battery is empty, then power is provided by the traction battery as a secondary source.

Battery manufacturers specify the nameplate capacity of a battery. The usable capacity of the battery is less than the nameplate capacity due to degradation over the life of the battery and a need to limit the depth of discharge to avoid excessive degradation. Allowing for 20% degradation over the life of the battery and a 20% depth of discharge margin, results in a conservative estimate of 60% usable capacity compared with nameplate.

4 RESULTS AND DISCUSSION

Results from the analysis of event recorder data have provided valuable insights into the energy requirements of different rail haulage tasks and what this means in decarbonising diesel locomotives. First, by way of example, the results from a single corridor are provided and then a summary of all the results across the 13 Aurizon operational corridors studied is provided.

4.1 Results for Moura Corridor

The Moura rail corridor is a good case study as it is a unit train operation (same train and route without it being split up) with distributed power (locomotives are deployed at different locations in the train), and the train is heavy with payload consistency trip to trip. It has a low energy requirement (a combination of distance and topography (mine to port)) making it a good candidate for battery deployment. The Moura haul is a metallurgical coal haul in Queensland and runs ~167 km from the Moura Mine to the RG Tanna Coal Terminal (port) in Gladstone. It typically carries ~8,160 tonnes of metallurgical coal from the mine, with a total train mass of ~10,660 tonnes, which travels back to the mine empty. The train has four GT42 (4000/4100 class) locomotives, two at the head of the train, one in the middle and one at the back.

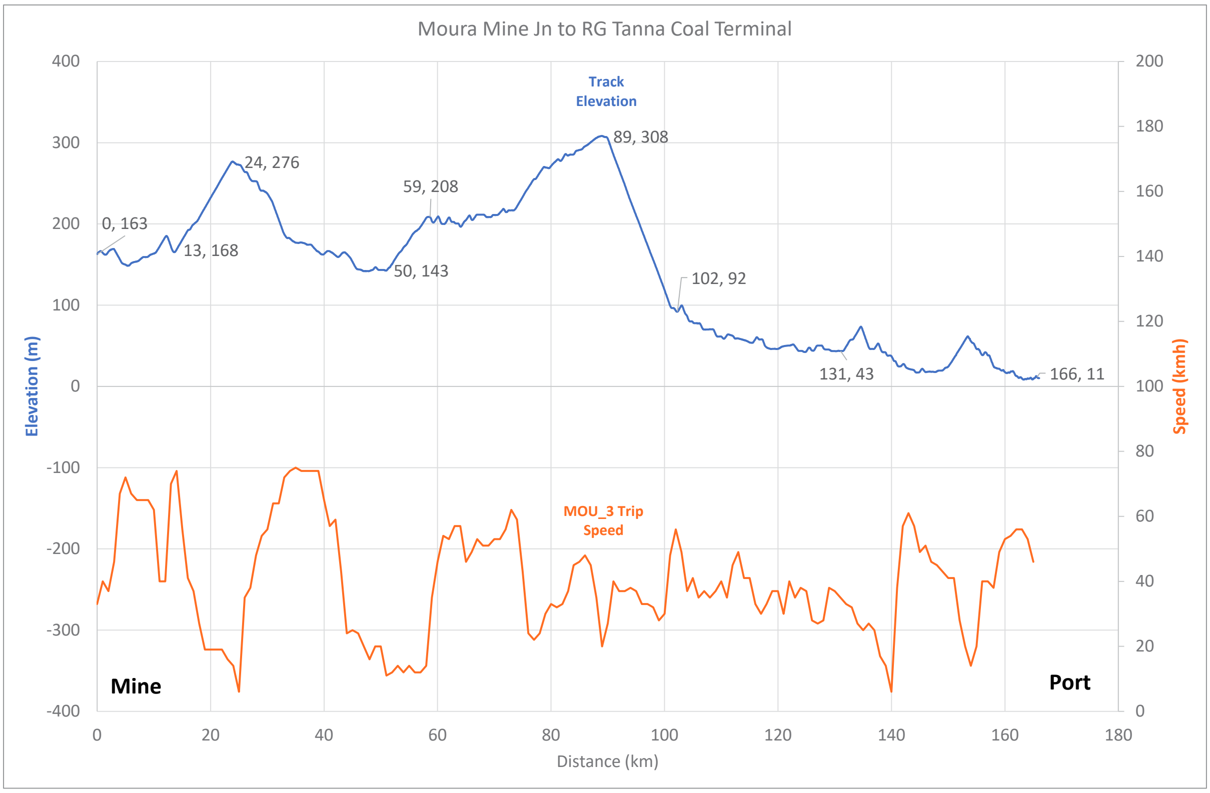

Figure 4: Moura Corridor Elevation and Speed Profile

Figure 4 shows the track elevation (blue line) and locomotive speed (orange line) for a single loaded trip from mine to port. The train has two climbs to traverse the range, the first of 113 m (max grade of 1.08%) and the second of 165 m (max grade of 0.72%), followed by a decline of 297 m (max grade of -1.54%) down to the port, with a total elevation change from mine to the port of -152 m. The first steep climb at 1.08% sets the requirement for four hauling locomotives. With a couple of long continuous declines fully loaded, there is an opportunity to recover a significant amount of RB energy at different times during the trip. For a typical run from mine to port the speed of the train varies constantly reaching a maximum speed of 75 km/h with average of 35 km/h overall.

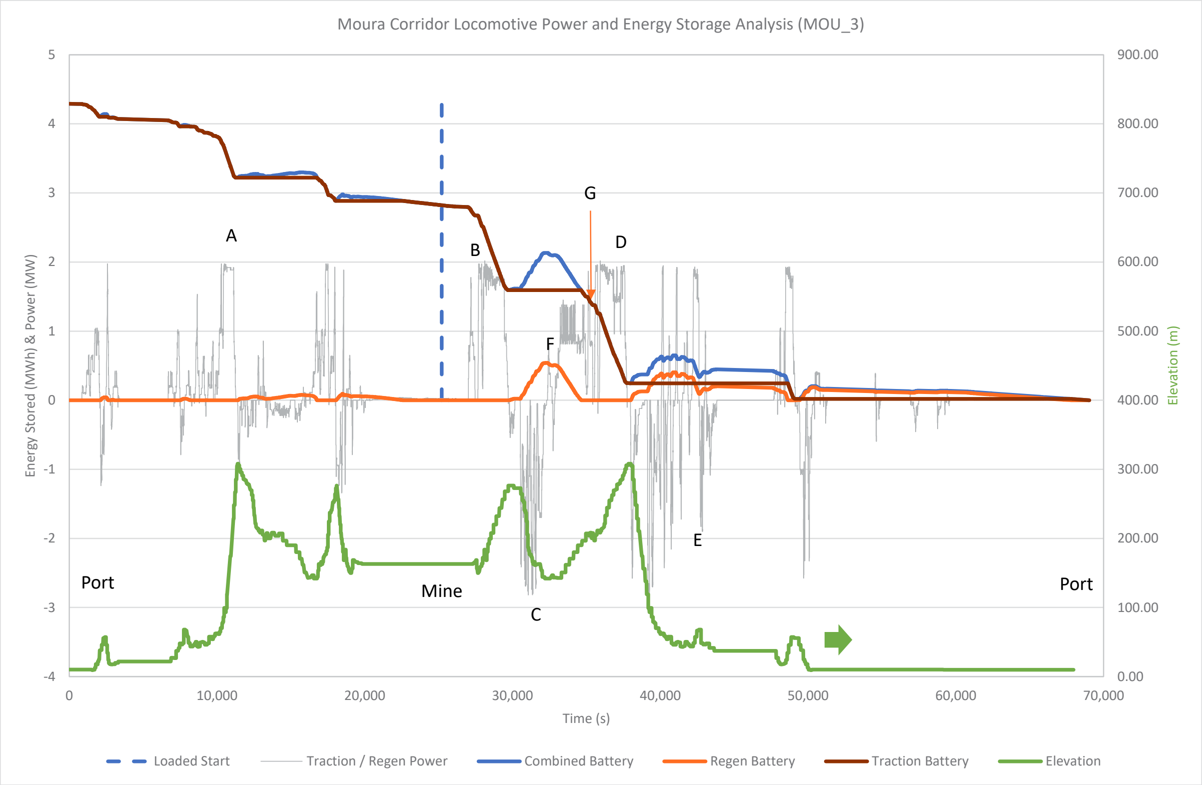

Figure 5: Moura Corridor Locomotive Power and Energy Storage Analysis

The locomotive power, energy storage and elevation profile from one of the round trips analysed for the Moura corridor is shown in Figure 5. Observing the locomotive power (grey line), the locomotive reaches full power climbing the hill despite the train being empty (A). Once the train is loaded, the locomotive operates close to full power when it climbs the first hill (B) and when it climbs the second hill (D). When descending, DB is applied after the first hill (C) and after the second hill (E). Note that the DB power is lower when going down the second hill (E) than the first hill (C) due to the additional need to use an air brake applied to the wagons rather than solely rely on the DB which is only applied to the locomotives.

Examining the calculated energy storage data in Figure 5, when the train descends the first hill from the mine while it is fully loaded, 0.53 MWh of energy is captured in the RB battery (F), and when ascending the next hill, the traction storage system is used when the RB battery is empty (G). The analysis shows a maximum capacity of 0.53 MWh is required for the RB battery (set by the maximum at F) and the capacity of the traction storage system needs to be 4.4 MWh. Breaking the journey into two, a storage capacity of 1.6 MWh is required from port to mine and 2.8 MWh from mine to port.

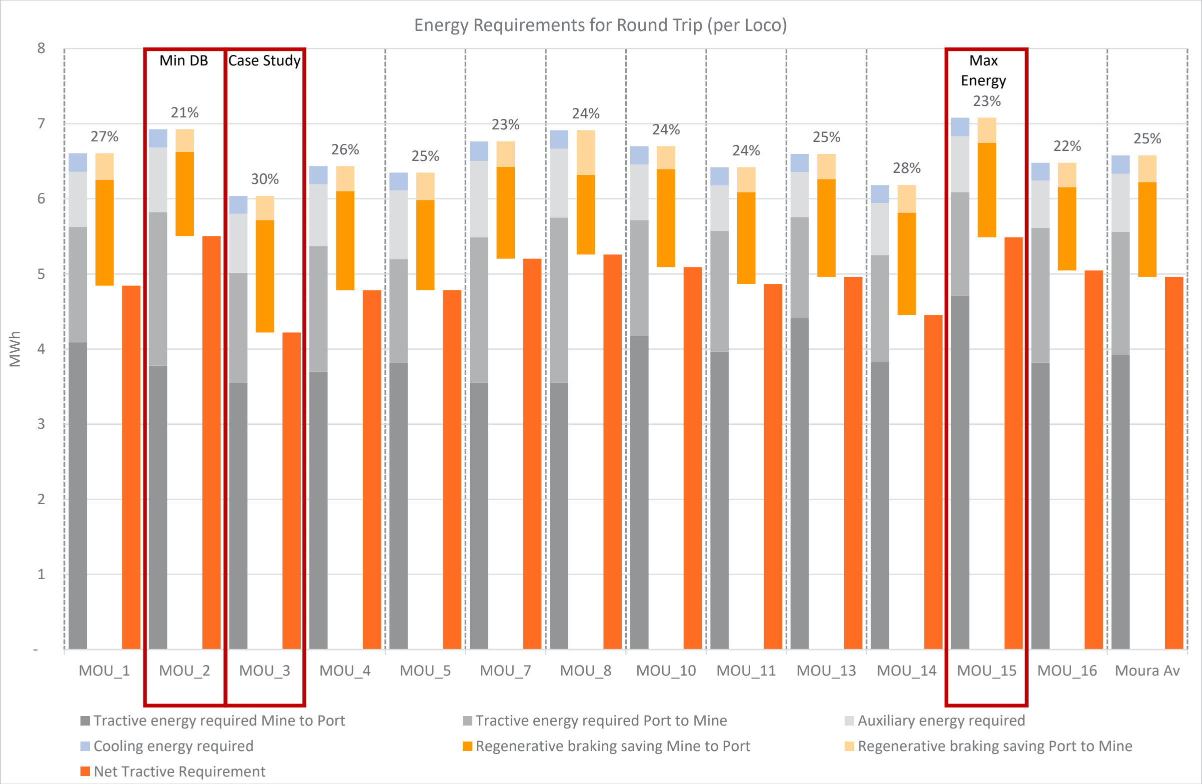

Figure 6: Moura Corridor Energy Cycle Analysis.

Sixteen round trips on the Moura corridor were analysed following the above methodology and results are shown in Figure 6. The first bar (greys and blue) in each group shows the total energy requirement for traction, auxiliary and cooling. The second bar (light and dark orange) shows the energy saving from capturing DB for regen. The third bar (dark orange) shows the remaining net energy that must be stored on board. The maximum energy demand is Trip 15 at 7.1 MWh with a DB energy storage of 1.6 MWh or 23%. The minimum DB storage is Trip 2 with 1.4 MWh or 21%, which has a total energy demand of 6.9 MWh. The maximum DB storage is Trip 3 (discussed above) at 1.8 MWh or 30%, having the lowest energy demand of 6.0 MWh. The standard deviation in the data is relatively low at 9% for both diesel energy and DB energy. Note that trips 6, 9 and 12 were excluded from further analysis as they were not representative of a typical haul.

4.2 Results Across Aurizon

The combined results across 13 corridors are shown in Figure 7. The graph shows the current diesel energy demand (in grey) could be delivered in the future by capturing and reusing the available RB energy (light orange) and supplementing this with the Net Traction energy (dark orange) which can be provided by either batteries or hydrogen fuel cells.

These results highlight the significant potential for energy savings through RB, which ranges from 17-38% with an average of 29%. The results also show there is a large range in energy requirements needed (between 2-68 MWh per locomotive) for each round trip. This presents a challenge going forward, as defining the platforms that can deliver this range of energy needs is crucial to ensure the success of our decarbonisation efforts.

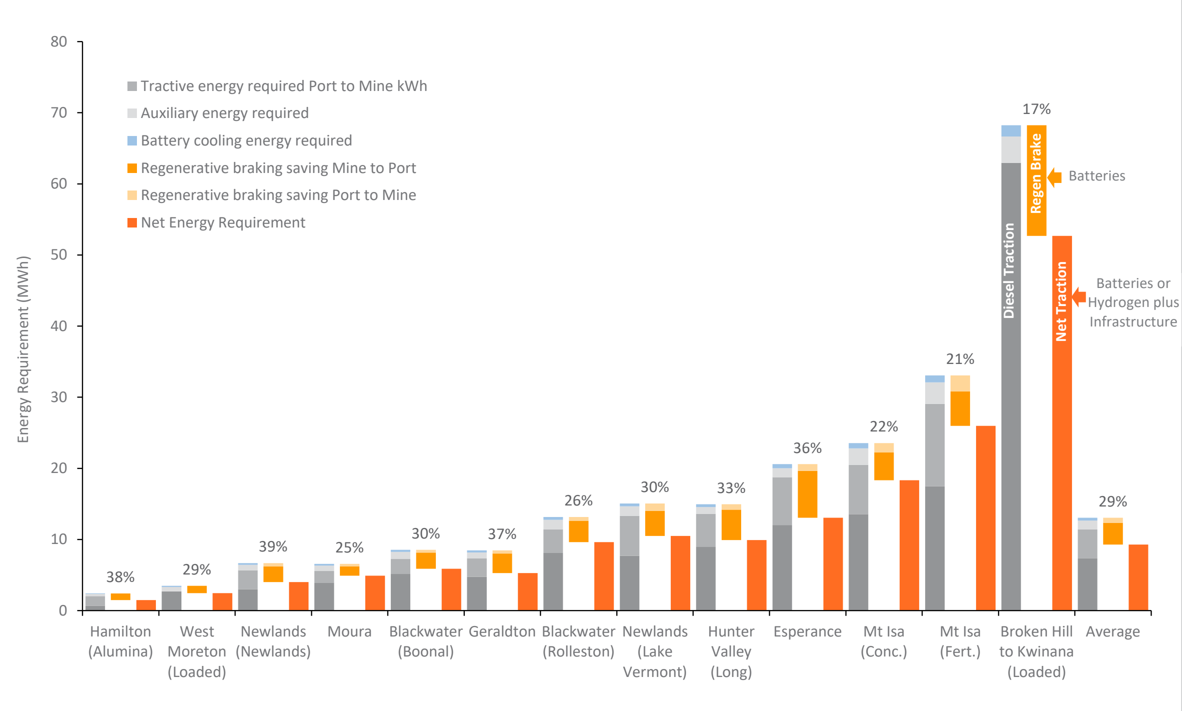

Figure 7: Corridor energy modelling across a range of hauls in Aurizon

The on-board energy capacities required to meet the locomotive energy demands in each corridor are shown in Figure 8. On the left-hand side, the graph displays the calculated energy capacity, and on the right-hand side displays the trip distance. The yellow bars represent the RB Storage Capacity required to capture and reuse the DB energy, while the orange bars represent the capacity that needs to be stored to provide the remaining energy for traction, auxiliaries, and cooling after accounting for RB energy (Traction Storage Capacity).

The Traction Storage Capacity needs to be provided once per round trip. Even though the total RB energy represents 29% of the total energy on average, the storage capacity is only a fraction of the total (0.4 to 2.0 MWh) because it is charged and discharged multiple times per trip. This demonstrates the importance of RB batteries as a critical aspect of decarbonisation.

As can be seen in Figure 8, the energy storage capacity required for a corridor is strongly correlated with the trip length. Between trips within a corridor there is currently a relatively large variation in the energy demand and resulting energy capacity requirements due to differences in driver behaviour (e.g. use of dynamic vs air brakes).

The expected usable capacity of a current prototype battery electric locomotive (BEL), accounting for degradation and depth of discharge limits, is currently around 3.3 MWh. As the technology matures, the usable capacity is expected to increase to around 6.7 MWh by 2030 with improvements in battery technology [5]. 6.7 MWh would be sufficient for a round trip in all corridors up to and including the Moura corridor or haul lengths of less than 400 km. For longer-distance corridors, other options need to be explored. Depending on the length, infrastructure requirements and operational constraints, these include range extension with battery electric tenders (BET) or hydrogen (fuel cell) electric tenders (HET).

A BET is a tender wagon that would provide power for the BEL and consists of a containerised system containing (i) batteries, (ii) water cooling systems, (iii) DC converters and (iv) a power link that plugs into BEL [5]. The DC converter is designed to regulate the voltage from the batteries to them to provide power to the BEL while in motion. A HET is the same as a BET, but replaces batteries with (i) hydrogen tanks, either in gaseous or liquid form, (ii) fuel cells which convert the hydrogen directly into electricity, producing water and heat, (iii) and large water cooling system for the fuel cells [5].

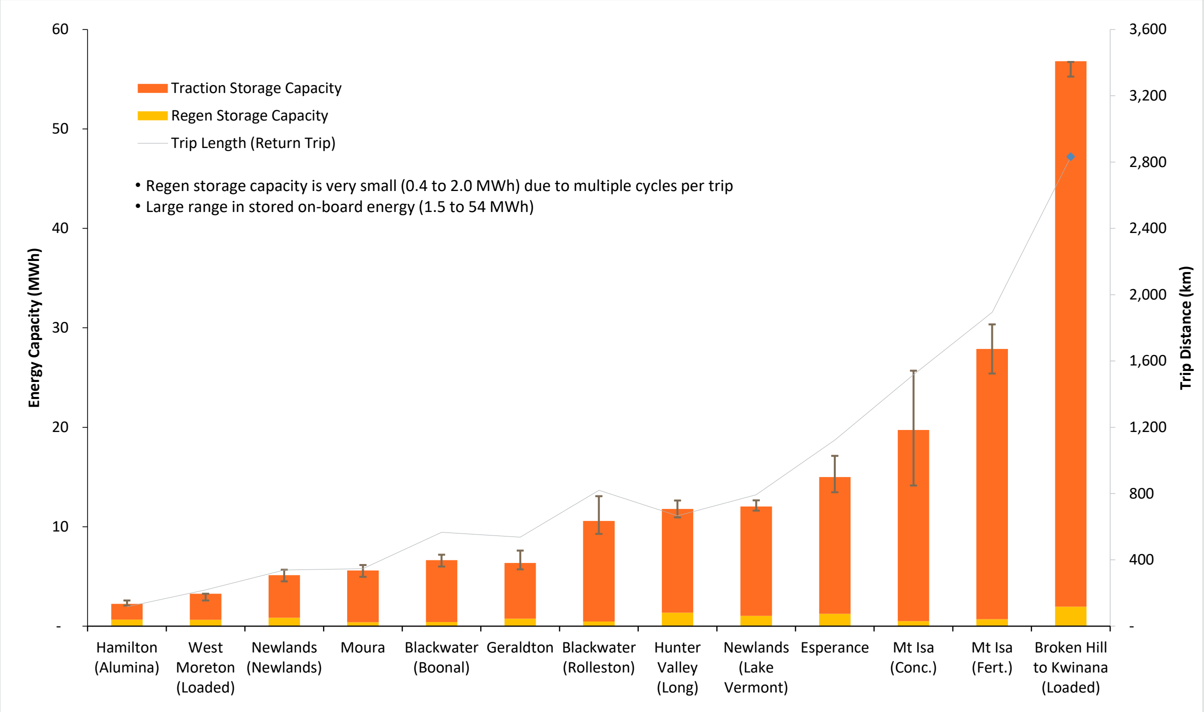

Figure 8: Energy requirements by corridor

The battery capacity of the BET is expected to be very similar to that of the BEL, with a current usable capacity of 3.6 MWh and 7.1 MWh as the technology matures [5]. Hence a combined BEL+BET using mature battery technology would provide a total usable energy of 13.8 MWh, enabling sufficient energy for round trips in corridors from Blackwater (Boonal) to Newlands (Lake Vermont) or distances of up to 850 km. The HET is expected to be 750 kg of gaseous hydrogen, providing 13.8 MWh of energy, or 1,250 kg based on liquid hydrogen, providing 23 MWh of energy [5]. Hence a combined BEL+HET using mature technology is expected to have a total usable energy of 29.7 MWh, sufficient for Esperance and Mt Isa or distances of up to 1,800 km. For longer hauls such as Broken Hill to Kwinana (2,800 km), HETs must be refuelled in at least one location. If recharging or refuelling options are available outside of the Aurizon depots, this will reduce the onboard energy required and may reduce the need for tenders.

This analysis shows that these platforms (BEL, BEL+BET, BEL+HET) would enable Aurizon to decarbonise their operations. However, these technologies are immature, with the BEL being recently deployed in limited numbers, and the BET and HETs are concepts. Significant development work is required to develop and prototype the tenders and to modify the BEL design so they can be powered by the tenders while in motion. Importantly, this interface between the tenders and the BEL needs to be developed and standardised so that any tender can connect to any BEL, providing fungibility of Aurizon's fleet across operations.

5 CONCLUSION

Energy modelling has been conducted to define the energy demands and onboard storage capacities for battery and hydrogen fuel cell technology to replace current diesel-electric systems. Based on a large operational dataset from multiple hauls across 13 corridors ranging in length from 100 to 2,800 km, the following conclusions have been identified:

- The RB braking potential across Aurizon is significant at 29% on average, ranging from 17 to 39%. This energy can be captured and reused within relatively small batteries of 0.4 to 2.0 MWh resulting in associated emissions and diesel savings. This demonstrates the importance of RB batteries as a critical aspect of decarbonisation.

- The net energy requirement after accounting for regenerative braking, has a wide range of 1.5 to 54 MWh per locomotive.
- Based on these significant onboard storage requirements, a future mature BEL (with a usable capacity of 6.7 MWh) would be able to service hauls up to about 400 km.
- For hauls above 400 km, range extenders in the form of BETs or HETs that plug into the back of the BEL, would be required.
- A BEL+BET with mature battery technology would increase the usable capacity to 13.8 MWh covering hauls up to 850 km and a BEL+HET with liquid hydrogen would increase the usable capacity to 29.7 MWh covering hauls up to 1,800 km.
- Significant development work is required to develop, prototype, and implement these zero emission solutions across Aurizon's business.

6 ACKNOWLEDGEMENTS

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