

# Towards Sustainable Heavy Haul Traction Energy: A Review

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**Summary:** The paper examined arguments for minimising energy consumption and emissions, versus continued use of fossil fuels, for heavy haul traction. The former suggested that electric traction within an open system including a smart grid supported by bulk electricity storage is an ideal, while the cost of electricity distribution infrastructure, continued availability of diesel fuel, and the challenges of up-scaling electrically hauled throughput tonnage impede achievement. It concluded that the outcome will likely reflect the risks associated with the respective investments.

**Index Terms:** Emission, energy, fuel, regeneration, risk, scalable, self sufficiency, smart grid.

## 1 INTRODUCTION

Bankable heavy haul railway business models frequently set revenue from bulk commodity exports off against locally sourced civils and labour, and imported remaining capex- and opex items, all adjusted for risk and discounted over project life. In this essentially global model, countries and railways that seek relative competitive advantage look to differentiate themselves from others. One significant differentiator is traction energy, either globally sourced diesel fuel or locally generated electricity.

Diesel traction launched heavy haul, and globally still powers most tonnage. However, some noteworthy heavy haul railways in Australia, China, and South Africa feature electric traction, a thought-provoking alternative. Relative to the diesel traction baseline, electrification may reduce variable energy costs, but concurrently increase both the amount of capital investment and the concomitant risk, and may ultimately constrain ability to up-scale throughput of coal, iron ore, or other bulk commodity.

Whereas general freight railway people might argue that shifting traffic from road to rail reduces the amount of energy consumed and pollutants emitted for a given transport task, heavy haul railways need to minimise energy consumption and harmful emissions in their own right, all the while differentiating themselves from their competitors as best they can. This paper reviews the global state of play between the heavy haul- and energy supply industries.

## 2 ON BOARD POWER GENERATION

On-board power generation, as in diesel-electric locomotives, avoids electrification infrastructure, although minimising fuel burn and harmful emissions calls for examination of the complete energy production and consumption cycle. While end-to-end heavy haul average grades may ascend or descend, actual topography typically superimposes steeper rises and falls, which induce short-time energy demands or surpluses. The latter assume, ideally, that friction braking is avoided. Electricity is arguably the only commodity that must be consumed the moment it is produced, so any short-time energy surpluses must either be stored on-board or dissipated. While this challenge is similar to that addressed by hybrid motor vehicles, locomotives haul many wagons, hence more substantial earthworks and possibly structures are needed to achieve economic ruling grades. In the same terrain, railway grades are therefore significantly flatter and longer between sign changes than road grades: This challenges and possibly limits the energy quantum that hybrid locomotives can store, as will be touched on later. This paper will now trace advances from this baseline position through state-of-the-art to emerging challenges and technologies.

### **3 POSITIVE AND NEGATIVE CHANGE AGENTS**

#### **3.1 Liquid fuel availability**

Energy provisioning materially differentiates heavy haul railways: Some countries possess reserves of conventional or unconventional oil, others of coal. Such differences inform perspectives on energy security, and it is instructive to explore them. While peak oil production is inevitable, its timing is uncertain. As depletion of conventional oil sources plus incentivised in-feed tariffs for renewables raise energy prices, advancing prospecting- and extraction methods add commercially exploitable unconventional oil reserves. Particularly interesting are techniques for accessing underground energy repositories, through directional and horizontal drilling, which have led to extraction techniques such as hydraulic fracturing, or fracking in common speech, to extract natural gas from shale rock [1], as well as underground coal gasification, to convert coal to gas while still underground [2]. However, while all continents are generously endowed with shale gas deposits [3, 34-35], hydraulic fracturing is still environmentally and hence politically contentious. Nevertheless, it seems more attractive than nuclear- or coal based energy, and could provide plausible backup for intermittent solar and wind power. As fracking is better understood and its risks mitigated, one might expect environmental and political issues to recede.

Oil and natural gas supplies have proven to be elastic—the higher the price, the greater the incentive to exploit reserves that could not be economically exploited at a lower price. Recent widespread interest in commercial shale gas extraction may delay peak oil and slow the transition to renewable energy [1]. It therefore appears that peak oil, while inevitable, might land softly.

#### **3.2 Energy storage**

##### **3.2.1 The quantum**

Descending grades that need electric braking to maintain speed for half an hour or more are not uncommon in heavy haul. An assumed 4500kW locomotive could generate 2250kWh, times the number of locomotives per train, to be stored between grade changes. As first approximation, energy storage and recovery times would be similar. An essential storage specification would also include high power, low latency, frequent deep charge-discharge cycling, and longevity. The following sections examine and compare candidate contemporary energy storage options.

##### **3.2.2 On board devices: Batteries, ultra-capacitors and flywheels**

Batteries always spring to mind. Molten salt batteries currently offer the highest economically viable energy- and power density. However, in common with other batteries, their charging rate is less than their discharge rate, and frequent deep charge-discharge cycling challenges longevity.

Ultracapacitors have comparatively recently become commercially available, currently applied in light urban rail service. They offer rapid charge and discharge, plus high charge- and discharge power, and can sustain highly repetitive deep charge-discharge cycling during their economic life.

Like ultracapacitors, on board flywheels can sustain a highly repetitive deep load cycling during their economic life, together with rapid charge and discharge, and high charge- and discharge power. The parameters in Table 1 relate to motorsport devices, which would probably be insufficiently durable for railway service: Railway grade equipment would be bulkier and heavier.

For perspective, Table 1 includes lineside flywheel energy storage. It is too heavy for on board application, and arguably even irrelevant in heavy haul service, because once surplus energy has been conducted off board, lineside storage would have to contend with other utilisation- and storage solutions, such as smart grids and pumped storage.

Considering only feasibility, and setting aside capex and maintainability, Table 1 shows that the mass and volume required to accumulate and store the quantum of energy regenerated by heavy haul trains in on board batteries, ultracapacitors, or flywheels, is at present still unworkable.

**Table 1: Comparison of selected energy storage devices by key parameters**

Storage Device	Sodium-Metal Halide Battery [4]	Ultracapacitor Energy Saver [5]	Onboard Motor-sport Flywheel [6]	Lineside Flywheel [7]
<i>Module parameters</i>				
Nameplate Capacity, kWh	15	1.0	0.1	1.4
Volume, m <sup>3</sup>	0.16	0.52	0.01	0.49
Mass, kg	200	428	25	1200
Energy Density, kWh/m <sup>3</sup>	92.8	1.9	8.5	2.9
Energy Density, Wh/kg	75	2.3	4.4	1.2
Maximum Charging Rate, kW	3	300	60	200
<i>Locomotive parameters</i>				
Regenerative Braking Quantum	4500kW x 0.5 hour = 2250kWh			
Capacity-limited Storage Volume, m	24	1170	264	781
Length of 3m x 3m Profile, m	3	130	29	87
Capacity-limited Storage Mass, t	30	963	507	1929
Charge-rate-limited Storage Mass, t	300	6.4	1.9	27.0

### 3.2.3 Smart grids

Heavy haul trains at lengthy intervals do not offer high diversity, but extending the traction power supply system to an external grid can potentially increase diversity. There might of course be exceptions, such as establishing a heavy haul railway in a developing country that has no grid. Where available infrastructure allows trains to transfer instantaneously surplus energy to their environment, it is best used directly by other consumers. When the latter cannot accept such energy, storage devices are indicated, although in-and-out losses render them a last resort.

At grid level, generation is becoming less controllable while consumption is becoming increasingly varied: The architecture and technology of transmission and distribution grids and their systemic interaction will therefore need to change. This means that tasks, obligations, and business activities of actors that participate in the electricity system must be clearly defined. Interfaces between regulated grid monopolies and competitive market business activities will be challenged due to increasingly bundled technical system effects, such as the massive introduction of distributed and concentrated storage [8]. To this one can add independent power producers, in which field heavy haul railways are a potentially major participant.

Smart grids use information and communication technology to automate acquiring and acting on information about supplier- and consumer behaviour to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity. Interventions include identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services [9]. Smart grids help make it possible to generate and use power efficiently and on demand: Each country in which the International Heavy Haul Association has members has already implemented smart grid initiatives, as follows:

*Australia:* The government is running a SmartGrid, SmartCity trial program [10] to introduce the benefits of smart grids. The Australian Energy Market Commission has recently issued smart grid related reports on mandated smart meter cost recovery and demand side participation [11].

*Brazil:* The smart metering market is about to boom driven by new regulations and utilities' need to combat non technical losses. It is at the Latin American forefront pursuing grid modernization for its electric utilities [12].

*Canada:* A combination of vast natural resources, large wealthy cities and sparsely populated wilderness challenges the country's energy infrastructure. Extensive planning and focus on innovation is helping Ontario build one of the world's most fully realised smart grids [13].

*China:* The release of China's latest five-year plan reinforces the perception that China truly understands that a smart grid is fundamental to future prosperity. It is guided by a thoughtful and cogent overall plan [14].

*India:* Several Indian state governments reportedly laid plans for smart grid projects, ranging from smart meter rollouts in Puducherry and Bangalore, to deployment of phasor measurement devices across the nation's five independent grid systems—a first step in synchronizing them [15].

*Russia:* Federal Grid Company will spend \$116 million on research and development to allow consumers to feed excess power into the grid and to prepare utilities for swings generated by the use of renewable energy [16].

*South Africa:* State-owned power utility Eskom has started to deploy a hybrid smart grid model that will enable smart demand-side management, automatic correction and the connection of variable, renewable-energy generation capacity [17].

*Sweden:* The state-owned public utility Svenska Kraftnät's mission is among other, to promote an open Swedish, Nordic and European market for electricity and natural gas [18]. *Norway:* A smart grid is under development, aiming at smart meters for all consumers by 2018 [19].

*United States:* The Department of Energy has created a partnership of industry and quasi governmental professional electrical power organizations to integrate subject matter experts in developing a roadmap and vision for the smart grid [20].

Heavy haul railways behave as independent power producers that can turn an external (to them) electricity grid to advantage. Smart grids potentially mean more to railways than grid stakeholders seem to appreciate, but several building blocks to actualise that potential are coming into place.

#### 3.2.4 Pumped storage

While direct consumption of transient surplus energy is preferable, when supply inevitably does exceed demand, pumped storage offers the largest-capacity available, providing >99% of world bulk electricity storage. It is an essential element of harnessing intermittent renewable energy: Installations of ≈500MW, using ternary machines with separate turbine, motor-generator and pump, store or discharge within seconds. Overall efficiency range is 70-87% [21]. Locomotive power outputs are comparable to those of wind turbines, while regenerative braking behaviour is comparable to other intermittent, independent power producers. There is thus natural affinity between an electrified heavy haul railway and a smart grid supported by pumped storage.

### 3.3 Emissions

United States long-term emissions standards, effective 2015 for new locomotives, are based on maximum diesel fuel sulphur content of 15 parts per million and catalytic after-treatment: Other jurisdictions have similar standards. They will reduce particulate matter by ≈90%, nitrous oxide by ≈80%, compared to 2008 standards, and substantially reduce hydrocarbon, carbon monoxide, and other toxic emissions [22]. Furthermore, shale-gas-extraction-, gas-to-liquid-, and coal-to-diesel technologies seem set to postpone peak oil by decades. Concurrently, the environmental impact of coal-based electricity is under pressure, with carbon sequestration techniques promising greener electricity. Thus while it appears that greenhouse gas emissions do not unduly constrain diesel traction anymore, greener coal-based electricity ups the ante for electrification.

### **3.4 Throughput scalability**

A last consideration before addressing external power generation is scalability. On board generation scales up traction power in proportion to train load and -frequency so that, within reason, train performance is independent of train size. By contrast, trains must share externally generated power through a network. Performance is then no longer scalable in direct proportion to the number of locomotives on a train, but depends on aggregate demand on the network. Conventionally, network capacity elements such as feeder lines and substations come in large chunks: Increasing capacity as traffic grows can therefore involve large increments. The essential trade off is thus between ability to open the train system to external supply and storage capacity, versus ability to scale capacity in a quick succession of small increments, as has been necessary during the recent commodities boom. This issue ups the ante for on board power generation.

## **4 EXTERNAL POWER GENERATION**

### **4.1 Criteria for implementation**

Electricity's variable cost generally undercuts that of diesel fuel, but the infrastructure to feed it to heavy trains is expensive. Setting aside the throughput scalability issue for the moment, the essential difference between on board- and external power generation is ability to transfer energy to and from the train environment. The latter ability requires regeneration, which while technically well established, requires the following insights to optimise its application in heavy haul railways.

### **4.2 Some regeneration considerations**

#### **4.2.1 Grade symmetry**

When the same motive power that hauls loaded trains must return with empties, steeper grades in the empty direction offer economic benefits. Many heavy haul lines therefore feature asymmetrical ruling grades—a solution mentioned in Wellington's classic [23, 608]. However, maximising regeneration requires eliminating train friction braking, which in turn requires symmetrical down- and upgrades, with due adjustment for the contribution of rolling resistance.

#### **4.2.2 Distribution on a three-phase network**

Matching regeneration of one train with demand of another train on the same of three phases may require relatively long-distance transmission. There may even be a time shift between such events, which would necessitate temporary energy storage. National- or regional grids offer ideal diversity for wheeling regenerated energy to other consumers or to storage. Acceptance of independent power production facilitates that systemic solution, and encourages renewables and pumped storage. Heavy haul railways and smart grids potentially have strong symbiosis.

#### **4.2.3 Self-sufficiency**

Importantly, energy self-sufficiency facilitates throughput scalability because, as throughput increases, so does regenerated energy. This can potentially reduce the number and capacity of feeder lines required to connect a heavy haul railway to a national- or regional grid.

## **5 SOME PRACTICAL APPLICATIONS**

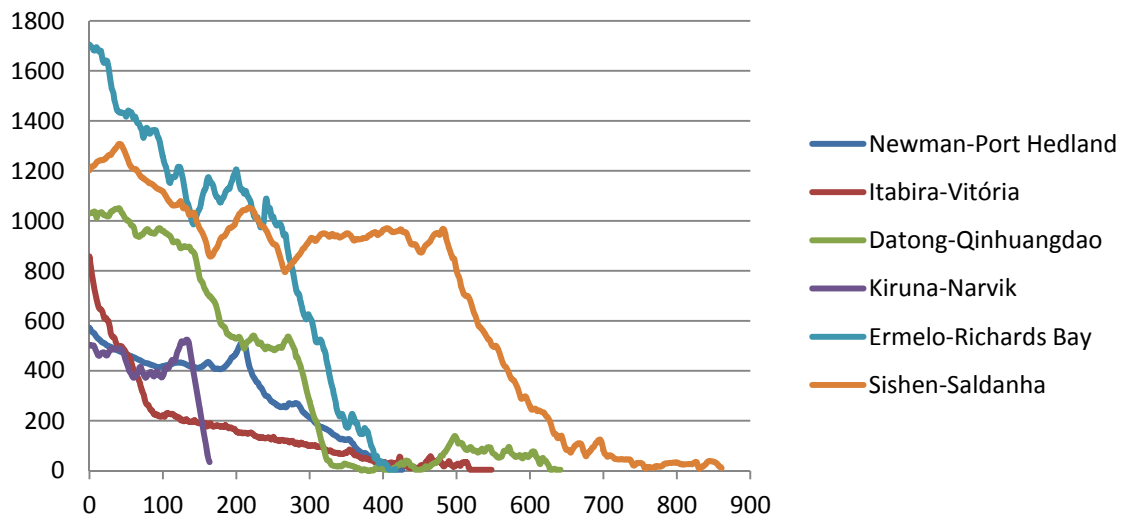
### **5.1 Introduction**

The authors applied the above review to examine six heavy haul railways, selected to illustrate the insights reported above, broadly following Wellington's notion of rise and fall [23, 327]. They all feature significant elevation drops from pit to port, combined with a comparatively short haul distance. This criterion excludes North American and Russian continental- or transcontinental

heavy haul railways, whose distance-to-elevation ratio is materially higher. For example, the Trans-Siberian railway descends from its eastern summit of 1317m at Mururinsky Pass to the port at Nakhodka over some 2900km, an average fall of 1 in 2200. This grade is flatter than that on which trains will run under gravity: It therefore cannot be energy self-sufficient, and regenerative braking in such settings must necessarily exploit whatever local opportunities exist.

## 5.2 Six examples

Vertical sections of Australia's Newman-Port Hedland, Brazil's Itabira-Vitória, China's Datong-Qinhuangdao, Nordic Heavy Haul's Kiruna-Narvik, and South Africa's Ermelo-Richards Bay and Sishen-Saldanha lines were plotted from Google Earth to construct Figure 1: Altitude measurements were statistically smoothed to mitigate possible indistinct imagery errors. The lines were selected to represent varied terrain characteristics, not to drill down into particular operations.



**Figure 1: Comparison of Elevation in meters versus Distance in km for selected railways**

Their energy consumption and regeneration contribution were then computed to construct Table 2. Tare axle load and re-use efficiency are assumptions. While the range of axle loads indicates sensitivity to that parameter for the different routes, it does not represent actual practice on a particular line. Note that as axle load increases, load-to-tare ratio also increases: The potential energy available in the loaded direction therefore increases proportionately more than the energy required to return empty trains, thereby improving self-sufficiency of the total railway system.

**Table 2: Energy requirements for selected railways as a function of axle load**

Gross tons/axle		Newman-Port Hedland	Itabira-Vitória	Datong Qinhuangdao	Kiruna-Narvik	Ermelo-Richards Bay	Sishen-Saldanha
	Tare tons/axle			5			
	Re-use efficiency, %			85			
25	Required Energy, Nm	7.5E+12	1.2E+13	1.7E+13	6.0E+12	1.7E+13	2.3E+13
	Available Energy, Nm	2.9E+12	6.9E+12	9.9E+12	5.4E+12	1.8E+13	1.3E+13
	Self-sufficiency, %	39	56	60	90	109	56
30	Required Energy, Nm	8.0E+12	1.3E+13	1.8E+13	6.7E+12	1.9E+13	2.5E+13
	Available Energy, Nm	4.0E+12	8.8E+12	1.3E+13	6.7E+12	2.2E+13	1.6E+13
	Self-sufficiency, %	51	66	70	100	121	64
40	Required Energy, Nm	8.8E+12	1.5E+13	2.1E+13	7.9E+12	2.2E+13	2.9E+13
	Available Energy, Nm	6.3E+12	1.3E+13	1.8E+13	9.1E+12	3.1E+13	2.3E+13
	Self-sufficiency, %	71	84	86	115	139	78

Table 2 shows the potential of regeneration to fulfil 39-139% of heavy haul traction energy requirements, under ideal conditions: Appreciate however an implicit assumption that all surplus energy is regenerated. On asymmetrically graded lines, as are most of the selected railways, if friction braking must supplement electric braking on long descents, then entropy must decrease the level of self-sufficiency. Braking practices vary among railways, and it is outside the scope of this paper to explore that field. Nevertheless, to illustrate the principle, South Africa's Ermelo-Richards Bay route, operating 26 tonnes/axle on 1.52% descending grades, supplements regenerative braking (on locomotives so equipped) by friction braking to maintain safe speed on long descents: The unavoidable energy dissipation reduces self-sufficiency from 112% to 79%. This could be decisive in weighing the relative merits of external and on board power generation.

## 6 DISCUSSION AND CONCLUSIONS

In addition to traditional hurdles such as return on investment, environmental impact, and broad stakeholder satisfaction, new challenges related to climate change, energy efficiency, peak oil, and sustainability have emerged, and heavy haul energy provisioning needs to consider them. From the perspective of commercially- or imminently available technologies, note the following:

Heavy haul baseline diesel traction uses comparatively expensive but nevertheless available fuel, holds no systemic interaction surprises, and easily scales throughput. By contrast, electric traction decouples railways from on board power generation and facilitates access to other electricity generators and consumers, through smart grids that typically also feature renewables infeed and bulk storage. Taking for granted that net metering should render transactions transparent to railways and other consumers, realising the full-potential of electric traction requires, as a minimum, investment in extensive catenary, matching vertical alignment to locomotive performance characteristics, plus high-capacity low-latency, long-lived energy storage. Where an extensive grid is within reach, adequate feeders and/or connections will also be required.

Which alternative should a new railway choose? Energy self-sufficiency could be decisive: Diesel traction would tend to lead where self-sufficiency is low and/or entropy is high; electrification would tend to lead where self-sufficiency is high and/or entropy is low. Key questions are: First, is the potential to regenerate energy high, in which case is it worth considering investment in electrification infrastructure to recover it? Second, if the first answer is positive, does the vertical alignment support full recovery of surplus potential energy, or does unavoidable friction braking dissipate a portion as entropy? Third, is there reasonable access to a sizeable smart grid?

Further challenges remain. Who is generator of last resort under abnormal system states—e.g. a self-sufficient heavy haul railway restarting after a maintenance shutdown? What capacity should a link to a smart grid supply? Re-grading existing lines might be unaffordable: Is realising the potential energy efficiency of an electrified heavy haul railway only possible on new lines designed to avoid entropic losses? What are the economic dynamics of margins between surpluses and consumption? Is it significant that private investors seem to prefer the lower capital risk associated with diesel traction, while state railways seem to take the longer view associated with electric traction? To conclude, much research remains in a fascinating field, but the key challenges have been identified, and the modalities of linking heavy haul railways and smart grids are in focus. The influence of unconventional oil on peak oil does however remain a wild card.

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