Analysis of the technical feasibility and the corresponding investment for the conversion of an electro-diesel locomotive to a hydrogen-based solution

Work Package 4 (WP4) Report

February 13, 2023

Programa de Energías Renovables y Eficiencia Energética en Chile

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Glossary of Terms

°C	Degrees centigrade – unit of temperature
~	Symbol used to represent an approximate figure
amp(s)	Abbreviation of ampere – unit of current flow within an electrical circuit
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASL	Above sea level – used to describe units if distance with regards to elevation
ATEX	the name commonly given to the two European Directives for controlling explosive atmospheres
bar	Metric unit of pressure (1 bar is equal to 100 kPa or approximately 14.5 psi)
BOM	Bill of materials
BTMS	Battery thermal management system
C-rate	Charge-rate – used to define how quickly a battery discharges
COP26	The 2021 United Nations Climate Change Conference
DC	Direct Current – used to represent a one-way flow of electrical charge
e.g.	'exempli gratia' used to abbreviate 'for example'
EC Type Approval	The procedure whereby an authority of an EU Member State certifies that a type of vehicle, system, component, or separate technical unit satisfies relevant technical requirements and administrative provisions listed in the relative instrument
EC79	Regulation set by the European Environment Agency on type-approval of hydrogen-powered motor vehicles.
EMD	Refers to the General Electric manufacturer's Electro-Motive Division
ft	Imperial unit of distance
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit – commissioners of this report
GPS	Global Positioning System
H2	Chemical symbol for Hydrogen
HGV	Heavy Goods Vehicle (such as articulated lorries)
Hp	Horsepower – unit of power
i.e.	'id est' used to further explain a previously mentioned subject
IEC	International Electromechanical Commission
ISO9001	The International Organisation for Standardisation's Quality Management Systems standard
kg/m3	Kilograms per metre cubed (volumetric representation of mass)
km	Kilometre – metric unit of distance (equal to 1,000 m)
km/h	Kilometers per hour – unit of speed
kN	Kilonewton – unit of force
kPa	Kilopascal – unit of pressure

kW	Kilowatt – unit of energy
kWh	Kilowatt Hour – unit of electrical capacity (typically used to describe battery capacity)
l	Litre – unit of volume
l x w x h	Length by width by height (used when describing physical dimensions)
Loco(s)	Abbreviation of Locomotive
m	Metre – Metric unit of distance equal to 1,000 mm (100 cm)
mm	Milimetre – unit of distance equal to one thousandth of a metre
MW	Megawatt – unit of electrical power
N°	Symbol used to represent a numerical reference
Ohm (Ω)	Unit of electrical resistance
PEM	Proton Exchange Membrane
PPE	Personal protective equipment
psi	Pounds per square inch – unit of pressure
s	Second(s) – unit of time (equal to
SIL	Safety integrity level
SoC	State of charge (when referring to a battery)
STS	Vanguard's Single Train Simulator software
t	Abbreviation of tonne
tonne	Metric unit of mass equal to 1,000 kg
TPRD	Thermal pressure release device
TRANSAP	Chilean freight operator upon who's locomotives this report is based
UK	United Kingdom
UKHA	United Kingdom Hydrogen Association
V	Volt – unit of electrical power
vs.	'*versus*' term used when comparing two opposing subjects
VSTS	Vanguard Sustainable Transport Solutions
wt%	Representation of weight as a percentage

1 INTRODUCTION

The first requirement for the study is a thorough understanding of the physical characteristics of the locomotives and their respective routes. From this, the equipment can be specified and the requirements for the surrounding infrastructure determined. This section will outline the key characteristics of the locomotives, the routes they are assigned to and the types of hydrogen-hybrid powertrain technologies that will be mentioned in this report.

1.1 LOCOMOTIVES STUDIED IN REPORT

Figure 1: TRANSAP Class 2300 Locomotive at San Antonio Harbor (courtesy of GIZ)

Two types of locomotives were selected for this report. Both were constructed by General Motors Electro-Motive Division (EMD) and are based on the same chassis type with the same traction motors. The difference between the two classes is the size of the prime mover fitted to the locomotives. The SD-39 is fitted with a 2300hp (1720kW) engine, and the SD-40 is fitted with a larger, 3000hp (2240kW) diesel engine.

The SD-39 locomotives can be coupled to increase range and tractive effort along certain routes. The locomotives running the central zone route have been modelled as doing so.

This report will produce a concept hydrogen power solution that fits onto the existing chassis of both locomotives. Whilst fitting the locomotives with a hydrogen-hybrid traction system will remove a significant source of carbon, particulate and other harmful emissions, it is intended, where possible, for the modifications to also improve the capability of the locomotives to fulfil the duties assigned to them.

The process for producing a mathematical model of each type of locomotive is discussed in Section 2 in this report.

1.2 Routes Modelled in Study

Two routes have been analysed: central zone and central – south zone. The first route runs to the south of Santiago while the second route runs further southern. The location of both routes is shown in the figure 2:

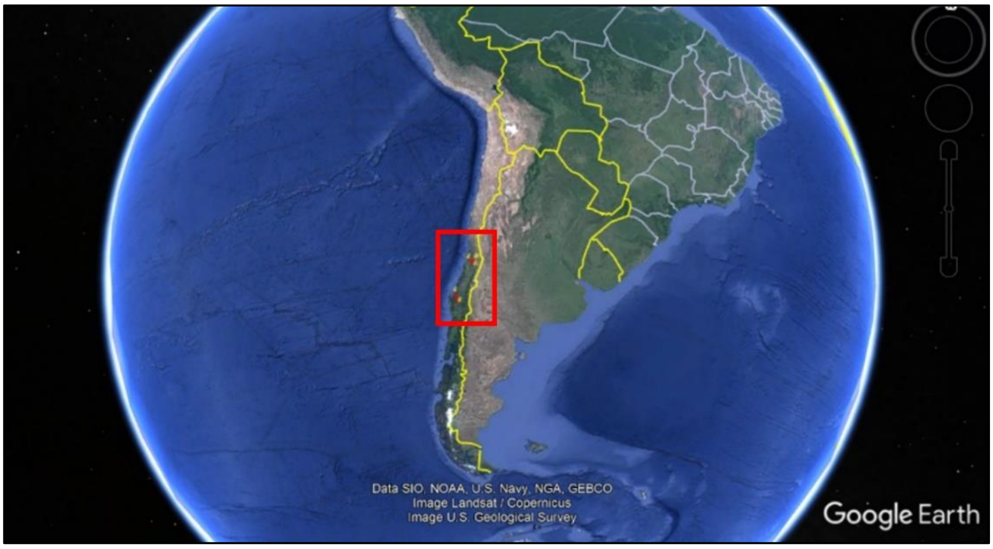

Figure 2: Location of Modelled Routes in Chile (courtesy of Google Earth)

Trains on both routes run loaded to the respective freight terminals at each port and return empty back to their origin locations. This informs the specification of hydrogen-hybrid locomotives for use on these lines. The elevation profiles of both lines are shown in figures 3 and 4:

Figure 3: Elevation profile of central zone route (courtesy of Google Earth)

Figure 4: Elevation profile of central - south route (courtesy of Google Earth)

The process for modelling both routes will be described in Section 2.

1.3 Hydrogen-Hybrid Power Systems

Vanguard Sustainable Transport Solutions have experience of designing, building, testing and operating hydrogen-hybrid power systems (also known as *powertrains*) from the UK based HydroFLEX 1, HydroFLEX 2 and HydroShunter train development projects.

A hydrogen hybrid power system consists of 3 main elements:

1. Hydrogen fuel cells
2. Hydrogen storage tanks
3. Traction batteries.

Figure 5: HydroFLEX, the UK's First Standard Gauge Hydrogen Train (courtesy of VSTS)

The fuel cells convert hydrogen from a storage system and oxygen from the atmosphere into electricity and water (as both steam and liquid water). No combustion is involved in the power generation process, it is purely chemical, therefore no harmful particulates are produced from the fuel cells. Fuel cells are also typically quieter than a comparable internal combustion engine, thus providing additional health benefits to train crews and a reduction in noise pollution around yards and depots.

Hydrogen is produced by the process of electrolysis. If renewable electricity is used to split water into its constituent hydrogen and oxygen, no carbon emissions are produced, thus giving an important climate-change-reducing benefit to the adoption of this technology.

Figure 6: The Fuel Cell Inside HydroFLEX 1 During Build (courtesy of VSTS)

Hydrogen has impressive energy storage density by weight. However, the energy storage density by volume is poor. As a result, technology must be used to either compress and/or liquify the hydrogen to store meaningful amounts within the space constraints of locomotive or multiple unit carriage.

This report will be based on equipment used to store hydrogen at a pressure of 350 bar normal working pressure; a pressure commonly used on hydrogen powered buses. However, developments are being made in the creation and use of higher pressure, cryogenic and cryogenic-compressed hydrogen, meaning that this study should be considered as the baseline for what can be achieved with hydrogen storage on a freight locomotive using existing, proven technologies.

Figure 7: 4x Compressed Hydrogen Storage Tanks Inside HydroFLEX 1 (courtesy of VSTS)

The traction batteries discussed within this report are based upon the lithium-ion traction batteries used on the HydroFLEX 2 train: a legacy project which involved members of the Vanguard Team who have contributed to the contents of this report.

The purpose of the traction batteries is twofold – to be discharged to provide peak power at times of high demand, and to harvest energy from regenerative braking of trains. This use suits the characteristics of lithium batteries, which are typically very power dense in terms of mass and volume, but not very energy dense when compared to the energy stored in hydrogen both in terms of mass and volume.

Figure 8: The HydroFLEX 2 hydrogen train at COP26 (courtesy of VSTS)

1.4 REPORT METHODOLOGY

The way in which the studies for this report have been performed begins with the selection of the vehicles themselves. Typically, the vehicles selected for the study are identified by the owner/operator. In the case of this study the locomotives have been selected by Chilean freight operators TRANSAP.

Once the vehicles have been identified, data is gathered on their physicality, operational characteristics, and their respective duty cycles. This allows virtual models of the vehicles and their routes to be created and represented in the form of a raw dataset upon which simulations can be performed.

When the raw data set has been created and agreed by all parties, it is loaded into Vanguard's Single Train Simulator (STS) software. From this, using calculations explained in section 2, the STS will generate a summary of requirements necessary for the vehicle(s) to achieve, or exceed, their duty requirements using hydrogen as the primary fuel source.

The results from the simulations are analysed and relevant conclusions/recommendations are made based on the real-world experience and judgement of the Vanguard Engineering Team. These conclusions and recommendations are recorded within a report which is supplied to the customer as a way of confirming whether a Hydrogen conversion is or isn't a feasible prospect.

The report is also generated in accordance with Vanguard's ISO9001 accredited Quality Management System – the formal procedure for which is outlined below.

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Project Received	Project is received following the Sales Process.
Project Document Created	A summary of the Project Scope is created in the Project Brief which is handed over to the nominated Project Manager.
Project Stakeholder Meeting Held	An Introductory Meeting is held to introduce the key Project Stakeholders to the Vanguard Team. Initial queries are discussed ahead of Project Kickoff.
Project Kickoff	The Project is considered live and the Programme of Works started.
Project Engineering Review	An internal review of the Project Documentation is held between the Projects and Engineering teams to determine the data required from the Client.
Project Data Requested from Client	The data required for the Work Package is requested from the Client.
Project Data Analysed	On receipt of the requested data, it is interpreted and analysed by the Engineering Team to ensure there are no further clarifications required from the client or omissions in the data.
Project Data Summary Generated for Client Approval	A Summary of the data received from the Client is generated by the Engineering Team. It is sent to the client for confirmation via email that the data on which the report will be based has been interpreted correctly.
Report Contents Created	On approval of the Project Data from the Client, the contents of the report is generated by the Engineering Team. This can be information such as, but not limited to, route simulations, calculations and concept drawings.
Draft Report Generated for Client Feedback/Approval	When the draft report is complete, it is sent to the client for feedback usually accompanied by a presentation to ratify that the contents of the report is what the client is expecting.
Final Report Generated for Client Feedback/Approval	On approval of the draft report, subject to any further amendments, the report is formally issued at Rev0.
Work Package Complete	

2 Route Simulation

Once the raw data for the locomotives and their routes has been gathered and approved, it is used to run virtual simulations of the trains as they would operate on their assigned routes. Many of the variables that need to be considered when converting a diesel-electric vehicle to run on Hydrogen are determined by establishing the way in which the trains perform along their respective routes. As such, it is this stage of the study that generates the information needed to begin to truly understand whether a hydrogen conversion is feasible.

Hydrogen-hybrid powertrains bring design challenges when compared with non-hybrid systems.

The energy storage battery element of the powertrain must store enough energy to complete the required journeys without running out of charge while being small enough to fit on the vehicle in terms of weight and space.

The hydrogen element of the powertrain is similarly challenging to design as the storage tanks take up a large amount of space. Therefore, there must be confidence that enough hydrogen can be carried onboard to fulfil a useful amount of work.

Simulating the duty cycles that the train is expected to fulfil before starting any future design development allows for the fuel cell, battery, and hydrogen storage elements of the design to be balanced correctly for the best possible results in use.

2.1 The Single Train Simulator

As covered in a separate report focused on decarbonising transport in Sub Saharan Africa (Calvert, et al., 2021), the Single Train Simulator (STS) is a software simulation tool developed by researchers at the Birmingham Centre for Railway Research and Education (BCRRE) for evaluating the energy consumption of railway traction. This can be calculated for many different types of traction, with outputs ranging from kWh for lineside electrification simulations, kilograms of hydrogen and battery final state of charge for hydrogen-hybrid trains or amount of diesel consumed, also measured in kilograms.

The STS is based on the first principle of longitudinal dynamics and the energy conservative principle. The longitudinal dynamics are expressed in the form of mathematical formulae which, when combined, form a simulation model. The model is then used to predict the motion of a train under a set of conditions, namely gradient, train mass, friction and traction force applied.

STS first computes the traction force F_T required to fulfil a given acceleration profile α using the formula:

$$m(1+\lambda)a = F(T - (a + bv + cv^2 + mg\theta))$$

m is train mass, a+bv+cv^2 is the summation of frictional forces and $mg\theta$ is gravitational pull. The acceleration profile α is derived from a given velocity profile v.

After obtaining the traction force required to fulfil a trip, STS then computes the energy required by the respective traction system. STS uses powertrain efficiency curves that are custom to the selected traction technology to provide more accurate energy estimates. The energy required at each step is computed using the formula:

$$E = \frac{F_t\Delta}{\eta}$$

Δ is the distance for which a specific F_T is applied and η is the powertrain's efficiency. Total energy consumption is then computed by adding the consumption of all steps. The energy calculation only accounts for traction requirements and does not account for hotel loads.

The STS is highly flexible by allowing the user to specify the railway route and the parameters of the train simulated, and modular enough to accommodate various traction systems both conventional and hybrid. The state-of-charge ζ of the energy storage device of hybrid powertrains is modelled using the formula:

$$\frac{d\zeta}{dt} = \frac{-i}{3600.Q}$$

i is battery current and Q is battery capacity. Battery current is computed using battery voltage and traction power.

2.2 The Single Train Simulator Methodology

Five main elements go into the production of a route simulation using the Single Train Simulator:

1. ***Route Length***
2. ***Station locations***
3. ***Route Timetable***
4. ***Speed Limits***

5. Elevation Profile

In terms of sourcing the above information, it is possible to source the route length and station locations from a map survey or from reference material produced by the railway. The route information produced and used in the simulator is included in this section.

Speed limits can be found in reference materials produced by the railway operator. The modelling of speed limits, stopping locations and dwell times in this report was achieved by analysing GPS data sent to the project team by TRANSAP. From this data, the speed and elevation profiles of the routes were determined.

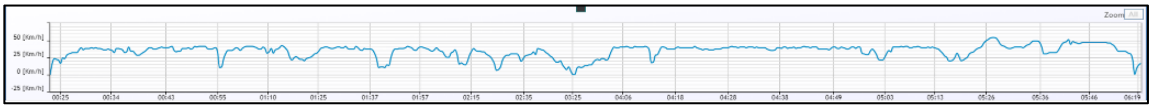

Figure 9: GPS Data (courtesy of TRANSAP)

2.3 Modelled Route Characteristics

The extrapolated characteristics of the routes are included in Appendix H. The Single Train Simulator measures speed in kilometers per hour, measures train stopping times in seconds and can either accept gradient profiles as a value of meters gained or lost every 1000m or by inserting the elevation above sea level of key points along the route. Both methods of inputting gradient data have been used in the simulation files of this report.

2.4 Modelled Train Characteristics

The trains each have simulation profiles created using the data returned to the project team by TRANSAP. It should be noted that the auxiliary load outlined includes the additional power required for the operation of auxiliary components that will become part of the new hybrid traction system, including, but not limited to, hydrogen extraction fans, hydrogen fuel cell freeze protection, hydrogen fuel cell cooling system, battery thermal management systems, electrical converter cooling systems, hydrogen fuel cell air compressor. It also considers all existing components that will be retained.

2.4.1 Train Resistance to Motion Calculations

The train resistance to motion characteristics have been created as a function of the cross-sectional area of the train, the number of powered and trailing axles on the train and the weight of the train to determine the Davis variables A, B and C in accordance with the methodology described in AREMA Manual for Railway Engineering (1999). As has been discussed in section 2.1, the Davis Equation is a key component to the equation used in the STS's calculations of train motion, shown below.

$$m(1+\lambda)a = F(T - (a + bv + cv^2 + mg\theta))$$

The determined Davis equations for the train configurations are as follows:

Table 1: Resistance to motion values used in single train simulator (courtesy of VSTS)

	SD-39 Unloaded	SD-39 Loaded	SD-40 Unloaded	SD-40 Loaded
Powered Mass (t)	**232**	**232**	**120**	**120**
Powered Axles	**12**	**12**	**6**	**6**
Unpowered Mass (t)	**944**	**3136**	**1200**	**3200**
Unpowered Axles	**128**	**128**	**178**	**178**
Davis A	**19.9**	**36**	**23.7**	**36**
Davis B	**0.39**	**1.11**	**0.4**	**1.11**
Davis B	**0.0096**	**0.0096**	**0.0096**	**0.0096**

2.5 Modelled Hydrogen-Hybrid System Characteristics

After conducting a series of simulations, it was discovered that it is theoretically possible to operate the central zone route using two SD-39 locomotives couped together, each fitted with 600kW of fuel cell power and 440kWh of battery capacity.

The central-south zone route required more fuel cell power to ensure that an adequate state of charge remained within the battery, therefore the SD-40 locomotive required 800kW of installed fuel cell power was required along with the same 440kWh battery used in the previous simulations.

2.6 Route Simulation Results

The primary aims for the route simulations are to determine the key requirements for the specification of the hydrogen fuel cell – battery hybrid powertrain. The simulator models the behavior of the battery and hydrogen fuel cell over the given route, this allows the power output of the hydrogen fuel cell and battery capacity to be determined. Using simulations to specify the components is an essential for verifying that the final powertrain configuration can perform adequately along all the selected routes. Another key element determined by the simulation is the total amount of onboard hydrogen fuel storage, and subsequent number of individual hydrogen storage cylinders required for integration into the vehicle.

The route simulation results are detailed below. All raw simulation output graphs are shown in Appendices A, B and C.

2.6.1 Central Zone Route Results

The settings for the central zone route simulation both uphill and downhill are shown in figures 10 and 11.

Figure 10: Central zone returning route simulation settings (courtesy of VSTS)

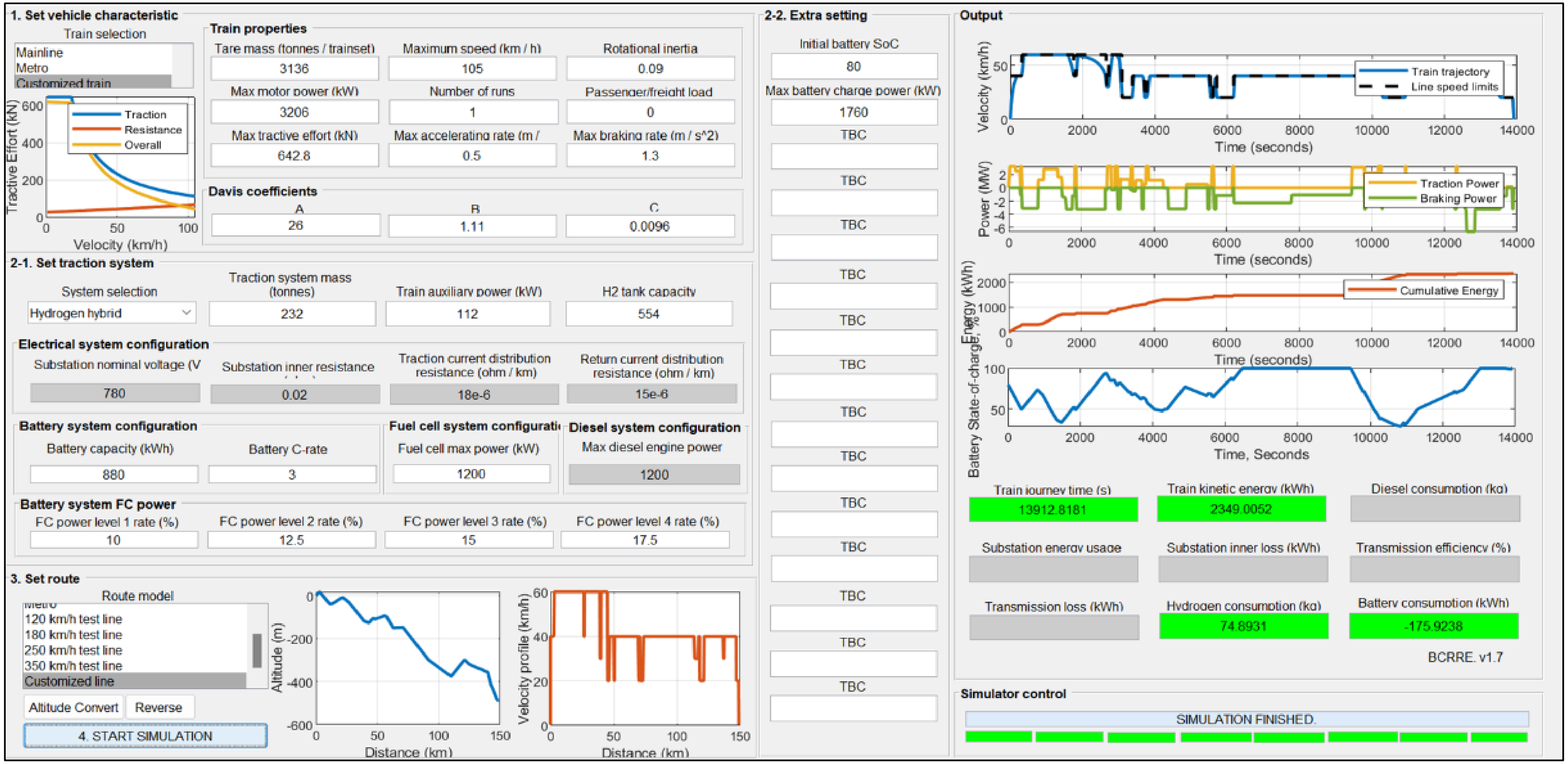

Figure 11: Central zone origin to destination route simulation settings (courtesy of VSTS)

The results for the central zone route are shown in figure 12. As the train has two locomotives, the results for both the whole train and each locomotive are shown on the map represented in figure 12.

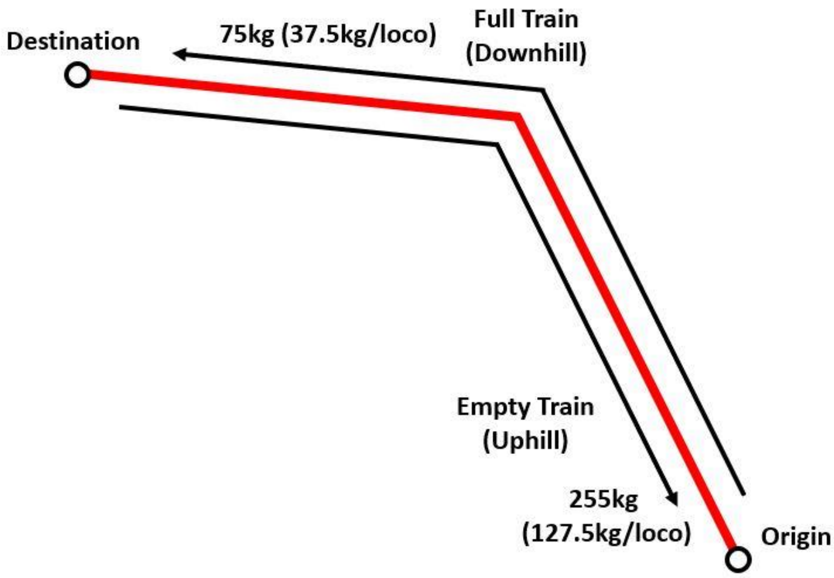

Figure 12: Central zone route Hydrogen Consumption Map (courtesy of VSTS)

Immediately, it is apparent that there is a great disparity in hydrogen consumption for each leg of the journey, over three times more hydrogen is required to pull the empty wagons back to the origin of the route. The reason of this can be explained by the ability for the hydrogen-hybrid traction system to harvest and re-use energy from regenerative braking. This is represented in figure 13.

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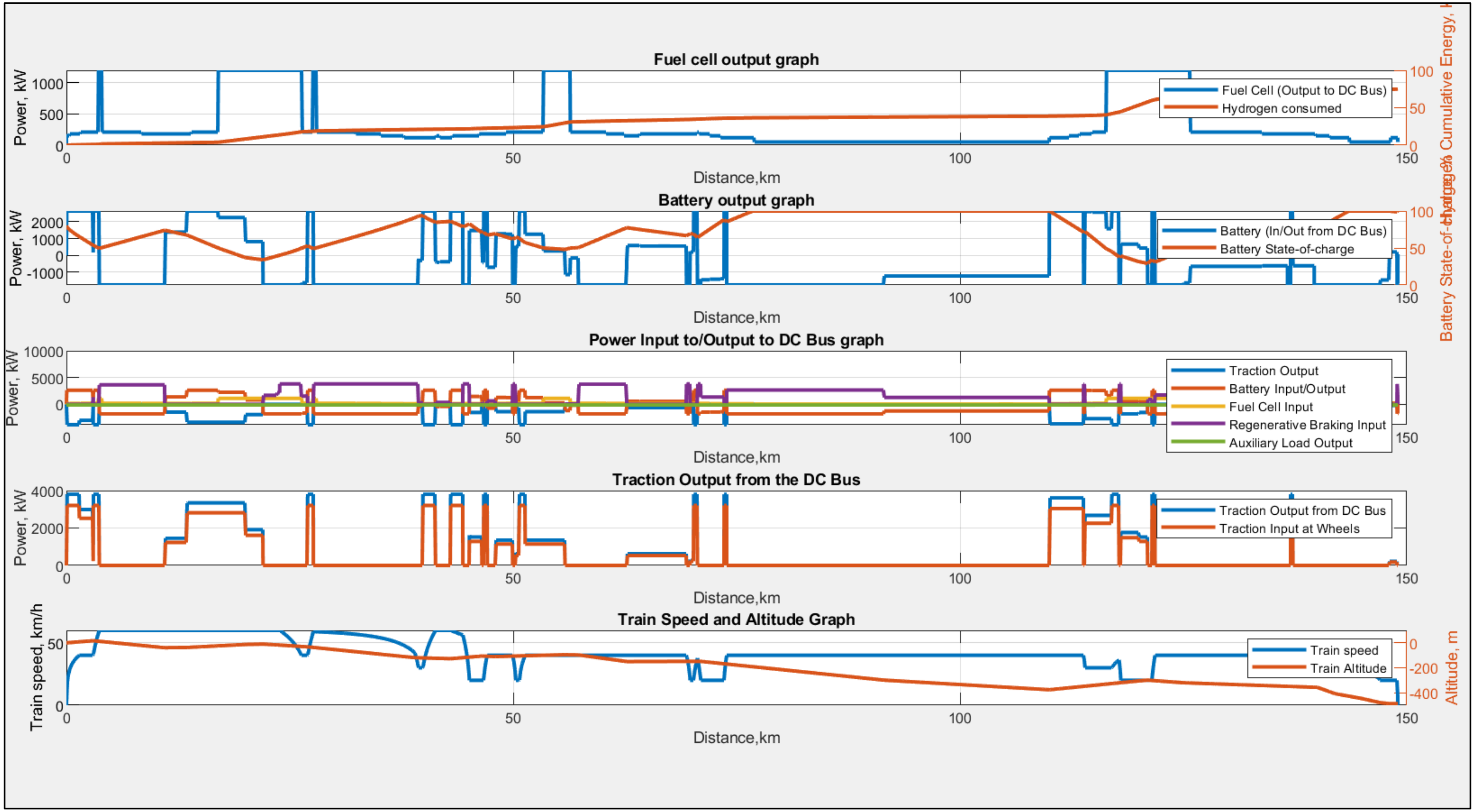

Figure 13: Downhill results (Origin to destination central zone route fully laden, courtesy of VSTS)

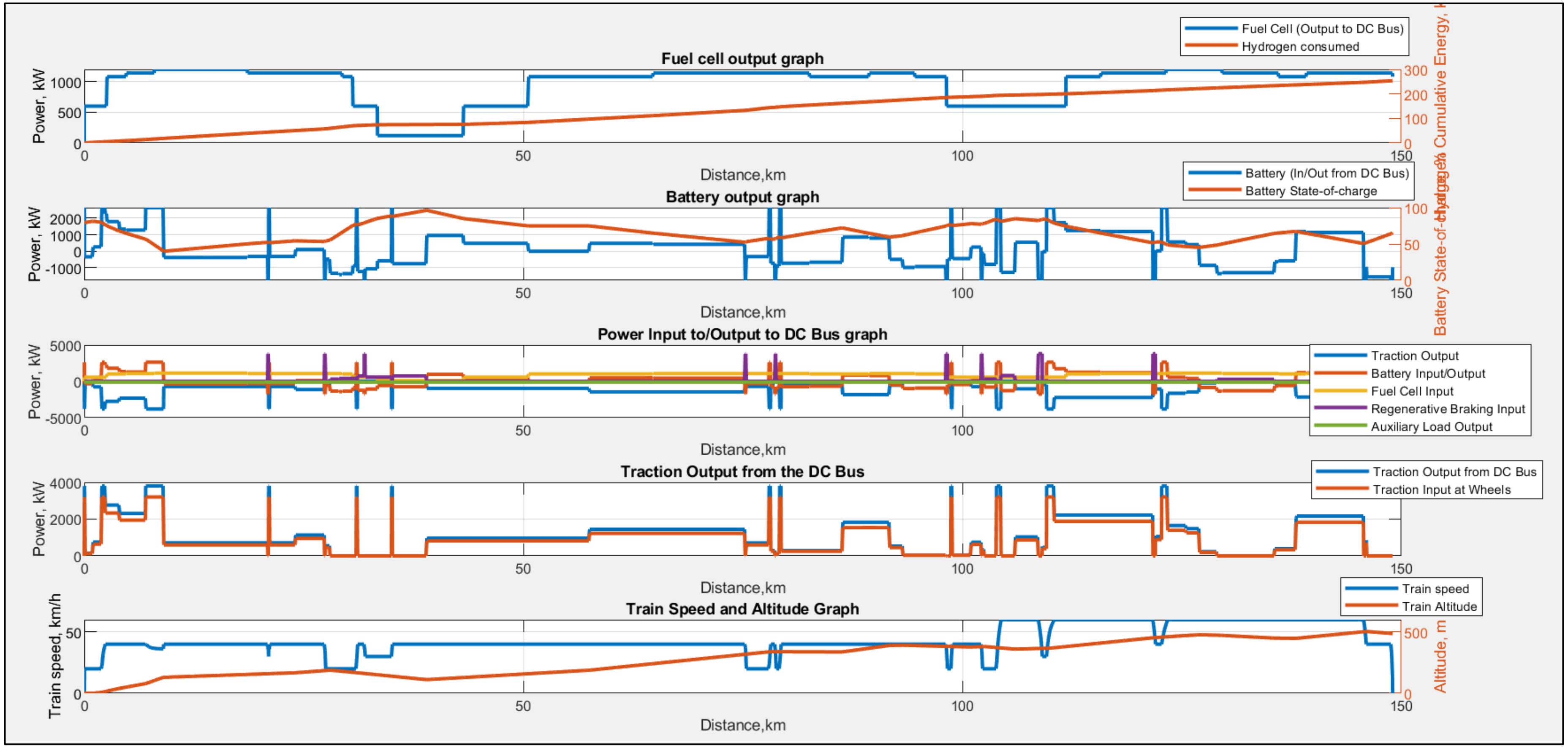

Figure 14: Uphill results (Destination to origin central zone route unladen, courtesy of VSTS)

Figure 13 shows the downhill, loaded route from Origin to Destination of the central zone. Figure 14 is the uphill return journey of the empty train.

As can be seen, the fuel cell output is much lower for the downhill journey as the battery is charged with energy harvested from regenerative braking. So much regenerative braking energy is created that the batteries end up fully charged between kilometres 75 and 120. Therefore, the fuel cells could, in theory, be switched off during this time. Auxiliary equipment could, in theory, be powered solely from the battery and the excess amounts of available energy would have to be discharged through the braking resistors as is current practice using dynamic braking.

On the return journey, the fuel cell output is much higher. The fuel cells must operate at maximum power for most of the trip to maintain an adequate battery state of charge, although there are periods where energy is harvested into the battery during regenerative braking. This phenomenon is shown in the overall energy graphs, figures 15 and 16 overleaf.

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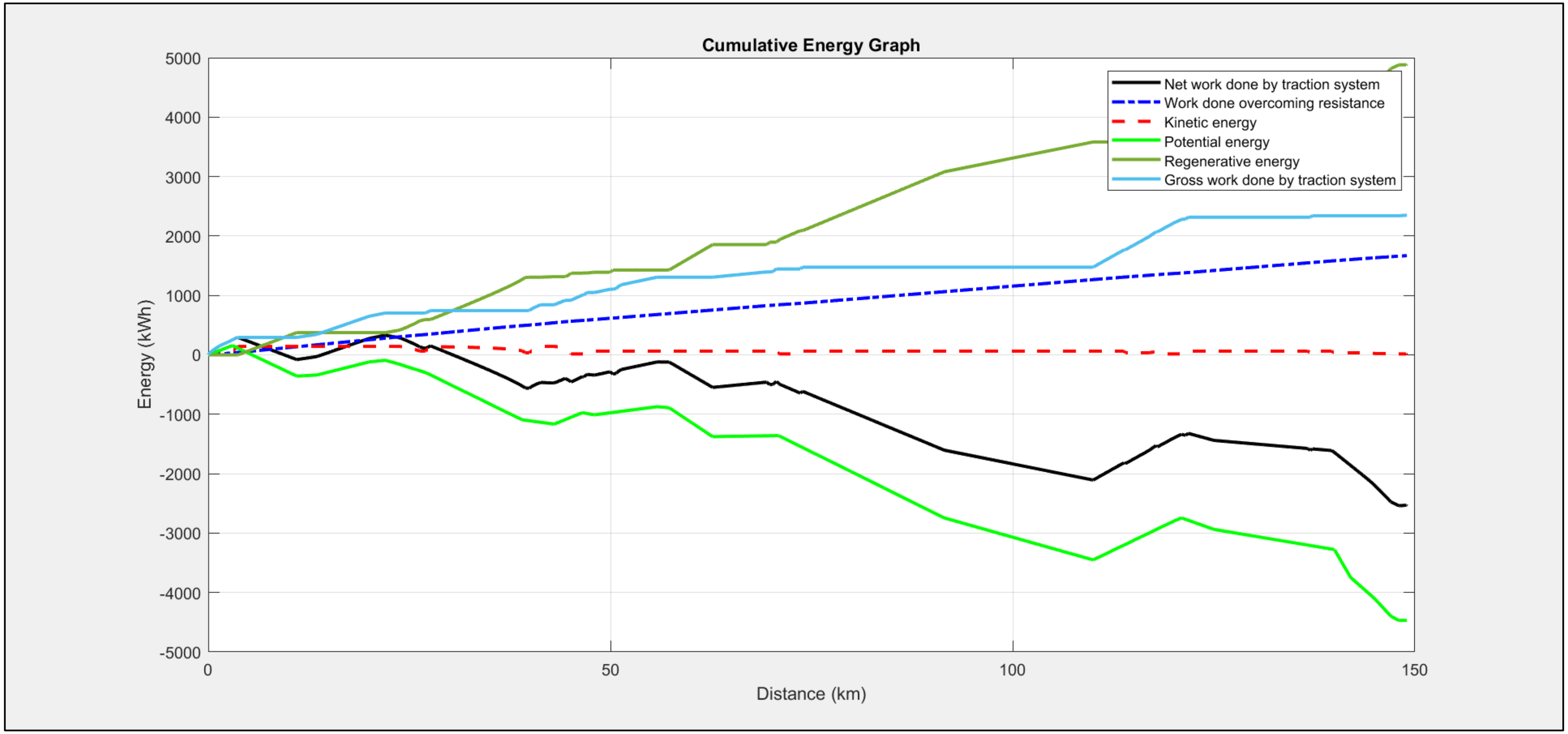

Figure 15: Origin to destination central zone route energy graph (courtesy of VSTS)

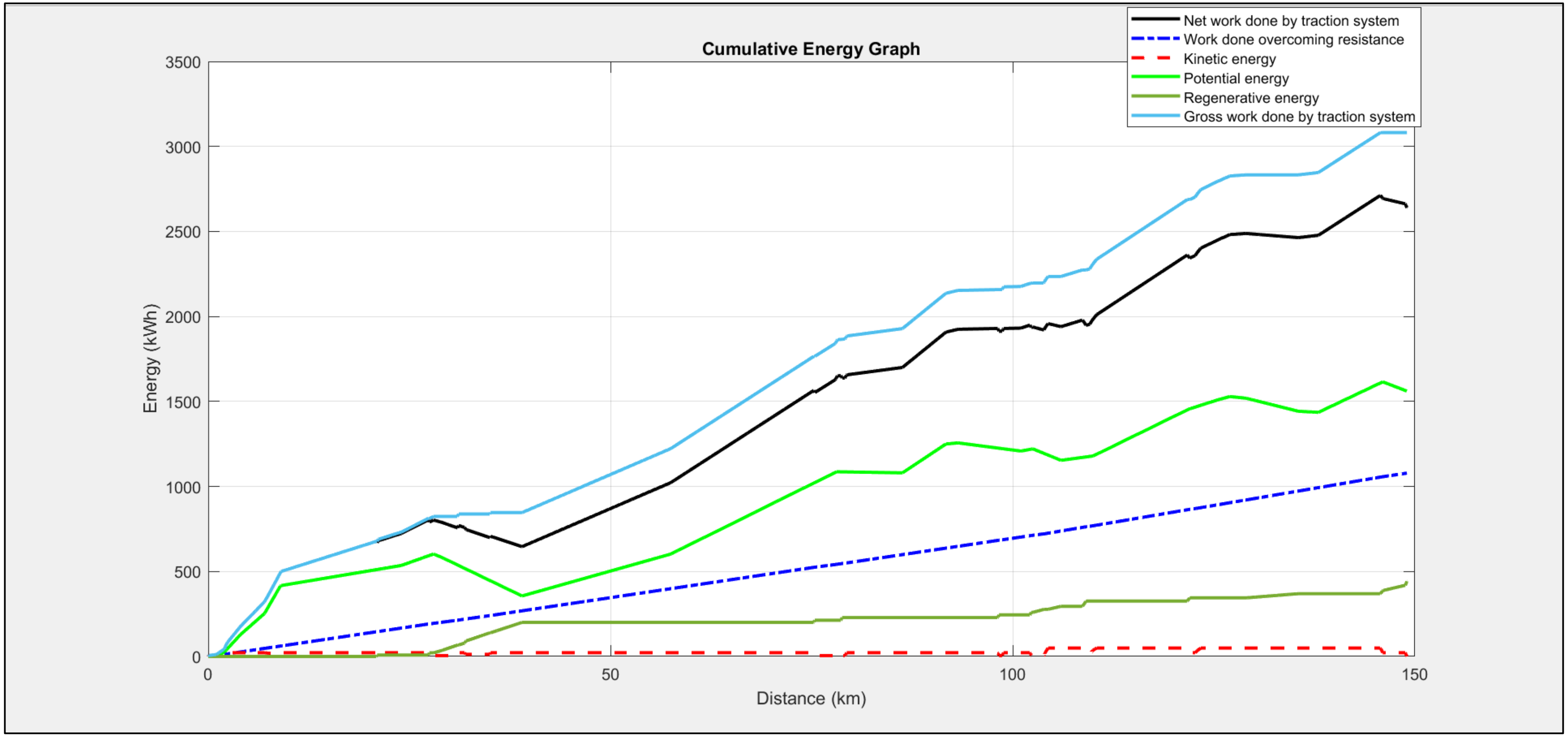

Figure 16: Destination to origin central zone route energy graph (courtesy of VSTS)

It should be noted that the figures shown for regenerative braking are the maximum amount of theoretical energy available from regenerative braking. This includes the energy that would have to be managed by dynamic or friction braking if the traction batteries become full.

As can be seen, minimal amounts of energy are harvested from regenerative braking on the uphill leg from destination to origin in the central zone route. However, very high amounts of energy are available on the downhill run of the full train if means of energy storage is available.

This section has shown a simulated prediction for energy that could potentially be harvested during braking. To confirm and correlate this simulation with reality, it could be possible to record and log the actual amount of energy dissipated during dynamic braking by measuring the current flow to the dynamic brakes and using the known resistance of the dynamic brakes. These values could then be compared against the regenerative braking forces outlined in this study.

2.6.2 Central -South Zone Route Results

The results for the legs of the journey from origin to destination of the central – south zone route are shown on the map represented in figure 17.

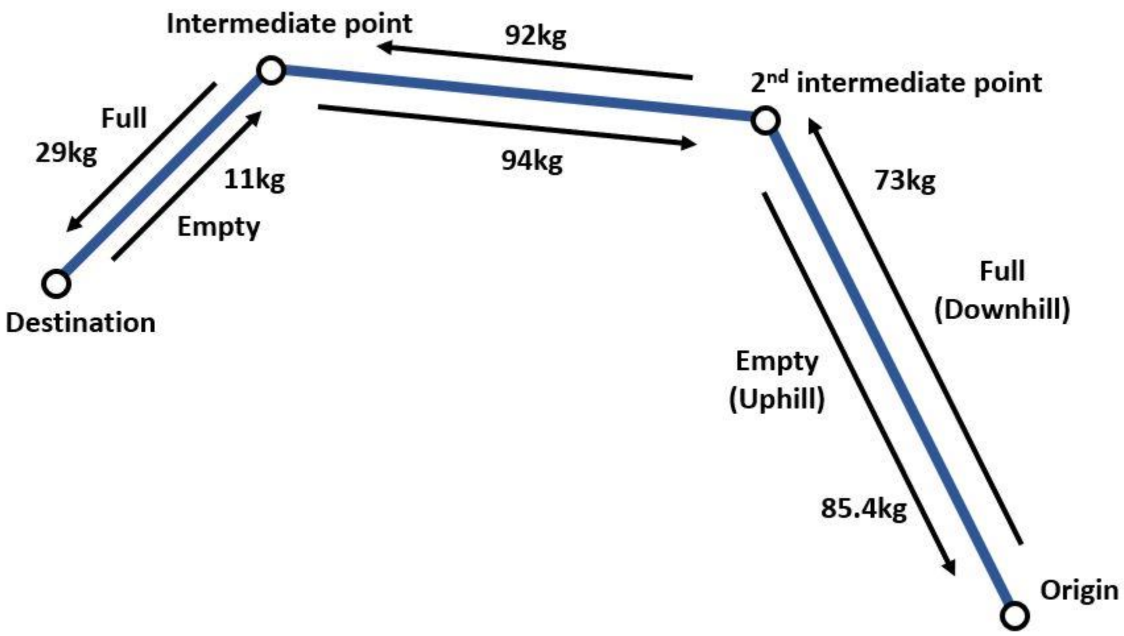

Figure 17: Origin to destination of the central – south zone route hydrogen consumption map (courtesy of VSTS)

It is immediately notable that the hydrogen consumption results for each direction between origin to destination of the central – south zone route are very similar. An inspection of the graphs shown in figures 18 and 19 for this section of route explains why this is the case.

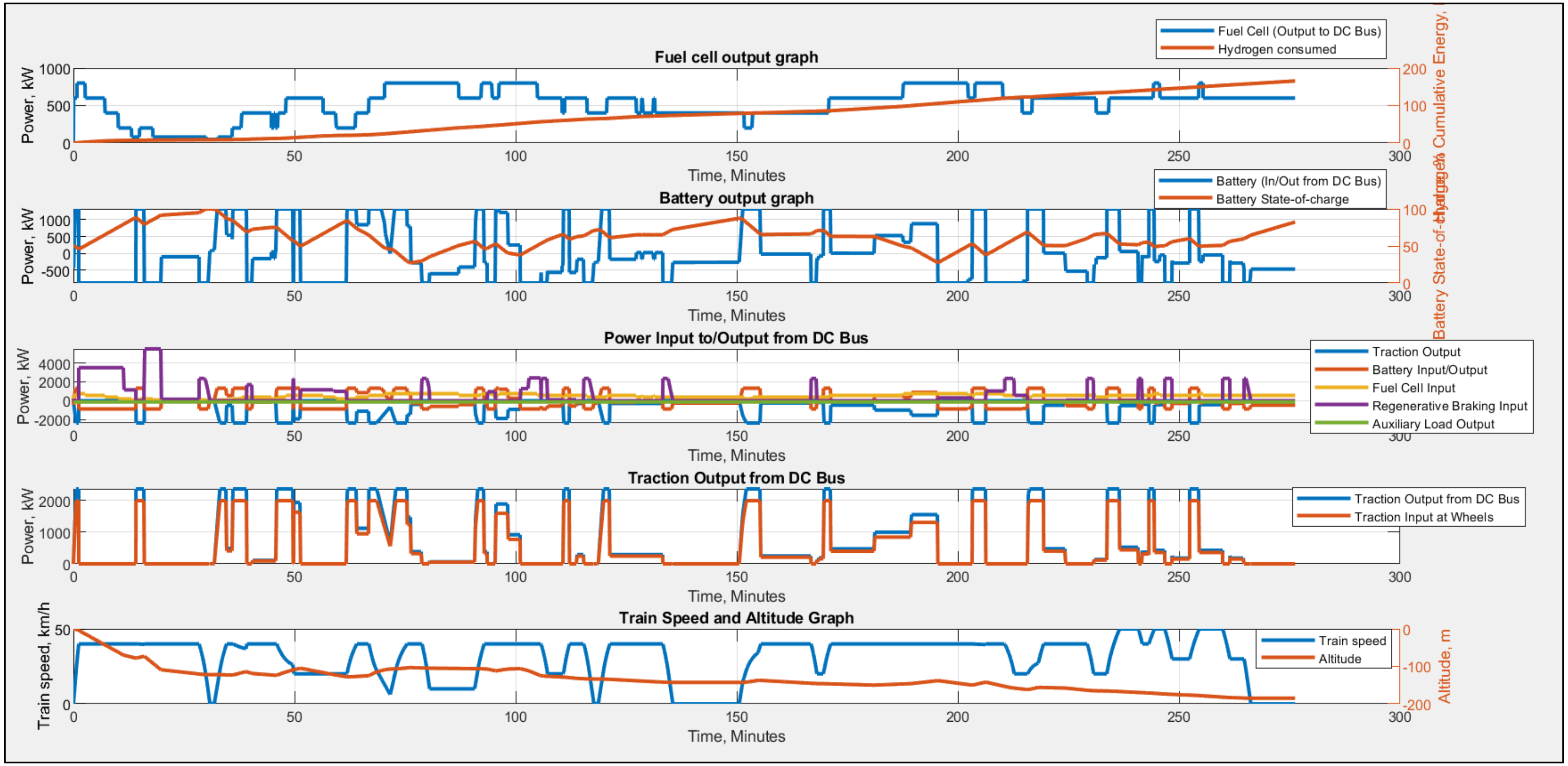

Figure 18: Downhill results (Origin to intermediate point of the central – south zone route fully laden, courtesy of VSTS)

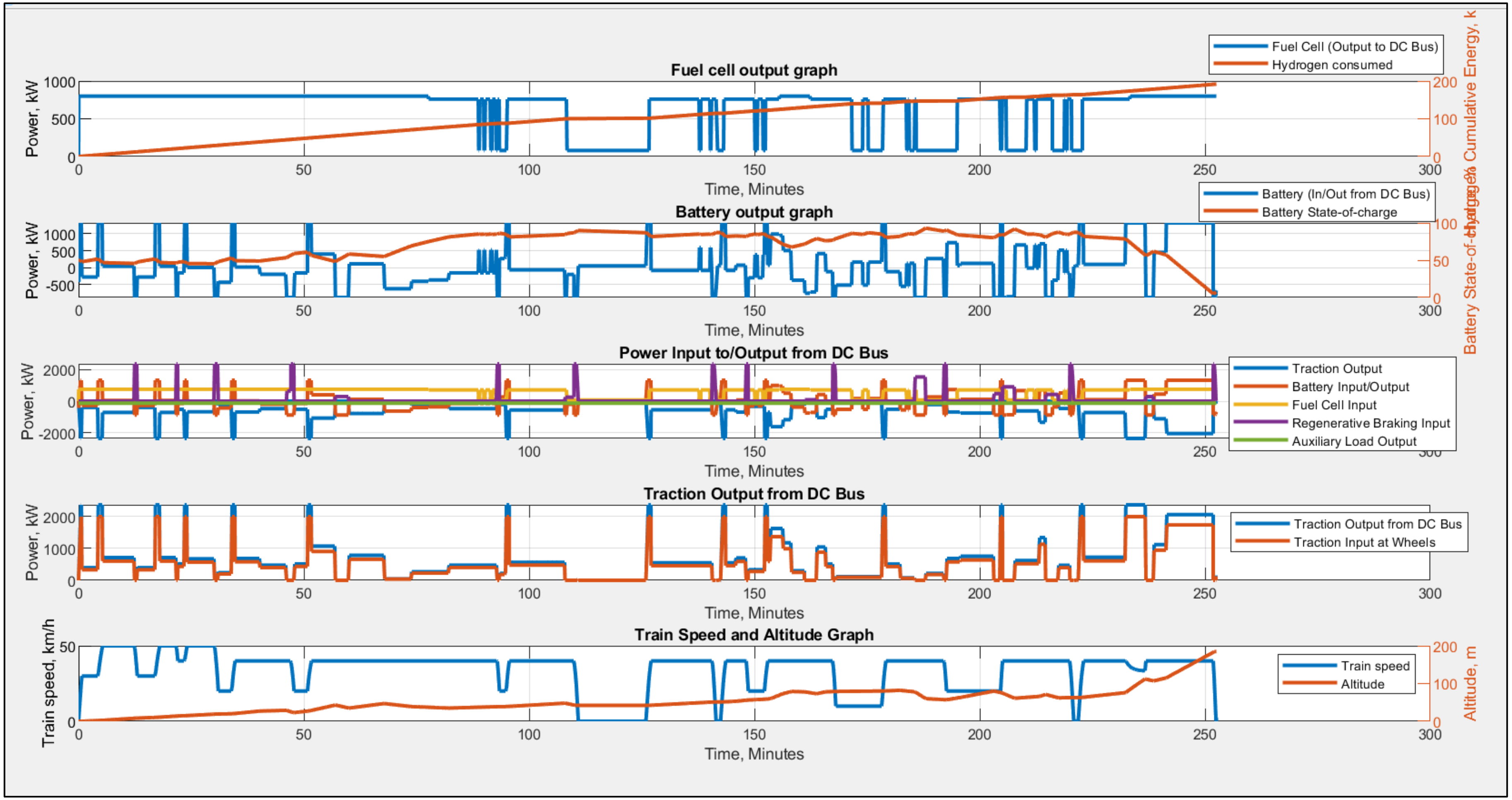

Figure 19: Uphill results (Intermediate point to origin of the central – south zone route unladen, courtesy of VSTS)

Figure 18 shows the downhill leg, and the empty return journey is shown in figure 19. It should be noted that the fuel cells spend most of their time at or just above half of the available power (800kW) on the downhill leg, whilst the fuel cells spend most of the journey at full output power during the uphill leg. The overall energy consumption on the initial part of the route (as the train is building speed) can be seen below in figures 20 and 21 overleaf.

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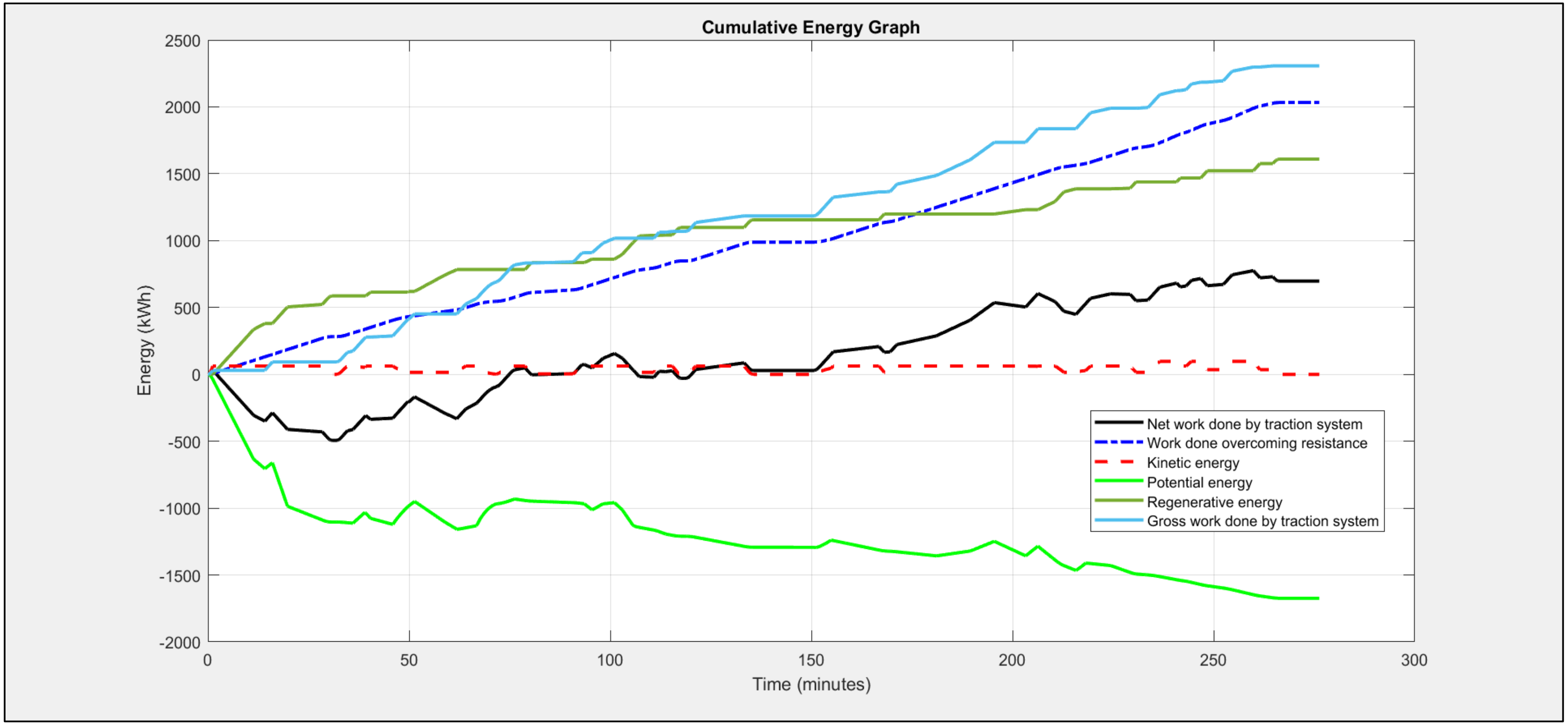

Figure 20: Origin to intermediate point of the central – south zone route energy graph (courtesy of VSTS)

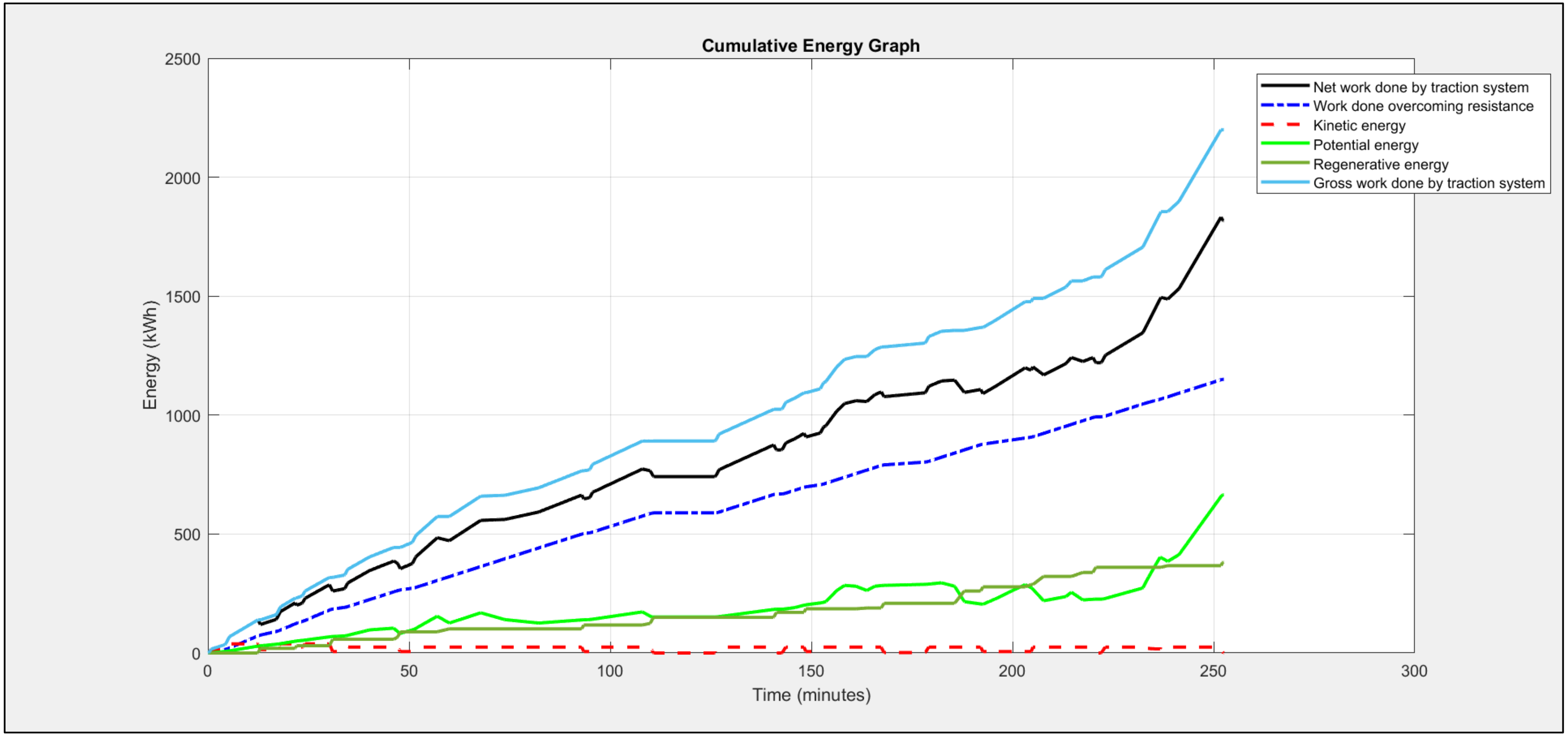

Figure 21: Intermediate point to origin of the central – south zone route energy graph (courtesy of VSTS)

As can be seen in figures 20 and 21, regenerative braking energy significantly reduces the required hydrogen consumption on the downhill leg.

As the section between intermediate point and destination of the central - south zone route is mostly flat, the hydrogen consumption for the full train is much higher than for the empty return trip as there are few opportunities for harvesting regenerative braking energy on the journey. This can be seen in the distance domain energy diagrams shown in figures 22 and 23. Note that whilst the energy traces are very similar, significantly more energy is expended on the full trip than on the empty return train.

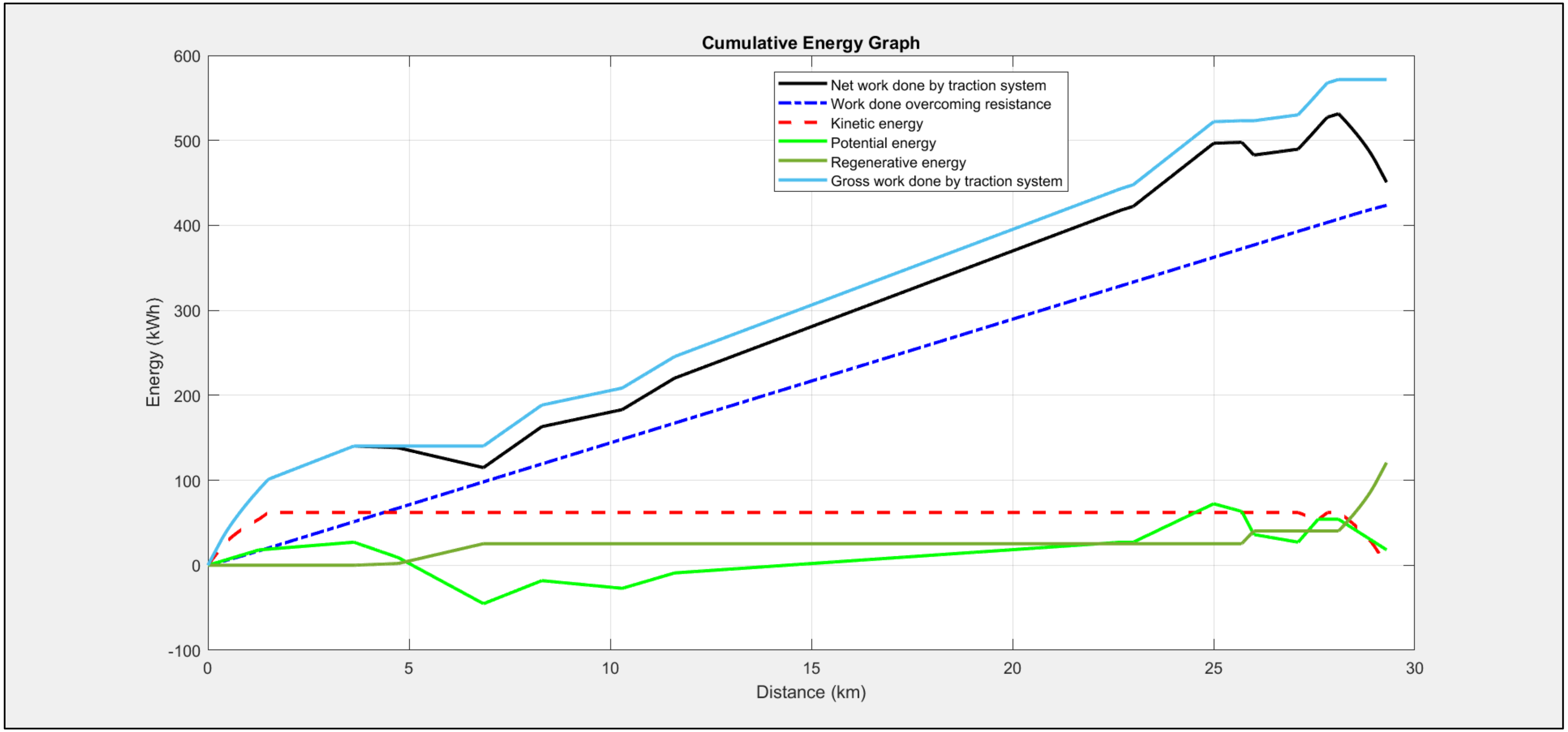

Figure 22: Intermediate point to destination of the central – south zone route energy graph (courtesy of VSTS)

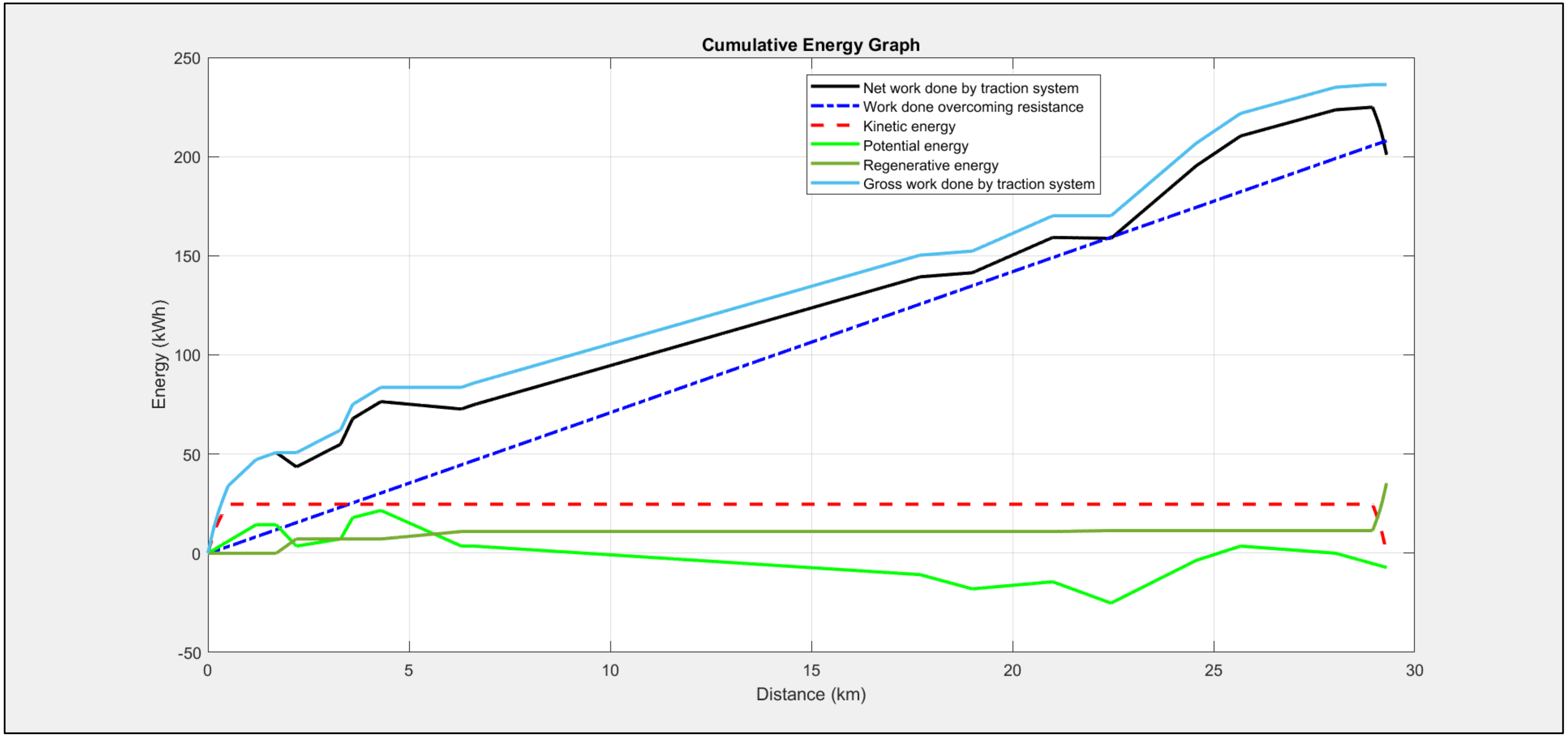

Figure 23: Destination to intermediate point of the central – south zone route energy graph (courtesy of VSTS)

3 BALANCING OPERATIONAL REQUIREMENTS AND PACKAGING

On completion of the simulations, a set of output data is generated which determines the minimum specification for the hydrogen-hybrid power train. Reviewing and manipulating this data allows the Engineering Team to identify equipment for the conversion and determine how it is housed in the locomotive or whether additional space is required beyond that already available.

The purpose of this section is to introduce the physical characteristics of the locomotives and establish a suitable combination of key components to fit within the given space. This then informs the foundations upon which a concept design can be discussed in the subsequent actions following the release of this report.

An assessment of available equipment has been made and is detailed in section 14 of this report.

3.1 PHYSICAL DESCRIPTION OF THE LOCOMOTIVES

The SD-39 and SD-40 locomotives are both North American style hood units. They have a single cab, positioned towards one end of the vehicle, with a short hood extending in front of the cab and a long hood situated behind the cab. For the rest of this report, the end of the locomotive with the short hood will be referred to as the “front” of the locomotive, and the end of the locomotive with the long hood will be referred to as the “back” or “rear” of the locomotive.

Superficially, the SD-39 and SD-40 are very similar. As stated previously, the primary difference between the two locomotives is the size of the prime mover (a 12-cylinder Type 645 engine in the SD-39 and a 16-cylinder Type 645 engine in the SD-40). There is, therefore, a disparity in power between the two classes. The comparative mass of each locomotive is converse to the power. The SD-39 weights 131t, whereas the more powerful SD-40 weights 120t.

From TRANSAP’s internal data, the prime mover equipment is in or under the long hood in both locomotives. It is therefore assumed that the equipment in this area, including engine, generators, compressors, and fuel tanks will be removed from within the long hood as part of a hydrogen conversion. Therefore, the traction equipment will be sited in this area in the concept design.

As there is only a toilet and sand storage in the short hood, it was decided that this space will not be used for any hydrogen traction equipment and will be left in its previous configuration, such that crew welfare facilities are retained.

As both locomotives share the same chassis and have almost entirely the same amount of bodywork, the concept hydrogen hybrid traction system that has been produced in this report would be equally applicable to either model of locomotive.

3.2 Key Metrics of The Locomotives

An assessment of the power, overall mass, and mass of key components within both types of locomotives is shown in table 2.

Table 2: TRANSAP locomotive key metrics (data courtesy of TRANSAP)

TRANSAP Locomotives		
Manufacturers Designation	SD39	SD40
Power (kW)	1725	2250
Mass (t)	131.5	120
Engine Mass (t)	12.8	16.5
Main Generator Mass (t)	7	7
Diesel Fuel Capacity (L)	5455	9092
Diesel Fuel Mass (t)	4.6	7.6
Mass Less Removed Equipment (t)	107.1	88.9
Mass of Removed Equipment (t)	24.4	31.1

Included in the table are figures for the mass of the engines, main generators and the volume and mass of diesel fuel carried by each type of locomotive. This data has been used to determine a baseline figure of the mass of the equipment that will be removed from the locomotives, to allow comparison between the predicted mass of the hydrogen-hybrid system and the mass of the equipment removed from the locomotive.

3.3 Benchmark Hydrogen-Hybrid Equipment Selection and Rationale

For this study, it was deemed appropriate for the configuration using the least equipment to successfully run on all routes to be established. Doing this means that all aspects of the vehicle and route requirements are met as a minimum by one system. This approach ensures that the system as described is also the most economical in the long-term as it will be simpler to maintain and more space efficient than developing multiple, different systems. Contingencies (explained in tables 11 & 12) are factored into the calculations behind the equipment selection to ensure the locomotives are guaranteed capable of meeting their specified requirements.

Since the 600kW fuel cell with 440kWh battery option was proven only to be suitable for the central zone route in a SD-39 locomotive, it could not be suitable for a train running in the central – south zone route. Therefore, the 800kW fuel cell with 440kWh battery option has been nominated for the benchmark concept design to ensure that all routes are operable by a SD-39 or SD-40 locomotive.

3.3.1 Benchmark Fuel Cell Selection

The fuel cell selected for use in the concept design is Ballard's FCmoveHD+ rooftop fuel cell. Whilst Vanguard have worked with many fuel cells produced by many different manufacturers, this fuel cell was selected as enough information is available open source from the manufacturer to produce a suitable concept. This model of fuel cell has been selected as a benchmark due to its physical characteristics being freely available (Ballard, 2022). Key information about the Ballard FCMoveHD+ can be found in table 3.

Table 3: Ballard FCMoveHD+ key technical information (data courtesy of Ballard Power Systems)

Net System Power	100 kW
Idle Power	9 kW
Dimensions (l x w x h) mm	1056 x 630 x 650
Weight	260 kg
Certifications	ISO 6469-2:20091 ISO 6469-3:20111 ISO 23273:20131
Operating Temperature	-30°C – +50°C
Humidity Tolerance*	30-95% relative humidity

*based on models similar to the FCmoveHD+

Figure 24: Ballard FCmoveHD+ 100kW (courtesy of Ballard Power Systems)

3.3.2 Fuel Cell Benchmark Battery Selection

The benchmark simulations determined that a battery capacity of 440kWh is suitable for use in SD-39 and SD-40 locomotives. This would entail a battery with twice the capacity of that fitted to HydroFLEX 2. The battery in question uses battery modules produced by Hoppecke and was integrated into the vehicle by Gemini Rail.

Figure 25: HydroFLEX 2 Departing Glasgow During COP26. The 220kWh Battery is located beneath this carriage (courtesy of VSTS)

As the dimensions and mass of the lithium-ion 220kWh battery fitted to HydroFLEX 2 are known to the authors, it is considered that this would form a suitable placeholder for a concept level design. The choice of this battery in this report has been determined as this is a benchmarking exercise. Other suitable batteries will be detailed in section 14.

Table 4: Battery module specifications (data courtesy of VSTS)

Equipment	L (mm)	W (mm)	H (mm)	Mass (kg)
440 kWh Energy Storage System	4400	2600	730	3230
Battery Module Converter	2090	880	610	640
Battery Temperature Management System	1310	1020	310	150

3.3.3 Quantity of Hydrogen Storage Required

The hydrogen storage requirements for each locomotive can be determined by analysing the results of the route simulations. The results from Section 2's assessment of hydrogen requirements is reproduced below in figure 26.

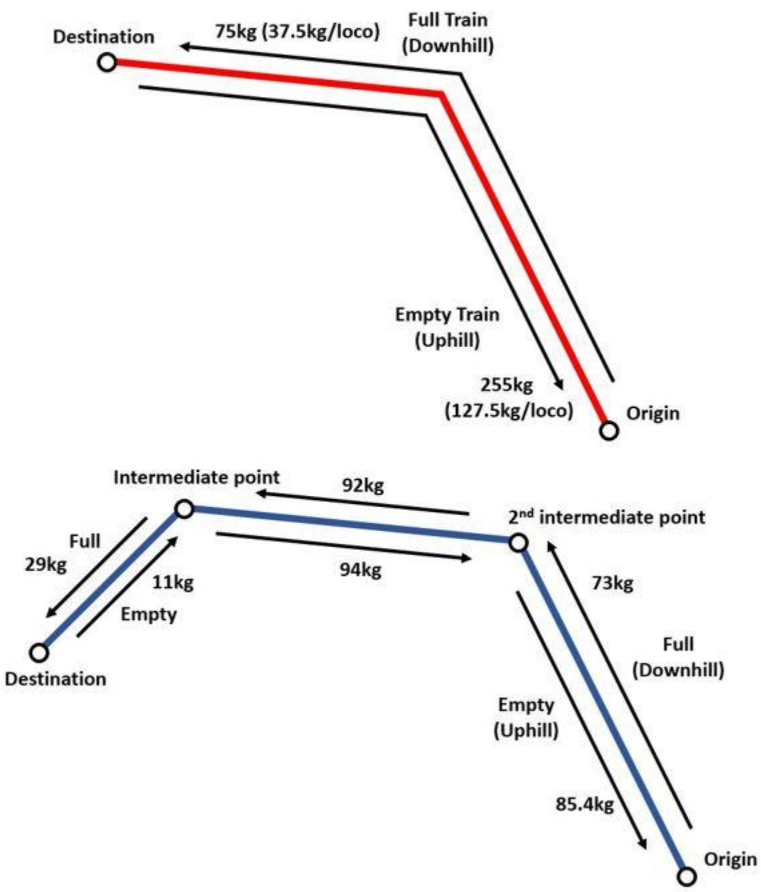

Figure 26: Route Map Comparison (courtesy of VSTS)

Communications with TRANSAP have detailed that the fuelling point for the central zone route is at origin and the fuelling location for the central – south zone route is at second intermediate point. The round-trip fuelling requirements per locomotive are as follows:

Table 5: Hydrogen consumption table (courtesy of VSTS)

Round Trip Hydrogen Consumption	
Origin to destination of the central zone route	165 kg
Second intermediate point to origin of the central – south zone route	158.4 kg
Second intermediate point to destination of the central – south zone route	226 kg

3.3.4 Hydrogen Storage Technology and Equipment Selection

The hydrogen storage technology that will be considered is compressed hydrogen tanks that are able to store hydrogen at a normal working pressure of 350 bar. These tanks are commonly used in hydrogen powered buses. Therefore, this type of tank is produced in large numbers and so is widely available.

It should be noted that whilst the normal working pressure of the tanks selected is 350 bar, the pressure in the tanks will, in practice, exceed this during fueling due to the temperature effects of the rapid compression of gas within the cylinder. The tanks used for this study are rated only for use at a maximum of 350 bar. Advancements in technology mean that 700 bar tanks may soon be a viable option for this application, however, at the time of writing, 350 bar is the accepted norm for railway use.

Figure 27: Luxfer Type 3 hydrogen tanks mounted to the roof of a bus before being harvested for the HydroShunter project. Note, the frost on the first and third hydrogen tanks has formed because they have just been vented rapidly. (courtesy of VSTS)

Four different types of compressed hydrogen tank exist. These are listed in table 6:

Table 6: Type 1-4 characteristics (courtesy of VSTS)

Type	Materials	Features	Application	Typical Pressure (Bar)	Gravimetric density (wt%)
I	All-metal construction	Heavy, internal corrosion	For industrial, not suited for vehicular use	175-200	1-1.7
II	All-metal hoop-wrapped composite cylinders	Heavy, short life due to internal corrosion	Not suited for vehicular use	263-300	2.1
III	Fully wrapped composite cylinders with metallic liners	Lightness, high burst pressure, no permeation, galvanic corrosion between liner and fibre	Suited for vehicular use. 25-75% mass gain over I and II	350-700	More than 5
IV	All-composite construction	Lightness, lower burst pressure. Permeation through liner, high durability against repeated charging. Simple manufacturability	Longer life than Type III (no creep fatigue)	350-700	More than 5

Only type 3 and type 4 tanks are suitable for use on land based mobile machinery. Therefore, both types will be investigated in the concept design.

The two types of tanks that will be modelled are the Luxfer W322N type III tanks and the Hexagon Purus Model G type IV tanks. Information on both types of tanks is available online (Luxfer, 2022) (Hexagon Purus, 2022).

Table 7: Comparison of Type 3 and 4 tanks (courtesy of VSTS)

Comparison of Type III and IV Tanks		
Tank Name	**Luxfer W322N**	**Hexagon Purus Model G**
Tank Type	III	IV
Tank Length (mm)	3165	3190
Tank Diameter (mm)	415	430
Hydrogen Capacity (kg)	7.8	7.5
Tank Liquid Volume (l)	322	312
Empty Tank Weight (kg)	141	101
Combined Tank and Fuel Weight (kg)	148.8	108.5
Weight Ratio (%)	5.53	7.43

For benchmarking, Model G tanks will be used in the concept design layout as the benchmark type of tank as it is slightly larger than the W322 type III tank. The mass implications of using each of the types of tanks will be discussed separately.

An explanation of why the larger tanks have been selected for this study is outlined in section 3.4.2.

3.4 HYDROGEN LOCOMOTIVE CONCEPT

A concept level design has been produced by Vanguard, shown in figure 28.

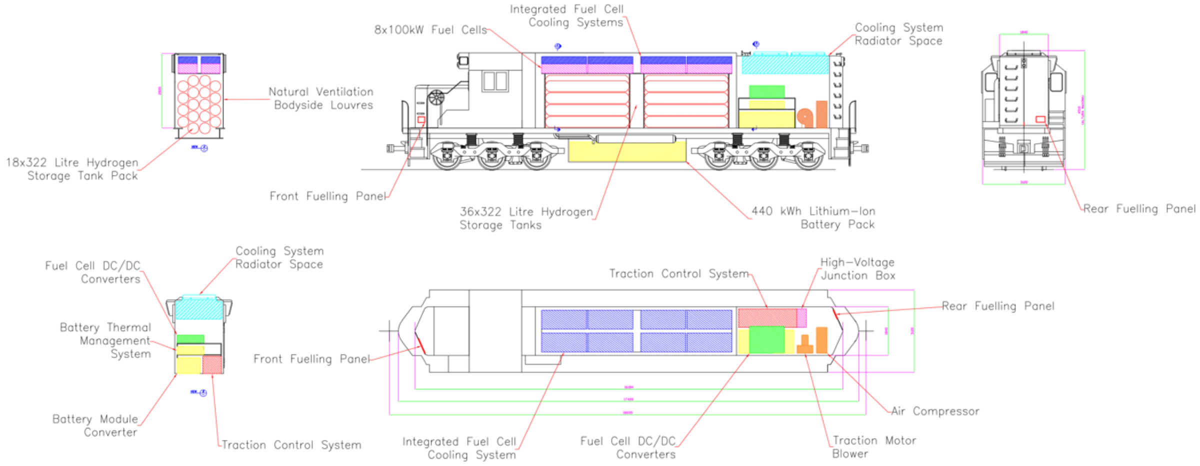

Figure 28: Concept design for hydrogen powered SD-39/SD-40 locomotives (see appendix item G for full size image, courtesy of VSTS)

3.4.1 TECHNICAL EXPLANATION OF CONCEPT DESIGN

The outlined hydrogen-hybrid traction system concept uses:

- 8x100kW fuel cells
- 1x 440kWh traction battery
- 36x 322L hydrogen storage tanks

Space claims for other ancillary equipment is modelled and labelled on the drawing at the end of the rear hood. This includes the air compressor, associated air tanks and traction motor blower.

It should be noted that the existing compressor onboard the locomotive is engine driven. As the engine is being removed, an alternative solution must be found. It is suggested that an electrically driven solution is used as a replacement, either a new electric compressor or driving the existing compressor with an electric motor.

As can be seen, following the removal of the engine, main generator, and other ancillary equipment, most of the newly free space has been claimed by two rafts of hydrogen storage tanks, comprising 18 tanks each, for a total of 36 hydrogen tanks. Fuel cells and fuel cell auxiliaries are located at the top of this space. The hydrogen tanks are located as close to the center of the locomotive as possible for crashworthiness reasons. This will allow either end of the locomotive to crumple to the maximum amount possible in a collision before compromising the integrity of the tanks and releasing high-pressure hydrogen.

To allow enough space to locate the fuel cells above the tanks, the dynamic brake equipment has been relocated to where the engine cooling radiators are on an unmodified locomotive. It is deemed necessary to retain the braking resistors as they will allow dynamic braking to continue if the batteries become full of energy from regenerative braking and thus are no longer receptive to the energy produced. However, as the braking resistors are also likely to get hot, it is far safer to relocate them away from any potential hydrogen venting zones to lower any risk of ignition in this way.

The space beneath the frames where the fuel tank is located on the original locomotive has been used to accommodate the traction batteries. There is enough space in this area to fit the benchmark 440kWh battery.

SAE J2600 standard fuelling receptacles are to be fitted at either end of the locomotive. This will allow for the receptacles to be accessed by fuelling equipment located on either side of the track by passing the fuelling nozzle across the gap over the center of the vehicle, as well as allowing fuelling from wagons that the locomotive is coupled to. The SAE J2600 standard is a widely used, and globally recognised technical standard, applying to fuelling connectors, nozzles, and receptacles for hydrogen vehicles with onboard gaseous storage. Compliance with this standard is recommended for any hydrogen railway vehicle, ensuring compatibly and providing additional passive safety measures during refuelling operations. Given a maximum working fuel pressure of 350 bar, the J2600 H35 pressure class is applicable.

It should be noted that any non-hydrogen specific equipment (such as pneumatic hardware) has been modelled in this report to offer like-for-like operation of the locomotive in it's current state following the conversion. Additional equipment can be added for redundancy if deemed necessary at the detailed design stage.

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3.4.2 Concept Design Mass Calculations

The mass of equipment to be added can be found in Table 8.

Table 8: Mass of hydrogen hybrid traction systems (courtesy of VSTS)

Mass of Hydrogen-Hybrid Traction System		
Type of Hydrogen Tank	3	4
Individual Fuel Cell Mass (kg)	260	260
Traction Battery Mass (kg)	8030	8030
Individual Tank Mass (kg)	148	101
Number of Fuel Cells	8	8
Number of Traction Batteries	1	1
Number of Tanks	36	36
Mass of Fuel Cells (kg)	2080	2080
Mass of Traction Battery (kg)	8030	8030
Mass of Tanks (kg)	5328	3636
Mass Allowance for FC Auxiliaries (kg)	*2080*	*2080*
Mass Allowance for Tank Frames (kg)	*5328*	*3636*
Total Mass of Equipment Added (kg)	22846	19462
Total Mass of Equipment Added (t)	22.8	19.5

The mass of the traction battery includes the framework and packaging. A 100% mass allowance has been added to the mass of the fuel cell, auxiliaries, and tanks to represent the supporting framework. The resulting masses are 22.8t for a hydrogen-hybrid traction system equipped with type 3 tanks and of 19.5t for a traction system fitted with type 4 tanks.

The mass figures for traction systems fitted with both types of tanks are shown in relation to the mass calculations conducted in a previous section in tables 9 and 10.

Table 9: Hydrogen hybrid locomotive mass calculations (Type 3 Tanks, courtesy of VSTS)

Hydrogen-Hybrid Locomotive Mass Calculations (Type 3)		
Type	2300	3000
Original Mass (t)	131.5	120
Mass Less Removed Equipment (t)	107	88.9
Mass of Type 3 Traction System (t)	22.8	22.8
Mass of Hydrogen Locomotive (Type 3) (t)	130	111.7
Mass Difference to Original Locomotive (t)	-1.6	-8.3
Mass Difference to 150t Allowance (t)	-20	-38.3

Table 10: Hydrogen hybrid mass calculations (Type 4 Tanks, courtesy of VSTS)

Hydrogen-Hybrid Locomotive Mass Calculations (Type 4)		
Type	2300	3000
Original Mass (t)	131.5	120
Mass Less Removed Equipment (t)	107	88.9
Mass of Type 4 Traction System (t)	19.5	19.5
Mass of Hydrogen Locomotive (Type 4) (t)	127	108.5
Mass Difference to Original Locomotive (t)	-4.9	-11.5
Mass Difference to 150t Allowance (t)	-23.4	-41.5

When compared with the original mass of the locomotives, both traction systems come in lighter than the original mass. This ranges from only 1.6t lighter than original for a type 3 conversion of a SD-39 locomotive to 11.5t lighter than original for a type 4 conversion of a SD-40 locomotive. Therefore, ballasting the locomotive might be required to return a hydrogen-hybrid conversion to its original mass.

Given the need to retain as much mass within the locomotive as possible for maximum adhesion to the rail, it is recommended that type 3 tanks be used in a locomotive conversion as the metal-based type 3 tanks are heavier than the composite based type 4 tanks.

Both locomotive types end up significantly below the 150t mass limit of the central zone route. As such, a different configuration of hydrogen-hybrid powertrain would be required to increase the available adhesive mass of a locomotive for use on this route.

3.5 Hydrogen Storage Concept Considerations and Operational Requirements

As mentioned, the locomotive concept features 36 type 3 or type 4 tanks. This results in an overall hydrogen capacity of 280.8kg using type 3 tanks, or 270kg when using type 4 tanks. Considering the need for a minimum amount of pressure to be held in the tanks to operate the fuel cells, this results in there being approximately 264kg of usable hydrogen available from a type 3 based locomotive and 255kg of usable hydrogen in a type 4 tank-based locomotive.

As mentioned, the max round trip requirements for the central zone line were 165kg per SD-39 locomotive and 226kg per full round trip from second intermediate point of central – south zone to destination using a SD-40. Therefore, it is theoretically possible for an adequate amount of hydrogen to be stored in the outline of a SD-39 or SD-40 locomotive using either type 3 or 4 tanks whilst still allowing for a small amount of shunting and other operations at the train's destination.

4 MECHANICAL AND ELECTRICAL REQUIREMENTS

This section will assume that the locomotives are fully fueled before each mainline trip. This assumption will then be used to inform fuel requirements for each fuelling point and thus determine the hydrogen supply infrastructure that will be needed to support operations of hydrogen trains on both routes analysed.

4.1 ROUTE PERFORMANCE REQUIREMENTS

4.1.1 CENTRAL ZONE ROUTE

It has already been established that the central zone route can feasibly be operated with a locomotive fitted with a hydrogen fuel cell hybrid system with 600 kW of fuel cell power, 440 kWh of battery storage and 11,592 litres of storage for 277 kgs of hydrogen. As described in section 3, the fuel cell stacks and associated cooling systems will be mounted above the hydrogen storage tank assemblies, with the traction battery mounted on the locomotive underframe.

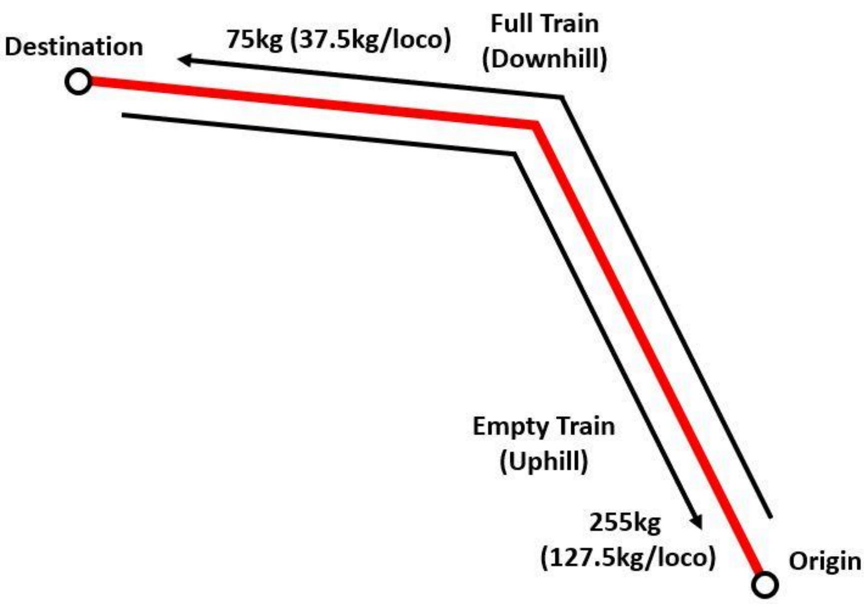

Figure 29: Simulated hydrogen fuel consumption for each route section (courtesy of VSTS)

Figure 29 shows the locomotive hydrogen consumption for this route, with consumption figures listed for representative freight flows in each direction.

Data has been provided in table 11 below to include a 50% contingency supply for any additional movements outside of the routes themselves (such as shunting and other depot-based activities). An additional 15kg allocation has also been added to prevent fuel cell stack starvation (the fuel cell back-pressure should not fall below 20 bar).

Table 11: Summary of hydrogen requirements – Central zone route (courtesy of VSTS)

Route	H2 Consumed on route per loco (kgs)	Contingency H2 Supply at 50% per loco (kgs)	Additional H2 to prevent fuel cell starvation per loco (kgs)	Total H2 required per loco (kgs)
Origin → Destination (return)	165	82.5	15	**262.5**

262.5 kg of onboard hydrogen storage per locomotive can be achieved in the space available. Operationally, this configuration would complete a round trip without refuelling, reducing operational and logistical complexity, and significantly reducing cost, as only one refuelling depot would be required.

4.1.2 Central – South Zone Route

It has already been established that the intermediate point to origin of the central – south zone route can feasibly be operated with a locomotive fitted with a hydrogen fuel cell - hybrid system with 800 kW of fuel cell power and 440 kWh of battery storage.

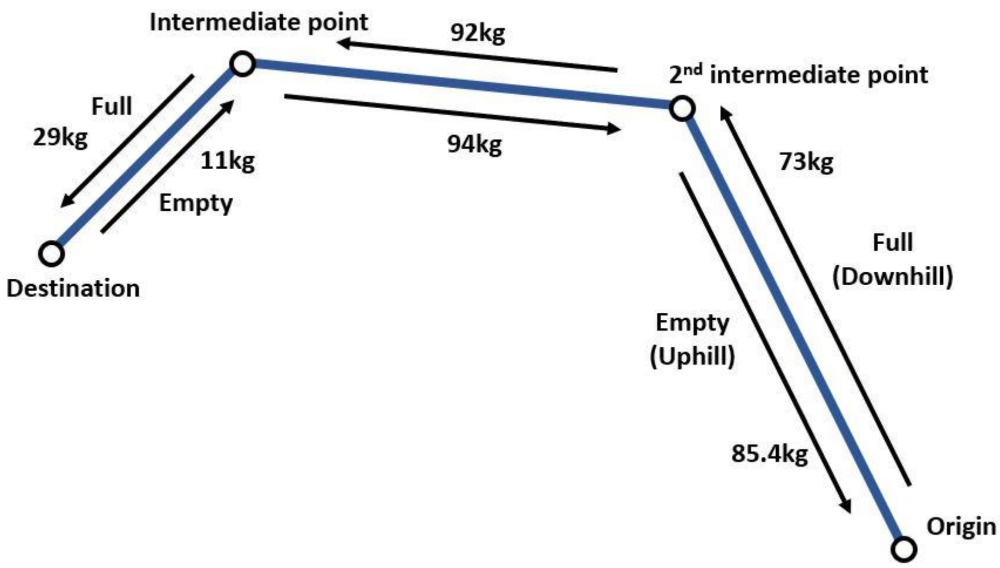

Figure 30: Simulated hydrogen fuel consumption for each route section (courtesy of VSTS)

Figure 30 shows the locomotive hydrogen consumption for this route, with consumption figures listed for representative freight flows in each direction.

Data has been provided in table 12 below to include a 50% contingency supply for any additional movements outside of the routes themselves (such as shunting and other depot-based activities). An additional 15kg allocation has also been added to prevent fuel cell stack starvation (the fuel cell back-pressure should not fall below 20 bar).

Table 12: Summary of hydrogen requirements – central – south zone route (courtesy of VSTS)

Route	H2 Consumed on route per loco (kgs)	Contingency H2 Supply at 50% per loco (kgs)	Additional H2 to prevent fuel cell starvation per loco (kgs)	Total H2 required per loco (kgs)
Second intermediate point → Origin return trip	158.4	79.2	15	**252.6**
Second intermediate point →Destination single trip	121	60.5	15	**196.5**
Destination → Second intermediate point single trip	105	52.5	15	**172.5**

Considering refuelling at destination and second intermediate point, the maximum hydrogen storage requirement for the intermediate point to origin route is 252.6 kg per locomotive.

This arrangement requires two different refuelling sites on the route and would likely require an adjustment in the railway timetable to allow for locomotive refuelling time.

While the former method of railway operations involved refuelling locomotives at second intermediate point of the central – south zone, this is not possible with a gaseous hydrogen storage solution in the locomotive space available. However, the use of hydrogen storage tender, would allow the former method of operations to be maintained, refuelling only at second intermediate point of the central – south zone. The use of only one refuelling site would likely lead to an overall reduced system cost and would retain existing timetables and avoid operational complexity. However, for the purposes of the electrical and mechanical integration of the hydrogen - hybrid system into the locomotive, it is assumed that only 252 kg of hydrogen storage capacity will be provided, requiring additional refuelling.

4.2 Major Component Requirements

Table 13 provides they key requirements for the locomotives on both routes studied. These figures are then used in section 14, where a supply chain study is undertaken to determine how these engineering requirements can best be achieved using products and components currently available commercially.

Table 13: Comparison of key requirements for each studied route (courtesy of VSTS)

	Central zone origin → Destination	Central – south zone origin → Intermediate point
Hybrid Traction Battery Capacity	440 kWh	440 kWh
Hydrogen Storage Capacity	262.5 kg	252.6 kg
Fuel Cell Power Required	600 kW	800 kW

This supply chain study produces a high-level bill of materials, with rough order of magnitude costs, for major components. Given the similarity in the hydrogen storage requirements between the locomotives for each route option (262.5 kg, 252,6 kg), it is suggested that a single hydrogen storage solution is found across both locomotive options. This solution can be found in sections 5 and 14.

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5 MECHANICAL INTEGRATION

The success of converting any vehicle to run on an alternative fuel relies heavily on how the new components replacing the old ones interface with the those which need to remain. This section focusses on the mechanical integration of the new system into the existing locomotives. It describes the interfaces required from the mechanical elements of the hydrogen hybrid power system.

Figure 31 provides a high-level overview of how the key elements of a hydrogen hybrid traction system could be packaged within the SD-40 locomotive. The diesel internal combustion engine, alternator, diesel fuel tank, traction motor blower, oil systems and fuel systems have been removed to allow the new equipment to be fitted. The short hood, containing the lavatory, has not been modified. The overall approach to this exercise has been to retain as much existing equipment in the locomotive as is possible. This reduces costs, but also retains key operating characteristics of the existing locomotive, such as driver visibility in both directions, a walkway on both sides of the locomotive and the overall locomotive weight.

In the long hood, a subframe used to mount the gaseous hydrogen storage tanks, hydrogen fuel cells and associated cooling will be positioned in the approximate location of the internal combustion engine. A key requirement of hydrogen systems is that they are positioned in a compartment and be physically separated from any equipment not essentially related to hydrogen systems, this is so that the hydrogen storage compartment can be adequately ventilated and free from any sources of ignition. For this reason, it has been necessary to relocate the dynamic braking system towards the rear of the locomotive. While it is understood that the relocation of this unit will incur increased design and manufacturing complexity, significantly less hydrogen storage space would be available if this was not done.

It is also essential that modifications are made to the bodysides around the hydrogen compartment. Hydrogen systems are designed around the philosophy of being ventilated as a passive safety measure. Therefore, the hydrogen compartment should feature louvres in the walls, as well as forced ventilation fans that operate in the event of a hydrogen leak being detected.

The hybrid traction battery will be mounted on the underframe of the locomotive, in the space previously occupied by the diesel fuel tank. It will be mounted using a fabricated steel frame.

Previously, both the traction motor blower fan, and the air compressor for the braking system were mechanically driven directly from the internal combustion engine. Given the engine is being removed, alternatives must be sourced. It is proposed that an electrically driven brake compressor, such as those used on electric and modern diesel locomotives, is used. A traction motor blower fan and motor will be used and selected such that the cooling effect is matched to the previous equipment. Both these components will be electrically powered and relocated towards the rear of the locomotive.

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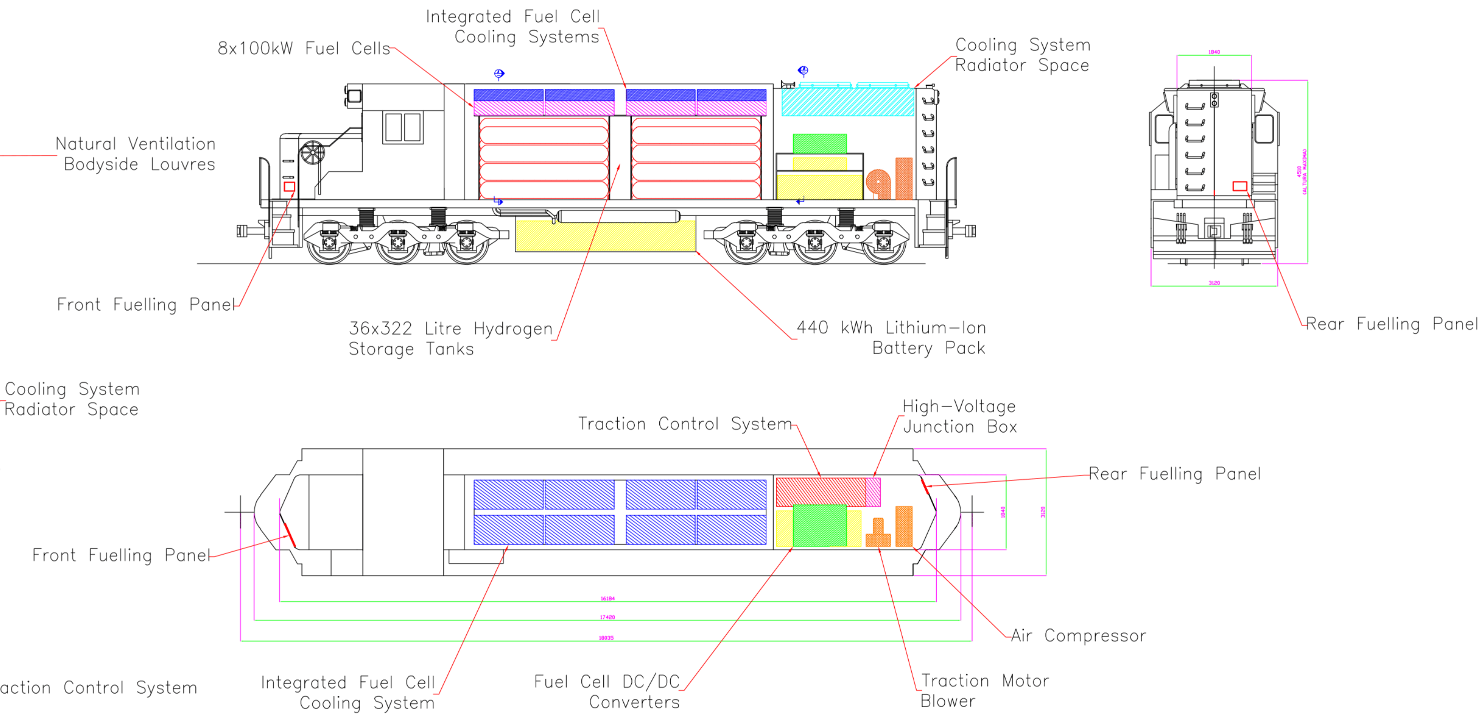
Figure 31: 2300/3000 Hydrogen Hybrid Locomotive (courtesy of VSTS)

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH



5.1 Key Interfaces

For the purposes of integrating the required elements of the hydrogen hybrid system into the 2300/3000 locomotive, it has been assumed that the major components have been selected based on the supply chain study recommendations (see section 14). These major components are 7.79 kg of Hydrogen at 350 bar gaseous hydrogen storage tanks, a 440 kWh lithium-ion battery pack and 100kW fuel cell stacks.

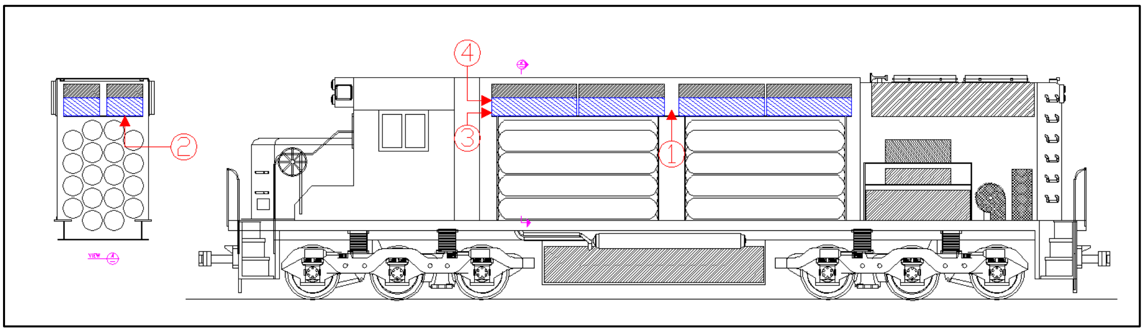


Figure 32: Key mechanical interfaces into the hydrogen fuel stacks (courtesy of VSTS)

Figure 32 shows the location of mechanical interfaces involved in the integration of the hydrogen fuel cell stacks:

Interface 1
Gaseous hydrogen fuel is supplied to the fuel cell stacks at a pressure of 8 bar. The fuel cells mechanically interface with the hydrogen storage system via stainless steel pipework, and various fittings and valves as bar of the hydrogen system. The hydrogen is regulated down from a pressure of 350 bar to the fuel supply pressure (8 bar).
Interface 2
The fuel cells are mechanically mounted to the hydrogen systems sub-frame within the locomotive body. It is likely that there will be a requirement for anti-vibration mounts between the frame and the fuel cell module.
Interface 3
Coolant must be constantly supplied to the fuel cell stack when in operation, with the use of a coolant pipe. This coolant will be provided at a target temperature from the fuel cell cooling modules (containing radiators and fans), which are mounted above the fuel cell modules.
Interface 4
Coolant must be constantly removed from the fuel cell stacks when in operation. This is

achieved using a coolant pipe, completing the coolant circuit.

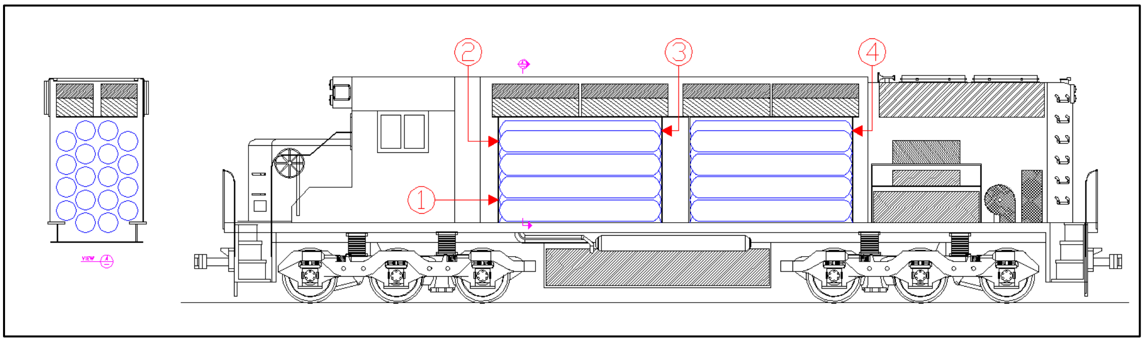


Figure 33: Key mechanical interfaces into the hydrogen storage tanks (courtesy of VSTS)

Figure 33 shows the key mechanical interfaces involved in the integration of the gaseous hydrogen storage tanks. The hydrogen storage tanks are fixed to a sub-frame within the locomotive structure, with each tank supported at each end. All fuel connections are also made at the tank end. This sub-frame should be designed and tested to various load cases, to ensure structural integrity is preserved in a crash or collision event. This is particularly relevant where the integrity of hydrogen storage cylinders and hydrogen pipework are critical in a collision or crash event.

The key mechanical interfaces involved in the integration of the hydrogen tanks are:

Interface 1
During refuelling, gaseous hydrogen is supplied to the tanks from one of two locomotive refuelling panels. Hydrogen supplied through the receptacle into a high-pressure fuelling line, through a check valve and coalescing filter to remove moisture and oils from the hydrogen. The high-pressure fuelling line is then connected to a tank end valve manifold.
Interface 2
Thermal Pressure Relief Devices (TPRDs) are fitted on the end of each hydrogen storage tank. In the event that the temperature around the TPRD rises above a setpoint (i.e. in the event of a fire), the TPRD opens and vents hydrogen to atmosphere. To facilitate this, the TPRDs on each end of every hydrogen storage has pipework directed upwards, out the roof of the locomotive.
Interface 3
For hydrogen to be fed towards the fuel cell stack modules, there is a fuel line between the storage tank end valves. Fuel is regulated down to a pressure of 8 bar in this fuel supply line,

then fed into the tanks via the tank end valve manifold.
Interface 4
The tanks are mechanically mounted to frames at each end. These frames are, in turn, mechanically mounted to the chassis frames of the locomotive. It should also be noted that, as per figure 31, tanks extend into the space previously occupied by the internal combustion engine sump. Therefore, the tank supporting frame should be designed to facilitate this.

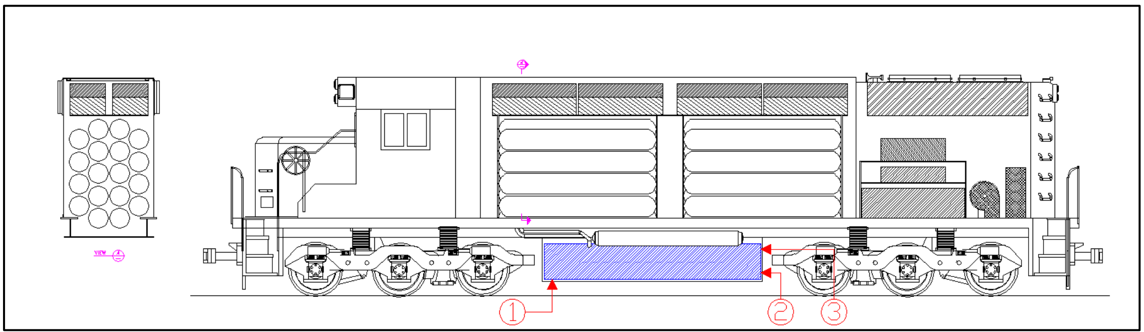


Figure 34: Key mechanical interfaces into the hybrid traction battery (courtesy of VSTS)

Figure 34 shows the locations of key mechanical interfaces involved in the integration of the hybrid traction battery:

Interface 1
The battery will be mechanically mounted to the underframe of the locomotive, in the space previously occupied by the diesel fuel tank. The practice of suspending traction batteries on the underframe of trains is an increasingly common and proven method.
Interface 2
The battery pack will be connected to the Battery Thermal Management System, BTMS, via connections for coolant flow. The BTMS is located within the body of the locomotive (see figure 31), and therefore coolant connections are required. This represents the mechanical connection for a coolant pipe delivering coolant to the battery module.
Interface 3
This represents the coolant pipe of the return circuit, delivering coolant from the battery module to the BTMS

6 ELECTRICAL INTEGRATION

Similar to the mechanical components, all electrical systems remaining in the locomotives must interface correctly with those of the new hydrogen-hybrid powertrain.

This section will review the current electrical configuration of the SD-39 and SD-40 locomotives and, based on that review, an electrical concept which is theoretically suitable for conversion to operation using a hydrogen-hybrid power system can be drafted.

The SD-40 locomotive will be used as the example throughout this section. The SD-39 is similar in terms of electrical equipment therefore solutions for the SD-40 will, subject to future detailed inspections, be compatible with the SD-39 also.

6.1 EXISTING ELECTRICAL SYSTEMS SUMMARY

The SD-40 is a 2238kW diesel-electric locomotive with 6 model D77 DC series wound axle hung traction motors driving 6 pairs of wheels. There is a main generator, (model AR10 – D14), consisting of a traction alternator (model AR10) with rectified output and a companion alternator (model D14). There is also an auxiliary Generator.” (© SD40-2 Operator's Manual, 5th Edition, 1978).

Power from the diesel engine is applied to the main generator. The DC output of the traction alternator with integral rectifier assembly is transmitted to the traction motors by means of heavy-duty power contactors and gang operated switchgear. The companion alternator drives the traction alternator field windings through a controlled rectifier, so that the power output of the main generator is maintained by varying the level of excitation current in the traction alternator field windings. The companion alternator also provides three phase AC power for the radiator blower motors, the filter blower motor and various control circuits. The rotor field of the companion alternator is excited by low voltage current which it receives from the auxiliary generator. (© SD40-2 Locomotive Service Manual).

The DC auxiliary generator delivers nominally 74 volts DC for control circuits, battery charging, lighting, and companion alternator rotor field. The auxiliary generator output is regulated to a stable voltage independent of engine speed, which varies according to required output power. The locomotive is equipped basically with the 10kW auxiliary generator, but the power demands of special equipment may require the use of an 18kW or 24kW three phase alternator with full wave rectifier assembly to obtain the 74V DC.” The regulation of the 10kW DC generator output voltage is achieved by varying the field excitation of the auxiliary generator using module VR10. If an 18KW or 24kW alternator with rectifier is required, then the output of the alternator is maintained to provide a rectified voltage of 74 volts DC using module VR 13 to adjust the alternator field current. (© SD40-2 Locomotive Service Manual).

The peak output voltage of the main generator is 1250V and the peak current is 4200A. These do not occur simultaneously (© SD40-2 Locomotive Service Manual).

The throttle handle has nine detent positions: IDLE and 1 through 8 plus a STOP position. It is moved from 1 to 8 to increase engine speed and hence power.” (© SD40-2 Locomotive Service Manual).

At low locomotive speeds, the traction motors are connected to the traction generator in three parallel strings of two traction motors in series. Transition occurs at higher speeds to connect the traction motors in full parallel” (© SD40-2 Locomotive Service Manual).

For dynamic braking, the traction motor fields are connected in series with the main generator output and the motor armatures are connected to heat dissipating resistor grids and fans. The braking grids are cooled by an exhaust blower to prevent overheating. The blower motor is connected across a portion of one braking grid.” (© SD40-2 Locomotive Service Manual). It is important to note that this type of braking is normally described as rheostatic braking, to be distinguished from regenerative braking, which the 3000 locomotive does not provide.

The dynamic brake handle has ten detent positions: Off, Setup and 1 through 8. (© SD40-2 Operator's Manual, 5th Edition, 1978). The position adjusts the field current in the traction motors from the main generator to achieve different dynamic brake rates. (© SD40-2 Locomotive Service Manual).

The 3000 locomotives as used by TRANSAP SA in Chile has extended Range Dynamic braking. (GP40-2 Converted to SD40-M, 2004). “High braking effort is maintained by shorting out a portion of the dynamic braking grids as locomotive speed decreases.” (© SD40-2 Locomotive Service Manual).

There is a model MS420 storage battery, with a nominal voltage of 64V with a capacity of 420Ah. (© SD40-2 Locomotive Service Manual).

A diagram of key components used in the locomotive traction system is shown in figure 35.

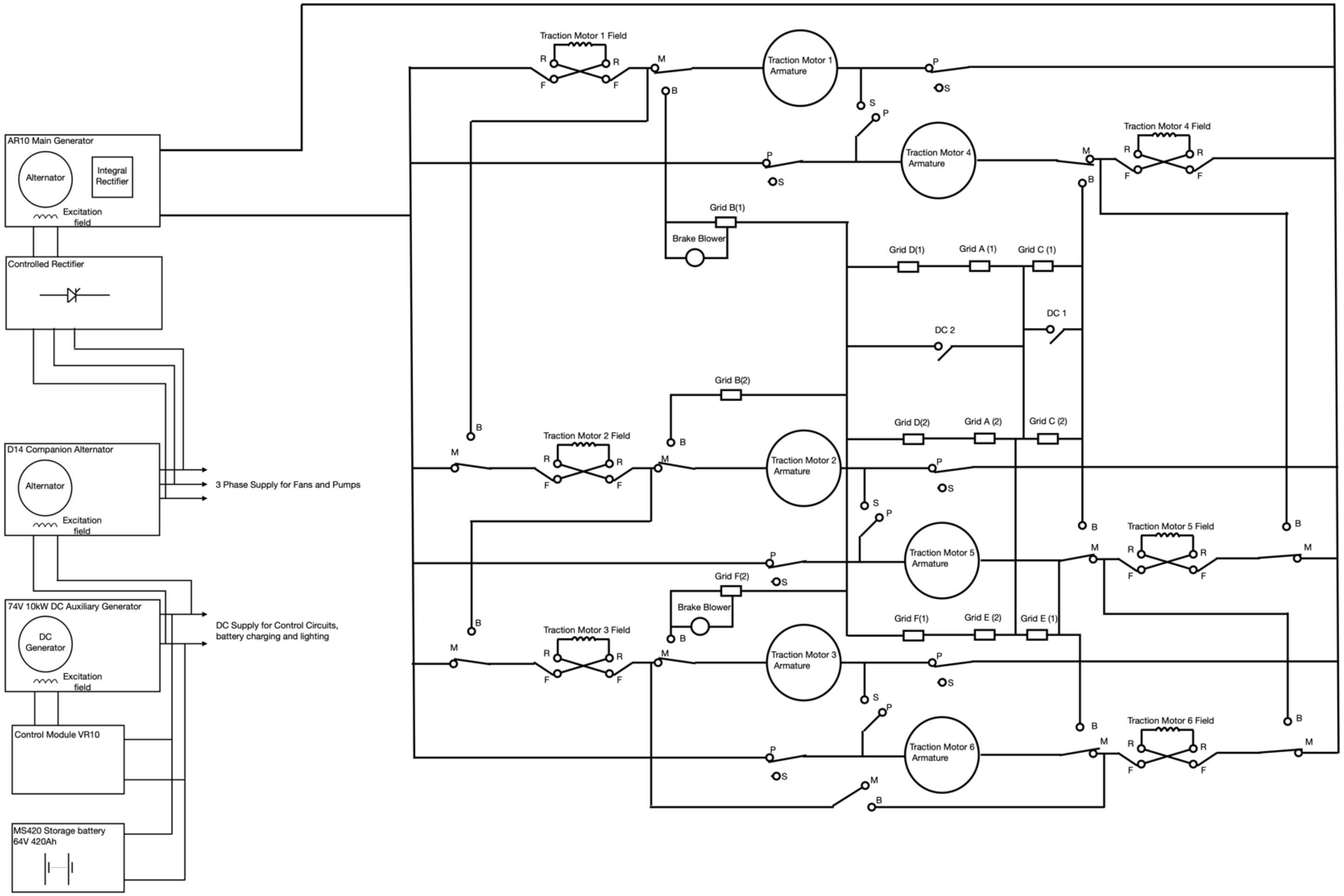


Figure 35: Traction System Overview Diagram (courtesy of VSTS)

6.2 ELECTRICAL CONCEPT FOR HYDROGEN HYBRID POWER

The required output of the new traction system is 3000hp (2238kW) for the SD-40 locomotive. The concept described in this report retains as much of the existing equipment and controls as possible, while using hydrogen as an energy source and a battery to provide variation in load power in a series hybrid configuration. An alternative, not considered in this report would be to convert the locomotive to modern AC motor control. This might result in savings in space but at considerable change to the existing locomotive.

The DC series wound motors have a maximum voltage of 1250V and a maximum combined current of 4200 amps. The combination does not occur at the same time as the power is limited to 2238kW. The fuel cell size determined by route simulations in section 2 is 800kW. It can be expected that a 10% drop in power will occur during the lifetime of the fuel cell, so the end of life power is 720kW. The system will be designed with the new power level of 800kW and it will be assumed a fall in power of 80kW in 2238kW can be tolerated during the lifetime of the fuel cell. There can be expected to be a similar fall in battery power, perhaps resulting in an overall fall of 10% power at combined end of life of battery and fuel cell. The end of lives may not occur at the same time in which case the reduction in power from new would be less than 10%. Alternatively, the size of the battery could be selected to allow reduction in power of the battery and fuel cells but still allow full power at battery/fuel cell end of life.

The auxiliary (non-motive) power in section 2.4 is quoted as 132kW. It is assumed that a major part of this power is for field excitation of the main generator in the current locomotive with the rest for fans and pumps, most of which are used on the internal combustion engine. The dynamic brake blower motors are self-powered from the brake grid resistors as shown in figure 36, therefore they are not part of the 132kW. It should be noted that Ballard fuel cells have integral compressors powered from the fuel cell stack itself, so the remaining balance of plant is coolant pumps and radiator fans, both of which have equivalent equipment used for the internal combustion engine in the current locomotive, so it is reasonable to assume that the auxiliary power load will be much less than 132kW.

To minimize the size of the battery, the combination of fuel cell power and battery power will provide the peak power of the locomotive. The proposal is to implement a DC chopper using an inductor/capacitor input filter, Silicon carbide (SiC) MOSFET device with flywheel diode to provide power to the traction motors or to the traction motor fields only, when dynamic braking is required. To minimize DC to DC converter equipment, it is proposed to use a battery voltage which is sufficient to power the chopper at all states of charge (SoC) of the battery and to only use a DC-DC converter to increase the voltage of the fuel cell to the battery. The initial estimate of the battery voltage required for this arrangement is 1600V at full SoC. This allows for a fall in battery voltage while still providing the full motor voltage of 1250V. The highest motor voltage occurs at low motor current in any case. The battery would need to provide at least 1438kW (=2238-800). A discharge C rate of 3.3 is required from the 440kWh battery modelled within this study to produce this amount of power.

Further work is required on modelling the system to check that 1600V is a suitable DC bus voltage and the battery C rating which can be applied to this application.

The proposed power supply for the traction motors is shown below in figure 36. This would replace all components on the left of figure 36, except for the MS420 storage battery, but would retain all the traction motor components and associated brake grids and contactors on the right side of figure 36.

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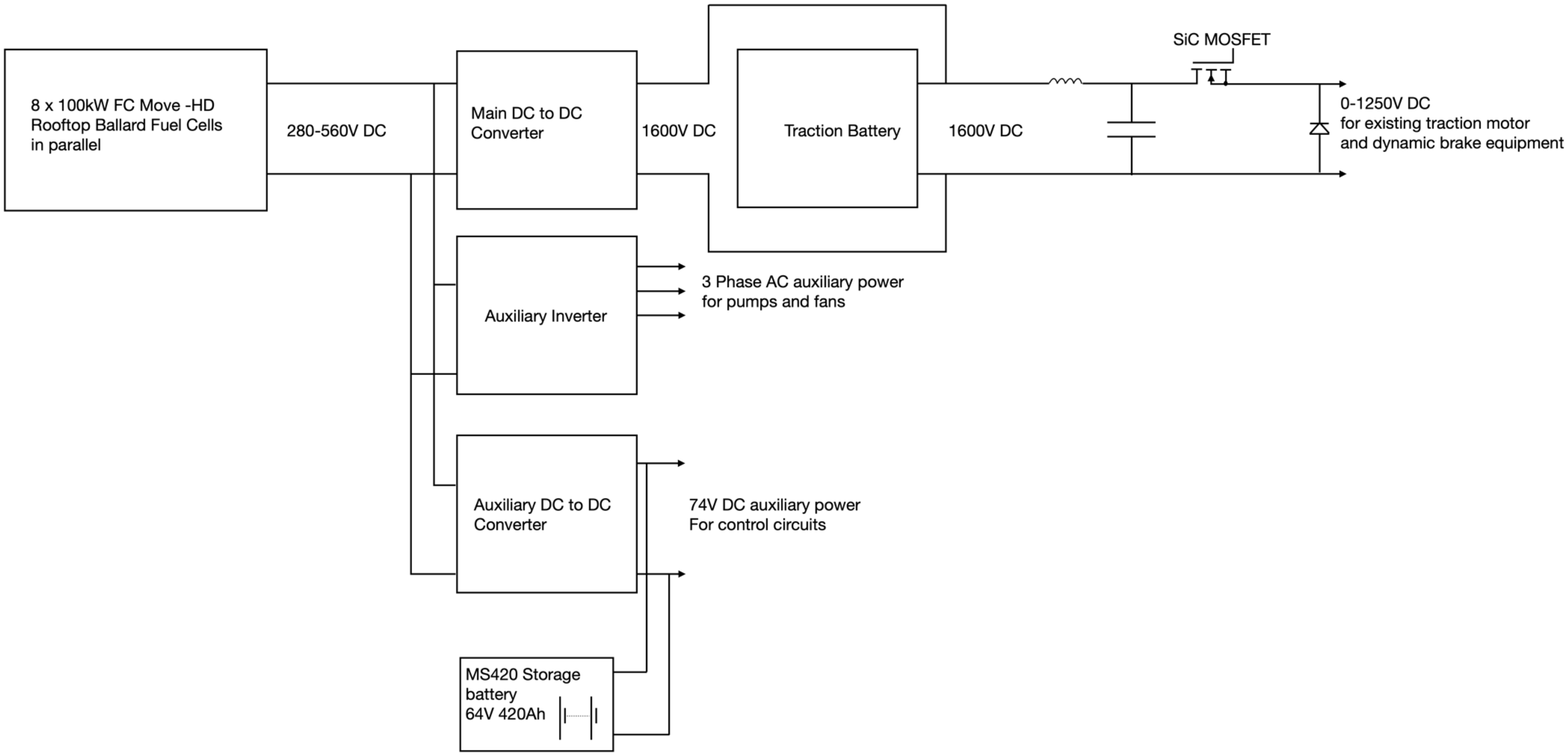

Figure 36: Concept Traction System Overview Diagram (courtesy of VSTS)

Due to the similarity between the SD-40 and SD-39 locomotives, it is recommended that a SD-39 modification would be achieved in the same manner as has been discussed within this section.

As the 1720kW prime mover power output of the SD-39 is lower than that of the SD-40, less fuel cell and battery power output is required at peak demand.

By using the same method described in section 3, it can be determined that the required battery peak output is 920kW for a train fitted with 800kW of fuel cell output (1720kW – 800kW) or 1120kW for a 600kW fuel cell output (1120kW – 600kW). This results in a battery size requirement of between 307kWh to 374kWh for the two fuel cell sizing options. Utilizing the 440kWh traction battery will give a maximum power output of 1920kW for a 600kW fuel cell system or 2120kW for a 800kW fuel cell system.

6.3 Control Concept for Hydrogen Hybrid Power

The control concept would replicate the existing control system to provide similar performance characteristics and minimal change. It will be necessary to examine the working of each individual existing control module to see what can be retained, what can be omitted, for example module VR10 (or VR13), and functionality that needs to be added in the form of a microprocessor controller.

7 Maintenance Requirements

A hydrogen-hybrid drivetrain requires different maintenance protocols to that of a diesel powered one. In many ways maintenance activities are simplified, streamlined, and made cleaner and more sustainable. This section provides an overview of the key differences in maintenance requirements of the locomotives in their current configuration versus when they have been converted to run on hydrogen. The expectations of maintenance crews is also detailed in the following sections to allow the operator management to assess workforce capacity requirements.

All maintenance tasks outlined in this section are indicative of the expected maintenance patterns for a hydrogen hybrid locomotive and are not exhaustive. More specific maintenance activities are also subject to the individual manufacturers of key elements as dictated by the result of a fully detailed design.

7.1 Fuel Cell Stack Maintenance

There are several maintenance tasks associated with ensuring the safe and reliable operation and longevity of the hydrogen fuel cell stack. Table 14 lists these maintenance tasks, alongside the frequency with which they should be performed.

Table 14: Maintenance tasks associated with the hydrogen fuel cell stack (courtesy of VSTS)

Maintenance Task	Task Frequency					
	2 Weeks	6 Months	1 Year	3.5 Years	5.5 Years	After a collision or fire event
Inspect system coolant level and coolant resistivity	✓	X	X	X	X	✓
Inspect the Hydrogen Purge Solenoid Valve	X	X	✓	X	X	✓
Inspect the Fuel Cell Stack for any hydrogen leakage due to gas cross-over within the stack	X	✓	X	X	X	✓
Check hydrogen supply pressure to the Fuel Cell: ensure that it is within specification	X	✓	X	X	X	✓
Inspect and clean the coolant strainer	X	✓	X	X	X	✓
Inspect and replace the process air chemical and particulate filter	X	✓	X	X	X	✓
Replace the Hydrogen Purge Solenoid Valve	X	X	X	✓	X	✓
Inspect the hydrogen recirculation pump and replace it if necessary	X	X	X	X	✓	✓
Inspect the hydrogen pressure regulator and replace it if necessary	X	X	X	X	✓	✓

7.2 Compressed Hydrogen System Maintenance

There are several maintenance tasks associated with ensuring the safe and reliable operation and longevity of the hydrogen fuel supply system and storage cylinders. Table 15 lists these maintenance tasks, alongside the frequency with which they should be performed. The European framework for hydrogen fuel cell systems in vehicles, EC79, and manufacturers' limits the life of cylinders based on filling cycles, or 20 years – whichever is soonest. Therefore, a method of recording the number of fill cycles must be employed.

Table 15: Maintenance tasks associated with the compressed hydrogen storage and supply system (courtesy of VSTS)

Maintenance Task	Task Frequency			
	3 Months	3.5 Years	20 Years	After a collision or fire event
Clean all hydrogen pipework	✓	X	X	✓
Undertake a complete visual inspection of the fuel supply system	✓	X	X	✓
Replace the hydrogen fuel supply coalescing filter	✓	X	X	✓
General, visual inspection of Tank End Valve	✓	X	X	✓
Detailed inspection, and re-certification, of Tank End Valve	X	✓	X	✓
Undertake a complete visual inspection of the fuel storage tanks	✓	X	X	✓
Replacement of Hydrogen Fuel Storage Tanks	X	X	✓	X

7.3 Hybrid Traction Batteries Maintenance

The lithium-ion hybrid traction batteries are largely maintenance free, with only minimal, periodic, inspections and checks. These are shown in table 16.

Table 16: Maintenance tasks associated with the hybrid traction battery (courtesy of VSTS)

Maintenance Task	Task Frequency		
	3 Months	3.5 Years	After a collision or fire event
Complete an external visual inspection of the battery casing for obvious mechanical damage	✓	X	✓
Check that key parameters within the battery management system software are within specification	X	✓	✓

7.4 Maintenance – General note

It is anticipated that this maintenance regime for the hydrogen hybrid traction system requires significantly less personnel maintenance hours required than for the existing diesel prime mover. This is aided by the lack of moving parts within the hydrogen hybrid traction system, and the complete remove of the oil system. Where heavy maintenance is required, this is likely to be the complete replacement of a self-contained component (e.g. fuel cell stack, electrical unit), although this is expected to be infrequent.

8 PRODUCT LIFECYCLE

This section will provide an insight into the overall longevity that can be expected from each element of a typical hydrogen-hybrid traction system. There are numerous factors that may affect the longevity of any piece of equipment or system including, but not limited to, the way in which maintenance procedures are performed, environmental conditions and storage as well as real-world vs. designed operational demands. As such, the following information is to be treated as indicative only.

8.1 HYDROGEN STORAGE TANKS LIFECYCLE

European Union (EU) commission regulation EU No. 406/20101 (implementing regulation for regulation EC79) specifies that the service life of gaseous hydrogen storage cylinders should not exceed 20 years. The regulation does give scope for manufacturers to specify a reduced service life, however, the recommended gaseous storage cylinders, have a manufacturer rated service life of 20 years. After this 20-year use cycle, the locomotive will require completely new hydrogen gaseous storage cylinders.

8.2 HYDROGEN FUEL CELL STACK LIFECYCLE

Given the lack of mechanical moving parts, hydrogen fuel cell stacks can be extremely durable, with a long effective service life. Where fuel cells are operated within manufacturer specified parameters (including an adequate cold start-up procedure, sufficient cooling, current draw within limits), fuel cells can have long service life, with over 25,000 operating hours stated by manufacturers2.

8.3 HYBRID TRACTION BATTERY LIFECYCLE

Large, lithium-ion batteries for use as the primary energy storage system in railway traction systems have an expected life of 5 to 8 years3. However, where a battery is part of a hybrid traction system, the depth of discharge (working battery states of charge) is considerably smaller than if the battery was used as part of a battery-only system. This operation at a shallow depth of discharge will considerably extend the life of the battery.

[1] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:122:0001:0107:EN:PDF
[2]https://www.ballard.com/about-ballard/publication_library/product-specification-sheets/fcmovetm-spec-sheet
[3] https://www.railwayage.com/passenger/you-can-rely-upon-lithium-ion/

The degradation of batteries over time typically results in a reduced overall storage capacity, with batteries in battery-only vehicles being replaced at 75% as the storage capacity is often critical in these applications. However, where a battery is part of a hybrid system, overall capacity is not critical. Therefore, it is expected that the batteries in the hydrogen hybrid locomotive, will have a significantly longer life than 5-8 years typically expected.

8.4 Equipment Warranties

Equipment warranties should be negotiated with the respective supplier at the point of sale. Integrating such equipment into a custom, hydrogen-hybrid powertrain means it is recommended that either extended warranties or service level agreements are integrated into the sale of the equipment by the manufacturer when it is ordered. Typically, supplier warranties range from between 1-2 years depending on the equipment application however it is best to try and agree warranty terms/service level agreements that are as close as possible to the intended design life to ensure the correct levels of support are provided by the supplier throughout the life of the vehicle.

9 Fuelling Infrastructure Requirements

The success of a hydrogen powered train service is entirely dependent on the availability of fuel. Given that the use of hydrogen as a motive power is still in its infancy, careful consideration towards identifying a reliable source of hydrogen must be given before operating any hydrogen-powered vehicle. Hydrogen trains also require approximately ten times more hydrogen than most other fuel cell powered land vehicles. For context, HydroFLEX 2 has storage for 277kg of hydrogen, whereas buses are currently on the market that only store 27kg (Wrightbus, 2022) so considerations should be made when sourcing hydrogen based on this increased demand.

This section will use the previously determined requirements for each journey to calculate daily hydrogen requirements for each route. Using this information, a concept logistics network can be determined, demonstrating the different options available for providing the required quantities of hydrogen.

Figure 37: Vanguard Sustainable Transport Solutions Refueller Filling HydroFLEX 1 with Hydrogen (courtesy of VSTS)

9.1 FUELLING STATION HYDROGEN DEMAND

The daily hydrogen fuelling requirement is calculated by multiplying the amount of hydrogen required at each fuelling location per train by the number of trains per day before multiplying by a further margin to ensure sufficient capacity in times of increased demand.

It is assumed that 2 trains per day operate on each of the routes, and a 50% margin will be added to the raw fuel requirements. This is to ensure that demand above the expected level can be satisfied and to allow for reserves of hydrogen to be built up following any supply disruption.

Using the data gathered in previous sections with the rules stated above gives results shown in table 17 for hydrogen requirements at each of the origin station of trains on the routes modelled.

Refuelling requirements calculator

Location	Destination location	Train hydrogen requirements per trip (kg)	Number of trips per day	Total daily hydrogen requirement (kg)	Fuel reserve margin	Total final hydrogen requirement
Central zone origin	Central zone via destination	330	2	660	50%	990
Central - south intermediate point	Central - south intermediate point via destination	226	2	452	50%	678
Central - south intermediate point	Central - south intermediate point via origin	158,4	2	316,8	50%	475,2
Central - south intermediate point total		384,4	2	768,8	50%	1153,2

Table 17: Fuelling requirements calculator (courtesy of VSTS)

9.2 Hydrogen Supply Options

The hydrogen supply options that will be considered are:

- Delivery to site in gaseous form
- Delivery to site in liquid form
- On site electrolysis
- On site cracking of ammonia

These will be investigated in turn:

9.2.1 Off Site Hydrogen Production, Delivered to Site in Gaseous Form

The compression and storage of gaseous hydrogen is described as “the conventional and easiest method of storing hydrogen” (Muhammad, 2021). Whilst the volumetric density of the hydrogen transported as compressed gas is less than transport as ammonia or in cryogenic liquid form, the equipment required to handle compression (boosters and high-pressure hydrogen pipework and tanks) is simpler and lower cost.

Hydrogen can be effectively transported in tube trailers or tube containers. These consist of multiple hydrogen cylinders bundled together to maximise hydrogen carried for volume taken up by tanks. These either are integrated into an HGV trailer chassis frame or fitted within an ISO container frame.

All types of compressed hydrogen tank have been used in tube trailers. Traditionally type 1 and 2 tanks have been used for transport of between 400 to 550kg of hydrogen at pressures between about 200 and 250 bar (Aliquo, 2016), but given the increase in demand for large quantities of hydrogen at high pressure type III and IV trailers are being developed that can operate at up to 500bar to store up to 1100kg of hydrogen within the tube trailer footprint (Enerdata.net, 2021).

9.2.2 Off Site Hydrogen Production, Delivered to Site in Liquid Form

It is possible to change the state of hydrogen from gas to liquid by cooling to cryogenic temperatures (less than -253 degrees Centigrade) and both uncompressed and compressed form. It is possible to transport cryogenic hydrogen in road tankers with a capacity between 40,000 and 60,000 litres (UKHA).

Multiplying the capacity of the tankers with the density of cryogenic hydrogen (70kg/m^3) gives a hydrogen capacity between 2836 and 4254kg per cryogenic road trailer.

Whilst vastly more hydrogen can be stored and transported in liquid form when compared to compressed gas, there are hazards involved in the use of hydrogen as a cryogenic gas. These have been assessed by the Health and Safety Executive (HSE) and are elaborated within a published position paper (Health and Safety Laboratory, 2010).

9.2.3 On Site Hydrogen Production Options: Electrolysis

Unlike diesel fuel, which is typically delivered to railway depots via road or rail tanker trucks or wagons, it is possible to generate hydrogen at the point of use. This can be practically achieved via electrolysis of water or by cracking of ammonia.

The most common method of on-site hydrogen production at present is electrolysis. This process is the opposite of fuel cell operation, in that electricity is used to split water into hydrogen and oxygen, instead of hydrogen and oxygen combining to form water and electricity.

Existing electrolyser projects can be used to determine the required footprint for an electrolyser system. Green Hydrogen Systems manufacture a 450kW alkaline electrolyser system that can produce 194.5kg of hydrogen per day packaged within a 20ft container body (Green Hydrogen Systems, 2021). The containers contain both the electrolyser and the ancillary equipment such as thermal management and gas compression boosters. The electrolyser containers from the reference will be used as a metric in the further comparisons.

9.2.4 On Site Hydrogen Production Options: Cracking of Ammonia

Ammonia cracking involves splitting ammonia molecules into their component nitrogen and hydrogen atoms via a process of preheating ammonia supplied in liquid form at 8.7 bar at 20 degrees centigrade in a heat exchanger, vaporisation and then cracking in a catalytic reactor at a temperature of 550 degrees Celsius. The production of 450kg of hydrogen per day requires 3.75t of Ammonia per day.

The use of ammonia for hydrogen production on site allows for the transportation of the ammonia feedstock to site in liquid form in ISO tank containers. A 20ft tank container can store 25t of ammonia (Tullyn, 2018). Given the maximum weight of the 20ft tank container (32700kg), only one full tank container could be carried per delivery truck. Therefore, a single truck delivery could provide enough ammonia to support 3000kg of hydrogen.

Whilst the feedstock for on-site hydrogen production from ammonia cracking requires the feedstock ammonia to be delivered to site and stored in tank containers, there is an advantage to doing so as more hydrogen can be stored in less space when in the form of liquid ammonia, stored at 8.7 bar at ambient temperature, than as compressed hydrogen gas.

9.2.5 Summary of Hydrogen Fuelling Options

The hydrogen delivery and generation capacity of all the hydrogen delivery technologies discussed are compared in table 18.

Table 18: Hydrogen supply option calculator (courtesy of VSTS)

Refuelling Option Analysis		
Technology	**Type of Equipment**	**Hydrogen per Delivery/**
Gas Tube Trailers	250 bar Tube Trailer	550kg per truck/wagon
	500 bar Tube Trailer	1100kg per truck/wagon
Cryogenic Tanker	Small Trailer	2836kg per truck/wagon
	Large Trailer	4254kg per truck/wagon
Ammonia Cracking	Ammonia Tanker	3000kg per truck/wagon
Electrolysis	20ft Electrolyser Container	194.5kg generated per day

These figures will be used in the next section to determine how much equipment and how many deliveries of hydrogen are required to sustain a hydrogen train service on the routes investigated.

9.3 Hydrogen Delivery/Generation Requirements Per Location

Using the figures ascertained for hydrogen requirements at each fuelling site and the amount of hydrogen that can be delivered or generated by each form of technology, table 19 shows the frequency of deliveries of hydrogen or ammonia or number of 20ft electrolyser modules required to provide the requisite amounts of hydrogen at each location.

Table 19: Hydrogen supply requirements calculator (courtesy of VSTS)

Refuelling location	Daily hydrogen requirement (kg)	Technology	Type of equipment	Delivery frequency/equipment required	
Central zone origin	990	Gas tube trailers	250 bar tube trailer	2	Deliveries per day
			500 bar tube trailer	1	Delivery per day
		Cryogenic tanker	Small trailer	3	Days between each delivery
			Large trailer	4	Days between each delivery
		Ammonia cracking	Ammonia tanker	3	Days between each delivery
		Electrolysis	20 ft electrolizer container	5	Containers
Central - south zone origin	1153,2	Gas tube trailers	250 bar tube trailer	2	Deliveries per day
			500 bar tube trailer	1	Delivery per day
		Cryogenic tanker	Small trailer	2,5	Days between each delivery
			Large trailer	3,5	Days between each delivery
		Ammonia cracking	Ammonia tanker	3	Days between each delivery
		Electrolysis	20 ft electrolizer container	6	Containers

9.4 Potential Existing Hydrogen Supply Options

Communication with TRANSAP and GIZ have given indications as to sources of hydrogen close to both routes. These are detailed below:

9.4.1 Central Zone Route

Communications with GIZ have indicated that hydrogen generations plants are located at Concón and Graneros.

The plant at Concón is operated by Linde and the hydrogen plant at Graneros is operated by Air Products. It has been indicated to the project team that there is surplus hydrogen available from these plants.

9.4.2 Central – South Zone Route

The Air Products facility at Lirquén is located approximately 50 km from the second intermediate fuelling point of the central – south zone route.

Communications with GIZ have indicated that there is not spare hydrogen generation capacity to provide for hydrogen trains from the Lirquén plant, however it is worth monitoring the plant's current, planned and future output as a potential source of fuel for this route.

10 Training Requirements

To ensure smooth operation of the trains following a hydrogen-hybrid conversion, it is important to make all personnel aware of any changes that may affect how they are accustomed to working with/around the locomotives. The following sections provide information on what the drivers and maintainers of the trains can expect to differ from how the trains are currently configured.

10.1 Driver Training

Subject to detailed design, it is assumed that, as far as reasonably possible, the experience of the locomotive driver will remain close to the previous locomotive. The air braking system will remain unchanged, and the dynamic brake will charge the battery, or function through the existing resistor bank. This process will be managed through software, with no driver input. The power handle/throttle will remain, and will achieve the same function, and control granularity as previously experienced by the driver. Drivers should be trained in basic fault-finding and rectification procedures associated with the hydrogen hybrid power system, as well as emergency response procedures associated with the hydrogen and battery system.

10.2 Maintainer Training

Hydrogen-fuelled trains provide a significant change for maintenance staff previously trained in maintaining diesel-fuelled trains. While the maintenance personnel demand is likely to be lower than requirement for the existing locomotive, the hydrogen hybrid power system will require maintenance staff with additional skills. A good working knowledge of the behaviour and dangers of gaseous hydrogen is required for all staff. Additional skills required will be competency in the installation, fault-finding, and maintenance of hydrogen fuel pipework and working around high-voltage battery systems.

11 Facility Upgrades

In addition to a robust fuelling infrastructure, onsite maintenance/storage premises need to be considered to ensure problem-free operations following a diesel to hydrogen-hybrid conversion. This section will explain the upgrades/alterations typically called for when keeping a hydrogen powered train.

11.1 Hydrogen Refuelling Facilities

As trains are constrained by the limits of the lines on which they operate, lineside hydrogen refuelling arrangements must be made.

During the early phases of testing a hydrogen train it is common that temporary fuelling arrangements are made. Examples of this are the cryogenic refuelling trailer provided to support Alstom iLint testing in Germany, temporary gaseous hydrogen deliveries provided to the Long Marston test track to support HydroFLEX testing in England.

When a fleet becomes more established, permanent facilities can then be established as the guaranteed large-scale offtake of hydrogen will justify the investment made in the facility. This has recently been achieved at Bremervörde in Germany. 16 iLint trains will be serviced at this site, which can produce up to 1600kg of hydrogen per day.

Fuel provision should be considered at the earliest stages of any hydrogen train project. Location, hydrogen generation or delivery methods and space claim of the site must all be accounted for. A detailed hypothetical case study for a method behind which this can be achieved has been produced by the UK Rail Safety and Standards Board.

11.2 MAINTENANCE/TRAIN STORAGE FACILITIES

The introduction of hydrogen fuelled trains into an indoor maintenance depot introduces additional risks to operation. These risks are primarily a result of hydrogen hazards, such as a hydrogen leak and subsequent ignition. Figure 44, Workshop Arrangements for Hydrogen Trains, shows several key passive and active safety measures. It should be noted that these hazard management strategies are supplementary to the additional safety measures onboard the locomotive, and in operating practice.

The depot structure should be equipped with hydrogen detectors and a hydrogen extraction system. The hydrogen extraction system should be positioned at highest point in the roof of the structure, as this is where vented hydrogen is likely to congregate. The lower explosive limit of hydrogen in air is 4%. If hydrogen is detected at 1% in air, the hydrogen clearance fans will operate, and exhaust the air inside the structure. This gives a significant safety factor in the hydrogen concentration before there is a risk of explosion.

Within the EU, legislation governing the use of explosive and flammable gases is referred to as ATEX legislation, specifically Annex I of Council Directive 99/92/EC. The term ATEX is derived from part of the French title of 99/92/EC, ATmosphère EXplosive, and is commonly used to refer to this framework. Under this framework, the depot building will be classified as a zone 2 area, as an area in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only. In zone 2 areas, all electrical equipment, and sources of ignition (e.g., sparks) should be rated for operation in an ATEX zone 2 area. While Chile does not fall under EU legislation, it is recommended that this (or similar) framework is adopted, or a specific risk assessment is completed for the depot space in relation to equipment as sources of ignition.

All depot lighting will be rated for operation in a potentially explosive atmosphere, as well as being suspended from the roof structure, such that any hydrogen will collect above the light. This arrangement is common practice is maintenance sheds for hydrogen fuel cell road vehicles and is shown in figure 38. If an inspection pit is used for locomotive servicing and maintenance, this should feature a hydrogen detection and forced ventilation system to reduce the risk of hydrogen collecting in confined spaces.

Alongside the detection of the presence of hydrogen in the maintenance structure, a system for the detection and mitigation of hydrogen fires should also be installed. This is commonly introduced in the form of standard industrial heat detection and a sprinkler system.

As far as is reasonably practicable, the use of tools likely to cause sparks and hot works such as welding and grinding should not be carried out within the same area as fuelled locomotives are stored. If hot works are required on a locomotive, this should individually risk assessed.

11.3 Specialist Equipment

Alongside additional tools and equipment required for the maintenance of hydrogen hybrid trains, it is likely that additional PPE is required:

- Anti-static overalls. These are work overalls designed and specified for environments where static build-up, leading to sparks, is not required.
- Portable Hydrogen Detectors. These are small devices to be worn by personnel where there is a possibility of hydrogen release, such as during refuelling or maintenance.

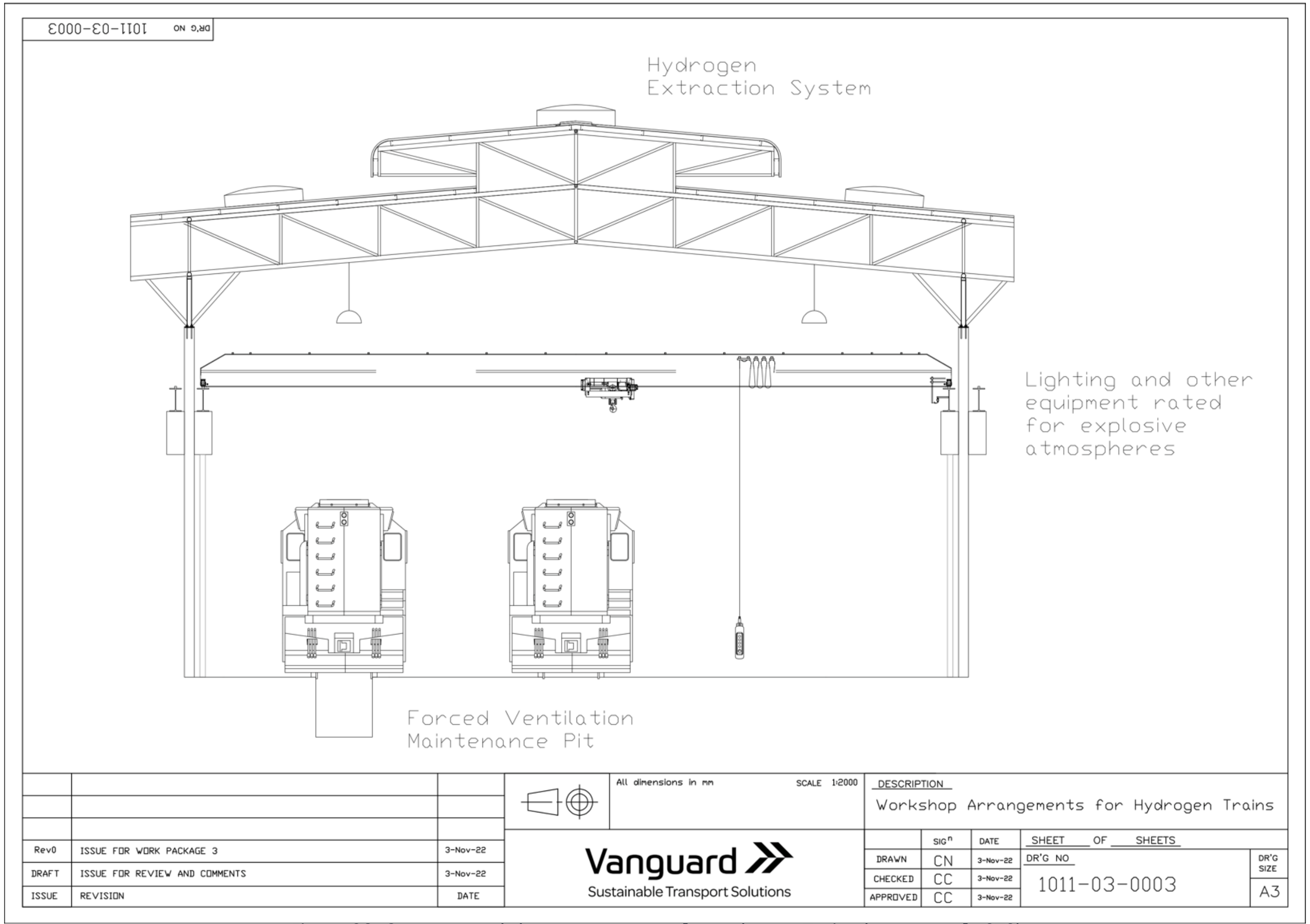

Figure 38: Concept Workshop Arrangement for Hydrogen Trains (courtesy of VSTS)

12 OPERATIONAL SECURITY AND SAFETY REVIEW

Any new form of locomotive or method of working can pose a significant risk to safety during installation, operation, and removal. In this case, the most significant change to the operational safety is the use of hydrogen as a fuel. This introduces some additional risks in areas such as locomotive refuelling, maintenance, and emergency procedures. However, the use of hydrogen as a fuel also reduces some risks associated with harmful greenhouse gas and particulate emissions.

A risk register, containing significant risks associated with the operation, refuelling and maintenance of the hydrogen hybrid locomotive, and measures taken to mitigate these risks can be found in table 20 below.

Legal and homologation requirements are described in section 13.

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Table 20: Hydrogen hybrid locomotive risk register (courtesy of VSTS)

Identified Hazard / Precursor	Cause(s)	Consequence(s)	Overview & Mitigations
Inadequate ventilation of containment zone	- Absence of provision of an 'escape route' for leaked or pooled hydrogen (e.g. Roof 'overhang'), - Inadequate design of containment area, - Inadequate containment of individual systems. - Clearance fan does not operate when required due to design or fault - Clearance fan is not effective in the clearance of hydrogen	Pooling of Hydrogen, causing personnel risk of: - Displacement of oxygen in containment area, - Asphyxiation of operating staff - Asphyxiation of maintenance staff, - Escalation of fire risk, - Escalation of explosion risk - Fatality Pooling of Hydrogen, causing equipment risk of: - Damage to locally ventilated equipment (increased exposure to hydrogen in atmosphere), - Embrittlement, - Equipment failure (e.g. air intake on fuel cell), - Increased likelihood of ignition/fire event, - Escalation of other hazards.	Hydrogen fuel has an extremely low molecular density (10 times lower than air), as such when it is vented into air it quickly disperses and rises. Ventilation to disperse any leaked Hydrogen is designed as follows: - The high pressure and low pressure sides of the system incorporate leak/flow detection - Hydrogen detectors will be installed inside the locomotive which will be checked as part of train prep. - The fuel cell has its own internal ventilation system within its containment box - In the event of the emergency stop being operated, the power is maintained to the clearance fans to provide forced ventilation in the locomotive. Ventilation fans should be provided anywhere Hydrogen is likely to accumulate in the event of a leak, including both the fuel cell compartment and the hydrogen storage tank compartment. Hydrogen detectors will require periodic testing and duplication (redundancy) in design and possibly diversity in supply. It is probable that the chosen design will be new to the rail industry.
Containment zone (ATEX zone) fails to contain Hydrogen	- Containment zone not adequately sealed, - Containment zone damaged (e.g. inadequate / future maintenance), - Containment zone fails in service (ie inadequate structural integrity), - Operators violate containment zone (ie open lockable door or hatch during service), - External event breaches containment zone (e.g. vehicle fire).	Pooling of hydrogen in non-containment zone: - Exposure to ignition source leading to explosion, - Asphyxiation (outside containment zone).	Hydrogen related equipment will be located within ATEX rated zones (Dangerous Substances and Explosive Atmospheres Regulations 2002) to ensure that all equipment within these zones meet the necessary spark/ignition requirements. These zones will ATEX zone 2, i.e. A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only. All staff areas of the locomotive (such as the cab) will be non-ATEX zones, allowing safe separation between equipment and staff. Hydrogen detectors will be located within these designated ATEX zones, as well as in non ATEX zones to detect any leakage of Hydrogen and compromising of ATEX zones. These detectors will be periodically tested, and their integrity reported to the driver as part of train preparation.

Inadequate hydrogen leak detection	- Inadequate detection system, - Air compressor unit draws in hydrogen before it can be detected by the detection system, - Poor locations of detection units, - Inadequate system venting, - Ill-defined response including actions, roles and responsibilities - Hydrogen detectors fail to detect released Hydrogen - Failure of Hydrogen detectors - Hydrogen detectors are switched off - Hydrogen does not flow through gutters as designed - Hydrogen concentration does not activate sensors - Hydrogen collects in areas without Hydrogen sensors	Pooling of Hydrogen, causing safety risk of: - Displacement of oxygen in containment area, - Asphyxiation of operators (2 operators present in/around containment area), - Asphyxiation of maintenance staff, - Escalation of fire risk, - Fatality Pooling of Hydrogen, causing operations risk of: - Damage to locally ventilated equipment (increased exposure to hydrogen in atmosphere), - Equipment failure, - Increased likelihood of ignition/fire event, - Escalation of other hazards.	Hydrogen detectors are to be positioned throughout the locomotive within ATEX and non-ATEX zones to achieve the most reliable detections, this includes above the Hydrogen cylinders and fuel cell assemblies. The hydrogen detection system is linked into the emergency shut down system. The sensor systems are designed to register at very low levels of hydrogen concentration to enable the systems to trigger and E-stop at a concentration level of 1%. This is below the 4% level where hydrogen can become combustible. The fuel cell compressor inlet does not take its air supply from the containment area and is therefore protected from hydrogen intake. Due to the low density of Hydrogen and therefore its rapid dispersal rate, it is not considered credible that the draw from the air compressor would prevent leaked Hydrogen from being detected by the Hydrogen detectors.

Release of high-pressure gas from hydrogen from storage system and network	Potential big volume release of high-pressure Hydrogen from Hydrogen cylinders, e.g. due to: - Cylinder rupture - Cylinder corrosion - Failure of TPRD (limited to one cylinder) - Failure of support frame (see specific hazard) Potential small volume release of high pressure Hydrogen from Hydrogen cylinders, e.g. due to: - Failure of hoses/connections, - Failure of/damage to pipework - Failure of valves, - Damaged/inadequate seals, - Over-pressurisation of cylinder	Human exposure to high pressure jet which isn't visible, causing: - Major Injury, - Fatality. Equipment exposure to high pressure jet which isn't visible, causing: - Damage to equipment, - Rupture of containment area. Hydrogen leakage - see related hazards for possible escalation.	The hydrogen storage system contains highly flammable hydrogen gas. This is stored at up to 350 bar in the storage tanks, and under normal circumstances is released to the fuel cell stack via a regulator. The high-pressure areas of the system essentially comprise of the refuelling system and the Hydrogen cylinders connections within an ATEX rated zone 2 containment. For refuelling hazards, see appropriate section. The Hydrogen cylinders are manufactured by Luxfer Gas Cylinders and uses a proven design to minimise any potential causes for leaks. If the cylinders have been manufactured in compliance with EC79, there are significant passive design safety measures required. The tanks are single piece aluminium, wrapped in carbon fibre. This construction has very good corrosion resistance and impact resistance. The pressure inside the cylinders is controlled by the system and can be manually checked by a pressure meter on the outside of the cylinders. In the event of over pressurisation of the system, or other related faults, the Hydrogen can be vented via an emergency vent to atmosphere. The tanks are also equipped with thermally reactive pressure relief valves that vent the tanks to atmosphere when temperature exceeds the threshold. These pressure relief valves are specified, installed and tested to the EC79 standard. They consist of quartzoid bulbs that are located within in the tanks that burst at 110ºC thus allowing the pressure in the tanks to evacuate to atmosphere. Maintenance of the cylinder will be conducted in line with the manufacturers specifications and will include checks for corrosion and other degradation on the cylinder and associated connections.
Release of low-pressure gas from Hydrogen storage output/Fuel Cell	Low pressure output pressurised to 16.5 bar, potential release through: - Fault in pressure relief device, - Rupture of flexible hoses - Failure of/damage to pipework - Failure of valves, - Failure of support frames (see specific hazard) - Damaged/inadequate seals	Human exposure to low pressure jet causing: - Minor Injury, - Major Injury Equipment exposure to low pressure jet causing: - Corrosion (long term). Hydrogen leakage - see related hazards for possible escalation.	The low-pressure area of the system is essentially the fuel cell and its connections within an ATEX rated zone 2 containment. For the fuel cells see appropriate section. The Hydrogen cylinders are designed to comply with the requirements of EC79 and feeds high pressure to the low-pressure system through a pressure regulator, at 7 - 11bar. This regulator is specified, installed, and tested to be compliant with EC79. The system also includes a filter to prevent contaminates from affecting the function of the valves and systems. The fuel cell low pressure connections are monitored by a leak detector in the regulator which uses flow rates. If a leak is detected, then the fuel cell will shut down and stop the low pressure flow. Leaks can also be identified by the Hydrogen gas detectors in the fuel cell and surrounding area, upon detection of Hydrogen (when levels exceed 1%), there is an automatic emergency shutdown.

			The low-pressure system in the fuel cell is fully enclosed within sealed secondary containment, the containment vents through the exhaust system directly out of the vehicle.
Hydrogen leaks due to failure of Hydrogen system components (e.g. tank end valves, regulator system, TPRDs)	- Inappropriate gas output pressure, - Uncontrolled gas output, - Rupture of hydrogen cylinder (over-pressure), - Inadequate maintenance, - Damage during delivery or installation. - Inadequate design/build, - Water ingress - Inadequate maintenance, - Corrosion of electrical connections. - Mechanical failure - Non detection of latent faults	- Cause of other hazards (release of high-pressure gas, release of hydrogen etc).	The regulator system, electrical end valves and TPRDs are part of the Luxfer provided high and low pressure design, compliant to EC79. The regulator automatically cuts the flow if it reaches a state of over-pressurisation. The main failure mode of the regulator is caused by contamination of Hydrogen which is considered in a separate hazard. To mitigate this, the system is installed with a coalescing filter (to remove oil/water) and on each valve there is also a particulate filter. If the regulator fails in an open position, this will be identified by the flow valve if a leak occurs and can be addressed by the stop valve at the fuel cell. If the regulator fails in a shut position, then the system will be unable to provide a Hydrogen feed to the fuel cell and this will be notified to the train operator. Maintenance of the regulator will be conducted in line with the manufacturers specifications. The electrical end valves are electrically supplied by the system (fuel cell and battery combination). If electrical supply is lost, the valves 'fail shut' as a safety condition. This is independent of the emergency release vent. Testing of all connections will be included in the installation validation procedure which is undertaken by competent staff. Maintenance of the end valves will be conducted in line with the manufacturers specifications and include checks for corrosion. Tank valves are required to close under certain circumstances but are otherwise undetected in their availability, therefore these could fail to control other hazards (e.g. pipe rupture) if there are underlying undetected faults in these components.

Hydrogen fire	- Release of Hydrogen and ignition sources present - Inadequate safety system response - Exposure to external fire - Auto-ignition of Hydrogen due to friction (see specific hazard)	- Further escalation of other hazards (see specific hazards), - Hydrogen cannot (easily) be extinguished - Ignition of hydrogen which cannot be put out by conventional firefighting means, stemming from ignition source present - Ignition of hydrogen via leak/release and lack of visible flames as hydrogen does not produce a visible flame - Traction system shutdown (if both Fuel Cell and Battery system are affected) so that locomotive cannot move to a safe location. - Reputation damage	The Hydrogen tanks are equipped with thermally reactive pressure relief valves that vent the tanks to atmosphere (outside of the vehicle) in the event of a fire around the tanks, quartzoid bulbs burst to release the Hydrogen via a vent pipe to the outside of the vehicle. These pressure relief valves specified, installed and tested to EC79 standard. When Hydrogen is released, either via system response or fault, electrical end valves close to prevent further release of Hydrogen, and train estop is activated (see related hazards). Emergency response hazards are also dealt with separately.
Train vents/releases Hydrogen in an unsuitable location: - ignition sources present - in an enclosed location (tunnel, maintenance shed)	- Hydrogen release due to inadvertent/failure operation of Hydrogen system components (e.g. TPRD, valves, etc) - Inadvertent operation of low pressure pressure-relief valve - High Hydrogen level in exhaust, - No prevailing wind to disperse Hydrogen into air	- Future ignition sources may lead to fire/explosion (including after locomotive H2 release event) - Risk of further hazard escalation - Risk of asphyxiation - Risk of Hydrogen pooling	Hydrogen could potentially be released from the locomotive due to emergency venting (i.e. TPRDs) or in the Fuel Cell exhaust. As the fuel cell exhausts is monitored to be less than 1% isolated Hydrogen (and will shut down if this is exceeded), it is considered negligible with respect to this hazard as trace Hydrogen would have quickly disperse within air. Otherwise, there should be no intention to manually vent the system (e.g. via a button), as unless released due to fire, the safest place for the Hydrogen is within the tanks. This hazard therefore primarily considers intentional system response venting of Hydrogen in an unsuitable location. Hydrogen fuel has a relatively low molecular density (~10 times lower than air), as such when it is vented into air it quickly disperses and rises. The exhaust vents out through a location to be determined to the exterior of the vehicle. This is adjacent to the cooling system fans, which provides a positive air flow away from the vehicle and thus prevents recirculation into the vehicle. The exhaust vent is above head height on the outside of the train and access will not be possible to this area in operation. The exit point is sufficiently far from other vehicle inlets. Therefore given the dispersing nature of Hydrogen in air, and the position of the exhaust, it is not considered credible that Hydrogen exhaust fumes may re-enter the vehicle.

			The project should utilise the research undertaking by the Hytunnel[4] project which recognises that there is an extent to which Hydrogen leaks can be prevented, and that should they occur within a tunnel, then appropriate preparation and focus needs to be considered for emergency response. Practically, it would not be a case of installing Hydrogen detection systems throughout infrastructure, as this would not be robust enough to detect all leaks and the presence of Hydrogen (e.g. that collected within voids or brickwork). Additional risk assessments would be required, considering the length of tunnels along the route.
Ignition sources in locomotive	Various equipment from the base vehicle could include: - Contactors in drivers desk cupboard, - Electrical equipment, - lighting This is in addition to equipment added such as: - Traction batteries, - Hydrogen fuel cell, - Other electrical equipment, - Equipment exhausts, - Static generated between items. - Switches	- Ignition of leaked or pooled hydrogen, - Fire event, - Fatality. - Asphyxiation	Hydrogen related equipment will be located within ATEX rated zones to ensure that all equipment within these zones meet the necessary spark/ignition requirements. These zones will ATEX zone 2, i.e. A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only. All staff areas of the locomotive (i.e. cab) will be a non-ATEX zone, allowing safe separation between equipment and staff. All electrical equipment (e.g. lights, terminals, cables) will need to meet the necessary ATEX requirements. Hydrogen cylinders and Fuel Cells will need to be assured to the specified level of containment. Furthermore, the vehicle will need to be risk assessed for potential ignition or spark sources, with all non-functional/necessary sources to be removed. See specific hazards for vehicle earthing and bonding requirements.
Existing depot areas and activities are not compatible with Hydrogen	- Wheel grinding cannot take place on vehicle as per existing arrangements. - Necessary exclusion zones cannot be achieved. - Evacuation procedure is not fit for purpose. - Emergency services provisions	- Sources of ignition for Hydrogen - Unable to carry out maintenance activities	Depot suitability needs to be risk assessed to ensure compatibility with hydrogen locomotives. The Operator will need to decide whether the train should be empty before entering the depot. Depot may need upgrade to ensure safe storage of Hydrogen containing equipment, for example ATEX rating, Hydrogen detection and Hydrogen extraction systems. Depot evacuation procedures to be updated and will need to incorporate exclusion zones and considerations for emergency services. Depot may need

[4] https://hytunnel.net/?page_id=31

	are not adequate. - Depot not compatible with Hydrogen train. - Adjacent maintenance activities create sparks (welding, grinding, electrical machinery) - Some depot sheds have existing gas heaters. - Sparks from 2-way radios and mobile phones.		upgrade to ensure safe storage of Hydrogen containing equipment, for example ATEX rating, Hydrogen detection and Hydrogen extraction.
Moving train emitting minimal noise on approach to depot, freight yard authorised walking route crossing	-'Hydrogen powered train quieter than diesel locomotives and the existing locomotive - Depot, yard staff does not hear train and crossed when unsafe to do so	- Collision with train resulting in workforce fatality and minor damage to train	This is a risk already dealt with, due to shunting / coasting movements with minimal generation of noise within the depot environment. Audibility of trains should not be the primary control for protecting depot staff on crossings. To be addressed by depot risk assessment and change management arrangements in line with their Safety Management System. Depot protection systems for movements to consider lack of audibility of hydrogen trains.
Failure of fuel cell	- Internal ignition of hydrogen gas, - Internal production of sparks, heat or fire, - Over-pressurisation of air, hydrogen or coolant, - Failure of air compression system, - Over current - Failure of coolant system. - Inadequate design of Fuel Cell and related systems - Damage during installation - Incorrect manufacturer used for installation - Physical damage to fuel cell	Consequences to safety including: - Hydrogen leakage - Displacement of oxygen in containment area, - Asphyxiation of operators, - Escalation of fire risk, - Fatality.	The fuel cell and associated equipment will be installed in accordance with the manufacturer's installation procedure, using specific lifting points designated by the manufacturer. The use of cranes and other specialised equipment will be controlled to minimise the effects of loading on the equipment during installation. Transport and delivery of components will be controlled by the approved suppliers. First Article Inspections (FAI) at the time of delivery and subsequent condition assessments will be carried out on the components. The fuel cell integrated control system controls the pressure of the Hydrogen fuel and shuts off the supply if the hydrogen is over-pressurised. Hydrogen fuel is fed through ATEX rated areas which are not exposed to potential spark/ignition sources. The Fuel Cell system also monitors temperature, voltage and current to ensure that inputs/outputs remain at a safe level. There are Hydrogen detectors within the fuel cell, and external detectors will be installed within the ATEX rated fuel cell containment. If Hydrogen leaks are detected, then this will trigger an emergency stop and fuel cell shut down. The compressor is part of the fuel cell design which is compliant to the principles of EC79. The fuel cell control system can detect failure modes in the air compressor and will shut off the air supply if it is outside acceptable

			tolerances. The fuel cell air compressor is controlled by the control system to automatically supply the necessary air to the fuel cell module, the amount of which will depend on the current being drawn from the fuel cell. The compressor prevents the entrance of contaminants into the air supply through particulate and chemical filtration at the intake. The fuel cell control system can detect the temperature of the compressed air and will shut off the supply if it is unsuitable. Ambient air temperature is not expected to cause this hazard as the maximum operable temperature of the fuel cells is 50 degrees celsius. The fuel cell is managed by a control system that monitors parameters such as system temperature and pressurisation. Where overheating cannot be mitigated by the cooling system, the control system will shut down the fuel cell.
Inadequate isolation of supply to Fuel Cell during maintenance	-Gas valve remains open when intended to be closed during maintenance	- Generation of undesired voltage during maintenance could lead to HV electric shock (fatality/major injury) - Potential release of Hydrogen	During operation the fuel cell will be locked within its own containment enclosure which disallows staff to get in close proximity. Maintenance of the fuel cell will be conducted in line with the manufacturers specifications, this will include adequate isolation of the system and discharging of residual voltages. Isolations will also be mandated where maintenance is occurring in close proximity to the fuel cell. After system shutdown, high voltages may remain on the fuel cell stacks for a length of time. During this time the stacks present a shock hazard and maintenance activities should not be performed. Residual reactants (oxygen and hydrogen) within the fuel cell module may cause the fuel cell output voltage to rise unexpectedly. Typical mechanisms for isolating train systems do not apply for hydrogen locomotives. This would normally consist of engine isolation or pantograph down, however the inclusion of Fuel Cells and Batteries means that hidden energy can be stored up. Fuel Cell will therefore require full discharge before maintenance activities can commence (even smalls amounts of Hydrogen can generate power). It is expected that the Fuel Cell would not be worked within (i.e. Line Replaceable Unit), however this will apply anywhere between Fuel Cell/Battery/voltage limiter and Dc/Dc converters (e.g. at connections to electrical cubicle). Electrical hazards are to be labelled on/in the fuel cell by fluorescent yellow 'ELECTRICAL HAZARD' labels. Otherwise, compliance to group standards required, to ensure separation, compartmentalisation and warning signs.

Inadequate operating condition of base vehicle	- Deterioration of base train during train downtime, - Inadequate re-commissioning activities, - Inadequate maintenance, - Inappropriate maintenance regime for vehicle in modified state - Inadequate replacement of deteriorated components, - Lack of pre-service inspections, - Unable to remove new systems to complete major maintenance tasks when they are due.	- Reduced effectiveness of equipment and train, - Failure of train.	The base vehicle will undergo a robust recommissioning process which will include checks of major and minor systems including: - Full brake test, - Compressor checks, - Traction Motor examinations, - Cab door examinations,
Train is stabled in unsafe location	- Stabling location has ignition risks in proximity, or could be susceptible to vehicle strikes (road or plant). - Stabling location is enclosed exasperating the consequences if a Hydrogen leak occurs. - Train is stabled near other trains in unsafe way (e.g. large collection of Hydrogen storage). - External operators operate other trains in vicinity of the hydrogen locomotive and may not be aware of its risks.	- Damage to equipment - Risk of ignition (fire/explosion)	Restrictions on stabling locations will need to be agreed with the operator and suitably risk assessed. Factors such as proximity to neighbours, ignition risks, other vehicle emissions etc need to be considered.

Unsafe refuelling operation	- Refuelling location not appropriate - Rupture of hoses draped between vehicles, - Service provider receptacle not compatible - Refuelling station pressure is not compatible with train. - Over-pressurisation of cylinders - Refuelling service provider not adequately competent, - Refuelling service provider not adequately risk assessed refuelling process/activity, - Unauthorised persons in close proximity to refuelling operation, - Hydrogen leakage, - Fast-fill operations generate heat of 65-70ºC, - Inappropriate earthing of refuelling van and vehicle (static). - Insertion of refueller/defueller nozzle into incorrect port - Incorrect fuel used (e.g. Diesel) - Refuelling causes static discharge - Refuelling occurs with train systems active	Consequences to safety including: - Fuel leakage outside vehicle, - Tripping hazard, - Exposure to high temperatures (e.g. rupture of hydrogen cylinders), - Serious injury. Consequences to operations including: - Unable to refuel vehicle, - Damage to refuelling interface, - Reputation damage.	Refuelling will be carried out when the locomotive is stabled and safely shutdown. No other activities may be carried out when refuelling is taking place and no personnel must board the locomotive during refuelling. No mobile phones or other electronic equipment, smoking or naked lights shall be in the vicinity of the refuelling activity As such an exclusion zone should be put in place during refuelling and warning signs erected around the refuelling point. Spark free tools shall be always used during refuelling. There may be a requirement to bond the internal pipework to minimise spark risk.

13 HOMOLOGATION REQUIREMENTS

Given the relatively recent adoption of hydrogen as a motive fuel, the governance of its use within rail vehicles is also still developing with specific homologation requirements still being drafted in many countries. The following sections are a summary of the most relevant standards and guidance relating to hydrogen powered rail vehicles currently available for projects such as this one.

13.1 HYDROGEN SYSTEMS

Hydrogen in Chile is regulated as a fuel under the Ministry of Energy and the Superintendency of electricity and fuels (SEC in Spanish). Outside the presence of any locally published standards specifically relating to the storage and use of hydrogen as a fuel for rail applications it is highly recommended to ask SEC if this project shall need it authorization.

In the absence of any standards or regulations specifically relating to hydrogen systems within trains, it is recommended that the project complies with standards under the European Community type-approvals framework. Under this framework the primary pieces of legislation relevant for the introduction of a hydrogen propulsion system are EC 79/2009, and EU 406/201, the associated implementing regulation. While the legislation is primarily aimed at hydrogen powered motor vehicles, there is precedent for the use of EC type-approval for the hydrogen system in isolation in a rail vehicle. The Alstom Coradia iLint hydrogen train used this approach to gain authorisation for the hydrogen system, then safe integration of the hydrogen power system into the train and the wider rail environment was completed using the Common Safety Method Risk Assessment as described in 402/2013/EC. Section 13.3 describes the standard European and UK approach for approving the use the hydrogen fuel cell trains.

However, given that EC type-approvals are only formally applicable to projects within the EU, a project outside of the EU can voluntarily conform with EC 79/2009, presenting a Technical File to a Notified Body against Hydrogen Legislation. This approach was used for the HydroFLEX 2.0 project, where the project voluntarily conformed to the EC type-approvals framework for the hydrogen storage and propulsion system.

In July 2022, the European Commission made the decision to withdraw EC 79/2009, and European type approvals for hydrogen vehicle systems and each installed components will be based on United Nations Regulation No. 134. However, UN R134 has a significantly limited scope when compared to EC 79/2009. For example, while EC 79/2009 considers pressure relief valves, pressure regulators, hydrogen filters and removable storage system connectors, these elements are omitted form UN R134. It is therefore recommended that any rail project voluntarily adopts and retains EC 79/2009 as the basis for compliance and components selection. The majority of gaseous hydrogen storage tanks available for use in vehicles have been designed and tested for compliance with EC79 or R134. Adherence to either standard represents a safe framework for the use and approval of hydrogen cylinders.

Notably, two standards are being developed for publication by the International Electrotechnical Commission (IEC) specifically for hydrogen fuel cell systems for use in trains, they are IEC 63341-1 'Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 1: Fuel cell power system' and IEC 63341-2 'Railway applications – Rolling stock – Fuel cell systems for propulsion -Part 2: Hydrogen storage system'. It is hoped that, upon completion and publication, these standards will be adopted for new rolling stock projects. These standards are due to be published in January 2025.

13.2 Battery and Electrical Systems

IEC 62928 *Railway applications. Rolling stock. Onboard lithium-ion traction batteries* is an international standard published by the International Electrotechnical Commission, IEC. It specifies the design, operational parameters, makes safety recommendations and type tests for onboard lithium-ion traction batteries for use in railway applications. Battery systems described in IEC 62928 are used for the energy storage system for the traction power of railway vehicles such as hybrid vehicles as defined in IEC 62864-1. IEC 62864-1 defines and provides a framework for series parallel hybrid traction systems in railway vehicles, shown in figure 44. Given the hydrogen fuel cell is to feed into a parallel hybrid system, with a lithium-ion battery provided as the energy storage system, it is recommended that the project is compliant with IEC 62928 and IEC 62864. A block diagram of a series hybrid system is outlined in figure 2 of section 4.1.2 of IEC 62864-1: 2016.

13.3 European Approach

Under the European Community type-approvals framework, the primary pieces of legislation relevant for the introduction of a hydrogen power system are EC 79/2009, and EU 406/201, the associated implementing regulation. While the legislation is primarily aimed at hydrogen powered motor vehicles (for use on roads), there is precedent for the use of EC type-approval for the hydrogen system in isolation in a rail vehicle. The Alstom Coradia iLint hydrogen train used this approach to gain authorisation for the hydrogen system, then safe integration of the hydrogen power system into the train and the wider rail environment was completed using the Common Safety Method Risk Assessment. However, given that EC type-approvals are no longer applicable following the UKs withdrawal from the EU, a UK project can voluntarily conform with EC 79/2009, presenting a Technical File to a Notified Body against Hydrogen Legislation. This approach was used for the HydroFLEX 2.0 project, where the project voluntarily conformed to the EC type-approvals framework for the hydrogen storage and propulsion system.

However, the safety measures in EC 79/2009 have not been proven in a railway context. Therefore, if these standards were to be adopted as codes of practice for rail, it is likely that technical changes, or guidance notes are created for the application of these standards in a railway environment. Given the relative novelty of hydrogen powered trains, there are other significant gaps arising from the use of hydrogen as a fuel in a rail vehicle. Some major gaps are considered below.

- **Applicability of EC 79/2009 to rail vehicle crashworthiness**

  The standards for the type-approval of the hydrogen power system (EC 79/2009 and EU 406/2010) are only applicable to road vehicles. However, EC 79/2009 and EU 406/2010 are being used as the primary source of requirements for the hydrogen power system by rolling stock manufacturers.

  Notably, an analysis of the engineering values found in Annex IV 'Requirements for hydrogen components and systems designed to use compressed (gaseous) hydrogen and their installation on hydrogen powered vehicles' should be carried out, against the requirements found in a relevant standard relating to passive structural safety, such as Railway Group Standard GMRT2100 'Rail Vehicle Structures and Passive Safety' in the UK and LOCPAS TSI 'Rolling Stock – Locomotive and Passenger' in the EU. This is due to the nature of crash and collision scenarios experienced by trains when compared to road vehicles. This analysis would also provide assurance the design parameters of the hydrogen system against forces and vibrations applied during normal rail operations.

- **Applicability of EU 406/2010 to the location of hydrogen systems in rail vehicles**

  The standards for the type-approval of the hydrogen power system (EC 79/2009 and EU 406/2010) are only applicable to road vehicles. Therefore, EU 406/2010 does not contain any requirements relating to the safe positioning of the hydrogen storage and propulsion system within a rail vehicle. This is especially relevant given that the hydrogen system may be positioned such that hydrogen is released into a part of the vehicle occupied by passengers. 'Flying ballast' – a phenomena where the aggregate used in the construction of trackwork becomes a projectile due to the forces of passing trains, has also been identified as a hazard for hydrogen systems placed on the underframe of a railway vehicle.

Given that EU 406/2010 only provides high-level requirements for the positioning of hydrogen propulsion and storage systems and does not consider the potential for 'flying ballast', the release of hydrogen into a compartment occupied by passengers and other hazards specific to a rail environment. Therefore, the requirements of EN 406/2010 should be assessed, considering the positioning of hydrogen systems within a rail vehicle. It is likely that the additional process of the Common Safety Method Risk Assessment (required in the UK and EU) would identify and provide a process for mitigation of these hazards. However, it is preferable for these requirements to be captured within the EC 79/2009 and EU 406/2010 framework already in use. A review of the engineering requirements for the safe positioning of hydrogen systems within a rail vehicle should be carried out and compared to requirements found in EU 406/2010.

- **3.4. Hydrogen emergency response standards & considerations**

HyResponse D6.3 includes guidance on the strategies and tactics to be deployed by emergency services for the management of hydrogen accidents associated with hydrogen powered road vehicles. Currently this guidance does not include any specific information on hydrogen powered rail vehicles. The emergency response requirements within HyResponse D6.3 do not consider any likely accident scenarios within the rail environment, including the release and ignition of hydrogen in enclosed structures following rail vehicles collision or derailment.

Therefore, the emergency response guidance within HyResponse D6.3 should be reviewed to consider its suitability for application to the rail environment. Of note should be the implications of a hydrogen accident within an enclosed structure, such as a tunnel, under a bridge or in an enclosed station. Direct engagement with first responder organisations and railway infrastructure managers should also be considered during the development of a hydrogen powered rail vehicle will also elicit suitable rail specific emergency response arrangements. This should particularly consider the procedures for the electrical isolation of any infrastructure-based electrification (overhead line equipment or conductor rails).

- **Applicability of safety integrity levels to hydrogen propulsion systems in rail**

  There are no specific rail requirements relating to the appropriate safety integrity level (SIL) for a hydrogen power safety instrumented system (as defined in EU 406/2010). Therefore, the applicability of EN 50129 'Railway applications. Communication, signalling and processing systems. Safety related electronic systems for signalling' should be considered for hydrogen power safety instrumented systems, given hazards and accident scenarios associated with hydrogen storage and propulsion systems.

- **3.7. Applicability of EN 45544 to hydrogen trains**

  Given the nature of possible hydrogen accident scenarios with a rail environment, alarm setting values will need to be proven to provide a suitable intervention point before hydrogen concentrations reach a lower explosive limit. Although alarm setting values for hydrogen detection are specified in BS EN 45544 'Workplace atmospheres. Electrical apparatus used for the direct detection and direct concentration measurement of toxic gases and vapours'; these values do not consider likely accident scenarios in a rail environment. Therefore, alarm settings may be inappropriate for the purposes and warning and escalation traincrew and passengers of an escalation of hydrogen pressures in particularly vulnerable rail environments such as in tunnels.

  Alarm setting values used in EN 45544 should be reviewed against foreseeable operational and accident conditions of a hydrogen powered train. Suitable alarm setting values should be selected such that the identification of a hydrogen hazard is made clear to traincrew at a suitable intervention point before a realisation of a hydrogen accident. The HyTunnel project will provide specific data and models for the accumulation of hydrogen in tunnels.

The FCH2RAIL (Fuel Cell Hybrid Power Pack for Rail Applications) project has conducted an extensive study and gap analysis of the legislative framework and technical standards[5]. This

[5] https://verkehrsforschung.dlr.de/public/documents/2022/FIRST_LEGISLATIVE_GAP_ANALYSIS.pdf

primarily considers the framework from the European perspective but should be considered in the development of any local guidance or framework.

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14 Supply Chain Study

It is prudent to consider the sourcing, costing and timescales involved with the equipment involved with a diesel to hydrogen-hybrid locomotive conversion well in advance of starting the detailed design phase of such a project. If the desired materials and components are out of budget or cannot be sourced within the timescales stipulated by the project, alternatives should be sought, or alternative actions taken accordingly. This section of the study will create a high-level bill of materials to provide an insight into the types of equipment available for the conversion and their respective advantages and disadvantages.

14.1 Bill of Materials

Using the outputs of sections 2, 3, 5 and 6, a high-level Bill of Materials (BOM) has been created, detailing recommendations for the fuel cell stack, gas storage cylinders and traction batteries (recommendations highlighted in green). Alternative hardware options have also been included. The BOM also includes the quantity of each component required and a justification as to why certain components were chosen over others. This BOM applies to both the SD-39 and SD-40 locomotives.

Table 21: Recommended equipment & suppliers (courtesy of VSTS)

Item No.	Item Description	Item Category	Qty. Required	Recommended or alternative?	Justification
1	**Luxfer *W322H35* G-Stor H2 Type III cylinder**	**Gas storage cylinder**	**36**	**Recommended**	**Proven equipment used by VSTS in previous projects. “Off-the-shelf” solution so good spares availability and shorter lead times. The additional weight of a type III cylinder (when compared to the equivalent type IV cylinders) does not significantly affect the weight of the locomotive.**
2	Hexagon Purus *Cylinder Designation 'I'* Type IV cylinder	Gas storage cylinder	33	Alternative	Not previously used by VSTS but suitable on paper. Type IV cylinders often present a higher cost then type III cylinders. However, type IV cylinders are significantly lighter than the equivalent type III. Therefore, if it is expected

					that the weight of the hydrogen - hybrid powerpack will exceed the weight of the existing equipment (internal combustion engine, generator etc.), type IV cylinders should be considered.
3	NPROXX H2 Storage Solutions Tank Raft	Gas storage cylinder	1	Alternative	Not previously used by VSTS, higher and longer installation costs plus bespoke system so higher overall costs. Type IV cylinders often present a higher cost then type III cylinders.
Item No.	**Item Description**	**Item Category**	**Qty. Required**	**Recommended or alternative?**	**Justification**
4	**Ballard Power Systems 100 kW FCmove-HD+ Rooftop module**	**Fuel Cell Stack**	**8**	**Recommended**	**Ballard Power Systems produce proven equipment used by VSTS in previous projects. The FCmove-HD+ Rooftop configuration of fuel cell stacks provides a power-dense solution, allowing easier packaging of fuel cell stacks and associated cooling systems within the locomotive body. It also offers a peak fuel efficiency of 57%.**
5	Cummins 90 kW HyPM™-HD90 power module	Fuel Cell Stack	9	Alternative	VSTS are familiar with fuel cell stacks produced by *Cummins*. Cummins' larger fuel cell stacks (including the HD90) typically operate at a high efficiency (59%). There is also significant precedent for the use of Cummins fuel cells in rail applications.

6	Plug Power 125kW ProGen P125 module	Fuel Cell Stack	8	Alternative	VSTS are familiar with fuel cell stacks produced by Plug Power in the ProGen range. ProGen fuel cell stacks have the significant advantage of featuring a fully integrated cooling system, reducing system complexity, and simplifying the process of integrating the fuel cells. P125 modules have a peak efficiency of 50%, lower than competitors. Therefore, it is recommended that 8 P125 modules are used, meaning a total fuel cell power of 1 MW. Each P125 module will then be de-rated to operate at 80% power. This will result in the modules operating closer to the peak efficiency and prolonging the life of the module.
7	**Hoppecke 220 kWh lithium-ion battery composition**	**Traction Battery**	**2**	**Recommended**	**VSTS are familiar with the Hoppecke range of railway traction batteries. 2 individual 200 kWh battery packs, totalling 440 kWh have been selected, as the individual 220 kWh module has been approved for use under IEC 62928 *Railway applications - Rolling stock - Onboard lithium-ion traction batteries*. It is likely that a single 440 kWh module could be created, however, it is likely that this approval process would need to be repeated, incurring an additional time and cost penalty.**
8	Akasol 111 kWh lithium-ion battery composition	Traction Battery	4	Alternative	Akasol lithium-ion batteries have precedent for reliable used in hydrogen fuel cell hybrid trains, and presents an option that is approved to IEC 62928. 4 individual 111 kWh cell compositions would be used, created a total of 444 kWh of battery capacity.

14.2 Hydrogen Storage Tanks

14.2.1 Luxfer

Table 22: Luxfer G-Stor H2 Type III cylinders (open-source data courtesy of Luxfer)[6]

Part number	Service pressure (bar)	Length (mm)	Diameter (mm)	Weight (kg)	Water volume (L)	H_2 capacity (kg)	Neck mount
L028H35-S	350	730	281	17	29	0.7	No
L028H35-N	350	730	281	17	27	0.65	Yes
L034H35	350	830	281	19	34	0.82	No
L039H35	350	926	281	21	39	0.94	No
Q042H35	350	740	340	26	42	1.01	No
Q052H35	350	875	340	29	52	1.25	No
Q095H35	350	1458	340	48	94	2.27	No
V068H35	350	850	400	36	68	1.65	No
V074H35	350	900	400	39	74	1.79	No
W150H35	350	1614	415	73	150	3.63	Yes
W205H35	350	2110	415	95	205	4.96	Yes
W322H35	350	3165	415	138	322	7.79	Yes
M053H70	700	1161	332	61	53	2.15	No

The Luxfer G-Stor H2 range of hydrogen storage cylinders have a significant history of use in a railway environment. The HydroFLEX project used Luxfer storage cylinders extensively, with HydroFLEX 1.0 using 4 x W205H35 units, and HydroFLEX 2.0 using 36 x W322H35 units. Luxfer G-Stor H2 cylinders are fully complaint with the EC/79 type approval framework.

[6] https://luxfercylinders.com/products/alternative-fuel/g-stor-h2-hydrogen-cylinders

14.2.2 Hexagon Purus

Table 23: Hexagon Purus Type IV cylinders (open-source data courtesy of Hexagon Purus)[7]

Cylinder Designation	Normal Working Pressure at 15°C (bar)	Outside diameter (mm)	Overall length (mm)	Cylinder weight (kg)	Water volume (L)	Hydrogen capacity (kg)	Neck mount	Approval
A	250	503	2342	94	350	6.3	Yes	TPED
B	250	654	2413	147	581	10.4	Yes	ABS/US DOT
C	250	653	4419	267	1170	21.0	Yes	ABS/US DOT
D	250	653	5689	342	1544	27.8	Yes	ABS/US DOT
E	300	509	2342	112	350	7.4	Yes	TPED
F	318	503	2342	94	350	7.8	Yes	TPED
G	350	430	3190	101	312	7.5	Yes	EC79/HGV2
H	350	430	2110	67	193	4.7	Yes	EC79/HGV2
I	350	509	2342	112	350	8.4	Yes	EC79
J	381	509	2342	112	350	9.0	Yes	TPED
K	500	520	2357	180	333	10.6	No	TPED
L	700	332	921	33	36	1.4	Yes	EC79
M	700	440	1050	59	76	3.1	Yes	R-134/HGV2
N	700	530	2154	188	244	9.8	Yes	EC79/HGV2
O	700	705	2078	272	457	18.4	Yes	R-134/HGV2
P	900	515	2783	365	254	12.4	Yes	PED/US DOT

[7] https://hexagonpurus.com/our-solutions/hydrogen-systems/hydrogen-type-4-cylinders

Hexagon Purus provide a significant range of hydrogen storage cylinders for use in heavy vehicles. There is also precedent for the use of Hexagon Purus cylinders in a railway environment. Hexagon have been selected to supply cylinders for Talgo's prototype fuel cell multiple unit train, Vittal-One[8] and Stadler's fuel cell FLIRT train for use in California[9] Alstom's Coradia iLint uses X-STORE hydrogen tanks supplied by Hexagon Experio[10] (now Hexagon Purus), providing 90 kg of Hydrogen storage per car.[11] The cylinder composition was produced by Wystrach[12]. Wystrach GmbH has now been fully acquired by Hexagon Purus.[13] Table [24] shows the range of cylinders available, alongside any approvals for each cylinder.

14.2.3 NPROXX H2 Storage Solutions

NPROXX provide a range of type IV hydrogen storage tanks and roof mounting system to be used on Siemens Mireo Plus H[14]. It Is therefore assumed that NPROXX cylinders are certified for use in a railway environment. Details and technical specifications of NPROXX hydrogen storage for use in mobility are not publicly available. However, consideration should be given to NPROXX due to their previous and continued use in a railway environment.

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8 https://hexagonpurus.com/news/hexagon-purus-selected-by-talgo-for-first-zero-emission-hydrogen-train-in-spain

9 https://hexagongroup.com/news/hexagon-purus-to-supply-composite-high-pressure-cylinders-for-the-development-of-the-first-hydrogen-powered-commuter-train-in-the-u-s

10 https://www.railengineer.co.uk/hydrail-comes-of-age/

11 https://www.urban-transport-magazine.com/en/hydrogen-fuel-cells-zero-emission-passenger-trains/

12 https://www.wystrach.gmbh/en/products/wytanksystems/

13 https://ml-eu.globenewswire.com/Resource/Download/574b3a68-ce23-47f2-b551-b1cf2c949901

14 https://fuelcellsworks.com/news/nproxx-develops-advanced-hydrogen-train-tank-mountings/

14.3 Hydrogen Fuel Cell Stacks

14.3.1 BALLARD Power Systems

Table 24: Ballard Power Systems PEM fuel cells (open-source data courtesy of Ballard Power System)[15]

Model	Net Power (kW)	Idle Power (kW)	Weight (kg)	Current (A)	DC voltage range (V)	Length (mm)	Width (mm)	Height (mm)
FCveloCity-MD	30	0	125	0 - 300	85 - 180	900	480	375
FCveloCity-HD85	85	4	256	10 - 284	260 - 419	1130	869	487
FCveloCity-HD100	100	6	280	10 - 257	357 - 577	1200	869	487
FCveloCity-HD6	150	-	-	-	-	-	-	-
FCmove-HD	70	8	250	20 - 240	250 - 500	1812	816	415
FCmove-HD+ Engine Bay	100	9	260	20 - 360	280 - 560	1056	630	650
FCmove-HD+ Rooftop	100	9	260	20 - 360	280 - 560	1996	802	440
FCwave	200	30	875	2 x 300	350 - 720	1220	738	2200

Ballard Power Systems are a significant developer and manufacturer of proton exchange membrane, PEM, hydrogen fuel cell stacks, primarily in the area of heavy-duty transport. There is also significant precedent for the use of Ballard fuel cells in rail vehicles. For example, a Ballard FCveloCity-HD100 was used on HydroFLEX 1.0 and The Arcola Energy/University of St Andrews Class 314 passenger train retrofit project utilises utilise a 70 kW FCmove-HD fuel cell.

[15] https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/motive-modules

14.3.2 Plug Power

Table 25: Plug Power PEM fuel cells (open-source data courtesy of Plug Power)[16]

Model	Rated Net Power (kW)	Idle Power (kW)	Weight (kg)	Current (A)	DC voltage range (V)	Length (mm)	Width (mm)	Height (mm)
P15	15	-	248	-	80 OR 280 - 430	985	674	567
P30	30	-	240	-	280 - 430 OR 500 - 750	1341	833	415
P85	85	-	240	-	280 - 430 OR 500 - 750	1005	700	400
P125	125	-	350	-	280 - 430 OR 500 - 750	1400	700	400

Plug Power Inc. are an American company, primarily developing Proton Exchange Membrane (PEM) hydrogen fuel cell stacks, with products aimed at the mobility and backup power markets. In 2020, Plug Power introduced 125 kW Progen fuel cell engines for heavy trucks and light railway applications.[17]

The HydroFLEX 2.0 train utilises 4 x P125 fuel cells, providing a total fuel cell power output of 500 kW. However, to increase the reliability and useful service life of the fuel cell stacks, the HydroFLEX 2.0 project took the decision to de-rate the maximum output of each fuel cell from 125 kW, down to 100 kW. This strategy enables a 400 kW total fuel cell output that is expected to remain constant throughout the service life of the train.

[16] https://www.plugpower.com/fuel-cell-power/progen/
[17] https://www.greencarcongress.com/2020/02/20200218-plugpower.html

14.3.3 CUMMINS (FORMERLY HYDROGENICS)

Table 26: Cummins HD fuel cells (open-source data courtesy of Cummins)[18]

Model	Rated Net Power (kW)	Peak Efficiency (%)	Weight (kg)	Current (A)	DC voltage range (V)	Length (mm)	Width (mm)	Height (mm)
HD 8	8.5	51	52	0 - 380	20 - 40	379	406	261
HD 10	10.5	53	47	0 - 425	24 - 48	408	406	261
HD 15	16.5	53	55	0 - 425	32 - 64	494	406	261
HD 30	31	59	72	0 - 500	60 - 120	719	406	261
HD 45	45	59	95	0 - 450	88 - 180	848	406	255
HD 90	93	59	360	0 - 500	180 - 360	1582	1085	346

Hydrogenics was a manufacturer of PEM fuel cell stacks and electrolyser stacks. In 2019, Cummins Inc. acquired a majority stake In Hydrogenics, and branded all former Hydrogenics products as Cummins.

The worlds first hydrogen fuel cell passenger train, Alstom's Coradia iLint uses a roof-mounted 200 kW PEM fuel cell composition built from 6 x 33 kW FC HyPM™-HD30 power modules by Hydrogenics[19] (now Cummins). It should be noted that the HD 90 fuel cell is simply a composition created using three individual HD 30 modules, with common manifolds and connections.

[18] https://www.cummins.com/new-power/technology/fuel-cell
[19] https://www.urban-transport-magazine.com/en/hydrogen-fuel-cells-zero-emission-passenger-trains/

14.4 Traction Batteries

Individual traction battery arrangements are not detailed here as batteries can be configured using standard cells by battery manufacturers and cell integrators into whatever arrangement is desired by the customer and specific project.

14.4.1 AKASOL

AKASOL provides the lithium-ion traction batteries for the Alstom Coradia iLint, with two battery systems providing a combined capacity of 220kWh, with a C-Rate of C3.[20] Each 800 V battery system has 111 kWh, with a mean discharge of 225 kW, and a peak discharge of 450 kW.21

14.4.2 HOPPECKE

Hoppecke provided the traction battery system for HydroFLEX 2.0. It has a capacity of 220 kWh and has a discharge rate of up to 400kW. This system was integrated into the train, by Gemini Rail Services, who provided auxiliary battery functional equipment, such as the battery thermal management system and battery module converter. Hoppecke are also the main battery supplier for VivaRail Ltd[22] in their D-Train family.

14.4.3 MITRAC (Bombardier, now Alstom)

The Bombardier Talent 3 electric-battery hybrid unit has four traction lithium-ion MITRAC batteries with a total capacity of 300 kWh[23]

14.4.4 DENCHI

HydroFLEX 1.0 utilised two 42 kWh Denchi lithium-ion battery packs.[24]

14.4.5 Rolls-Royce/MTU

As part of the MTU EnergyPack arrangement, there a selection of rail-approved large lithium-ion traction batteries are available from Rolls-Royce/MTU for use in hybrid drive systems.[25] Batteries are available in configurations with storage up to 122.4 kWh.

[20] https://www.akasol.com/en/news-akasol-alstom-order
[21] https://www.urban-transport-magazine.com/en/hydrogen-fuel-cells-zero-emission-passenger-trains/
[22] https://www.hoppecke.com/en/news/vivarail-and-hoppecke-long-term-supply-of-batteries-for-class-230s/
[23] https://www.toi.no/getfile.php?mmfileid=52027
[24] https://link.springer.com/content/pdf/10.1007/s40534-021-00256-9.pdf
[25] https://www.mtu-solutions.com/eu/en/products/rail-products-list.html?wcmmode=388

14.5 Costings

In 2022 the nominal cost of each component part of the system as described by this study is as follows:

Table 27: Costings summary (courtesy of VSTS)

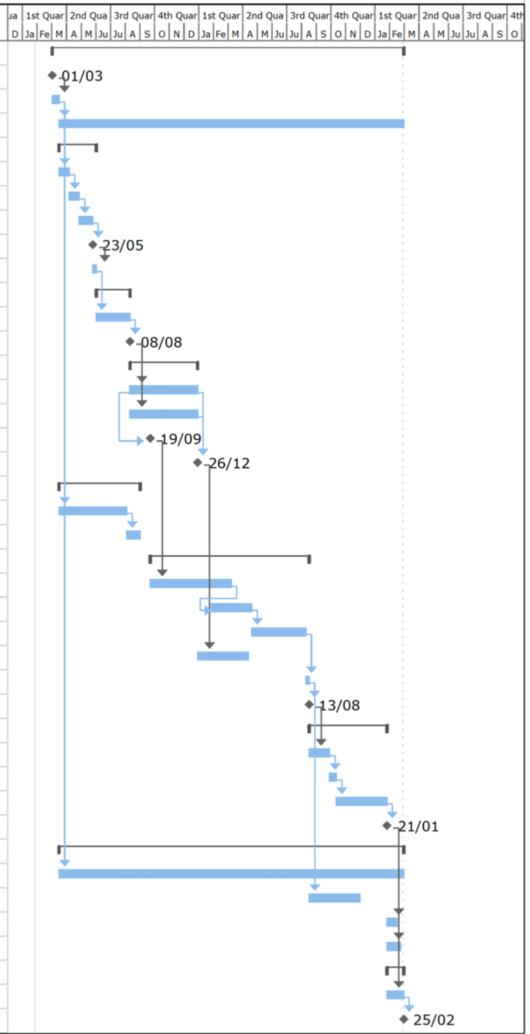
	Hydrogen Storage	Fuel Cell Stack	Lithium Traction Battery
Price per unit	$2,700 per kg of stored hydrogen	$2,500 per kW of fuel cell output power	$600 per kWh capacity
Total for project	$756,000 (based on storage for a nominal 280kgs)	$1.5 million for a 600kW system $2m for an 800kW system	$264,000

The figures in table 27 are indicative only and do not include costs such as, but not limited to, Project Management, detailed design, travel/accommodation, plant hire, commissioning, control systems design and supply, shipping fees/duties and warranties. A nominal provision of between 25% and 50% of the total values from table 27 should be made to account for these additional costs.

15 Transformation Plan

Based on the data limited to that on which this report is written, a top-level transformation plan can be found in figure 44. A more detailed transformation plan would be drafted on completion of detailed design when every aspect of the design has been established.

	Task Name	Re	Duration	Start	Finish	Predecessors	Work
1	**WP1 Project Management and Mobilisation**		**520 days**	**Wed 01/03/23**	**Tue 25/02/25**		**0 hrs**
2	Project Start		0 days	Wed 01/03/23	Wed 01/03/23		0 hrs
3	Project Mobilisation		2 wks	Wed 01/03/23	Tue 14/03/23	2	0 hrs
4	Ongoing Project Management		102 wks	Wed 15/03/23	Tue 25/02/25	3	0 hrs
5	**WP2 Detailed Feasibility**		**55 days**	**Wed 15/03/23**	**Tue 30/05/23**		**0 hrs**
6	Route Review		3 wks	Wed 15/03/23	Tue 04/04/23	3	0 hrs
7	Simulation		3 wks	Wed 05/04/23	Tue 25/04/23	6	0 hrs
8	Equipment and Packaging Study		4 wks	Wed 26/04/23	Tue 23/05/23	7	0 hrs
9	Base Concept Chosen		0 days	Tue 23/05/23	Tue 23/05/23	8	0 hrs
10	Design Brief Created		1 wk	Wed 24/05/23	Tue 30/05/23	9	0 hrs
11	**WP3 Concept Design**		**50 days**	**Wed 31/05/23**	**Tue 08/08/23**		**0 hrs**
12	Concept Design		10 wks	Wed 31/05/23	Tue 08/08/23	10	0 hrs
13	Concept Design Finalised		0 days	Tue 08/08/23	Tue 08/08/23	12	0 hrs
14	**WP4 Detailed Design**		**100 days**	**Wed 09/08/23**	**Tue 26/12/23**		**0 hrs**
15	Detailed Mechanical Design		20 wks	Wed 09/08/23	Tue 26/12/23	13	0 hrs
16	Detailed Electrical/Concept Design		20 wks	Wed 09/08/23	Tue 26/12/23	13	0 hrs
17	Major Components Ready for Procurement		0 days	Tue 19/09/23	Tue 19/09/23	15SS+6 wks	0 hrs
18	Design Ready for Manufacture		0 days	Tue 26/12/23	Tue 26/12/23	15,16	0 hrs
19	**WP5 Standards Compliance**		**120 days**	**Wed 15/03/23**	**Tue 29/08/23**		**0 hrs**
20	Standards review		20 wks	Wed 15/03/23	Tue 01/08/23	3	0 hrs
21	Recommendations for project		4 wks	Wed 02/08/23	Tue 29/08/23	20	0 hrs
22	**WP6 Procurement and Build**		**235 days**	**Wed 20/09/23**	**Tue 13/08/24**		**0 hrs**
23	Major Component Lead Times		24 wks	Wed 20/09/23	Tue 05/03/24	17	0 hrs
24	Sub-Assembly Build		12 wks	Wed 24/01/24	Tue 16/04/24	23FS-6 wks	0 hrs
25	PMU Assembly		16 wks	Wed 17/04/24	Tue 06/08/24	24	0 hrs
26	Locomotive Modification		15 wks	Wed 27/12/23	Tue 09/04/24	18	0 hrs
27	QA Approval		1 wk	Wed 07/08/24	Tue 13/08/24	25	0 hrs
28	PMU Ready for Testing		0 days	Tue 13/08/24	Tue 13/08/24	27	0 hrs
29	**WP7 Testing and Commissioning**		**115 days**	**Wed 14/08/24**	**Tue 21/01/25**		**0 hrs**
30	Initial Static Testing (load bank & locomotive test		6 wks	Wed 14/08/24	Tue 24/09/24	28	0 hrs
31	Integration with Locomotive		2 wks	Wed 25/09/24	Tue 08/10/24	30	0 hrs
32	Dynamic Testing		15 wks	Wed 09/10/24	Tue 21/01/25	31	0 hrs
33	Testing Completed		0 days	Tue 21/01/25	Tue 21/01/25	32	0 hrs
34	**WP8 Commercialisation and Next Steps**		**510 days**	**Wed 15/03/23**	**Tue 25/02/25**		**0 hrs**
35	Marketing		102 wks	Wed 15/03/23	Tue 25/02/25	3	0 hrs
36	Development Plan		15 wks	Wed 14/08/24	Tue 26/11/24	27	0 hrs
37	Lessons Learnt from Build		3 wks	Wed 22/01/25	Tue 11/02/25	33	0 hrs
38	Next Steps		4 wks	Wed 22/01/25	Tue 18/02/25	33	0 hrs
39	**WP9 Project Close/Reporting**		**25 days**	**Wed 22/01/25**	**Tue 25/02/25**		**0 hrs**
40	Final Reporting		5 wks	Wed 22/01/25	Tue 25/02/25	33	0 hrs
41	Project Closed		0 days	Tue 25/02/25	Tue 25/02/25	40	0 hrs



16 Summary

Based on the findings within this report, it has been determined that it is theoretically possible to power a SD-39 or SD-40 locomotive using hydrogen as a fuel. The reliability of these conclusions has been determined based on the accuracy of the data provided, the availability of equipment at the time of writing and the judgements made owing to Vanguard's real-world experience with diesel-hydrogen conversions.

Notably, it was discovered that despite the limited space available within the locomotive body, between 270kg and 280kg of hydrogen could be carried onboard, of which between 255kg to 264kg would be usable whilst preserving the minimum pressure in the tanks needed to operate the fuel cells. This, crucially, could be achieved using readily available equipment already proven for use within rail vehicles (at the time of writing).

Alongside methods of integrating the new technology with existing technology within the locomotives and following closer inspection of the locomotive control systems, it has also been established that there should be minimal changes to the way in which the locomotives are operated and even potential reductions in the maintenance activities required for the locomotives (and resultant cost savings).

Finally, subject to closer inspection, the consideration of hydrogen supplies (both existing and conceptual) has been deemed sufficient for the operation of a hydrogen powered freight service across the given routes.

16.1 Recommendations

It is recommended that out of the two routes and locomotives investigated, the central zone route and the SD-39 locomotive is the most suitable for the adoption of Hydrogen-Hybrid technology. The main reasoning for this is as follows:

1. A SD-39 locomotive on the central zone line will require 25% less installed fuel cell power compared to a SD-40 conversion for the central – south zone route (600kW vs 800kW).
2. Twice as much hydrogen can be carried in each train as two locomotives are used instead of one. Theoretically, two round trips could be achieved by a train powered by two SD-39 locomotives without fuelling.

3. The Air Products facility at Graneros is located only 17km away from the central zone route´s origin fuelling point by road. Thus, a source of hydrogen is potentially available close to the route.

16.2 Next Steps

All outputs from this initial feasibility study are the result of remotely gathering and processing information around the locomotives, their respective routes and the nature of the environments in which they are used as supplied by the operator.

Before any definitive conclusions over whether to perform any diesel to hydrogen conversions are made, a proposal for the detailed design work and execution of the works must be agreed upon to enable all parties build upon the foundations laid by this report and facilitate the conversion(s) to the satisfaction of all parties involved.

This would most likely involve a site visit from Vanguard to thoroughly survey the locomotives in question in addition to commercial discussions with GIZ and TRANSAP.

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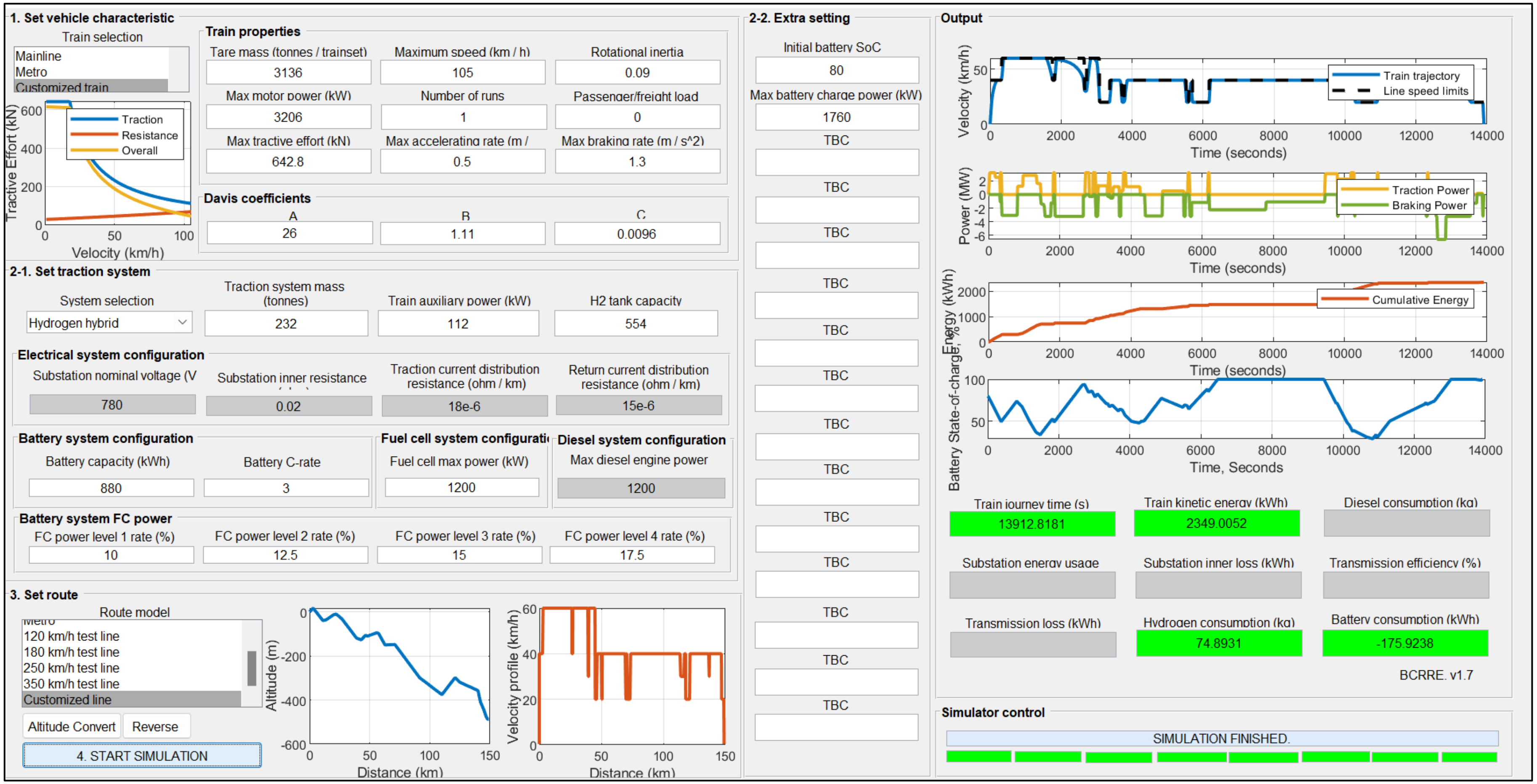
Appendices

Appendix A: Origin to Destination of the Central Zone Route Results



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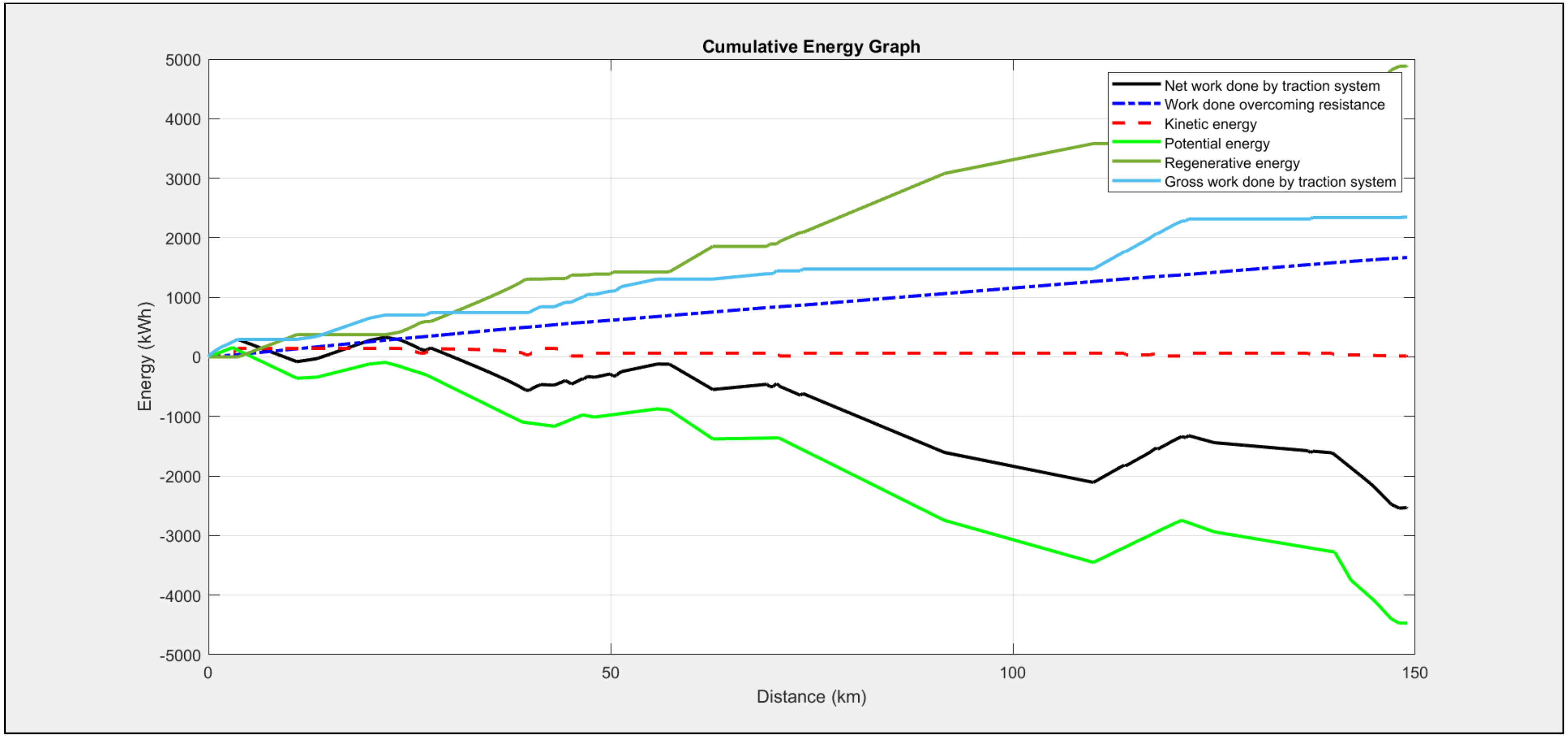
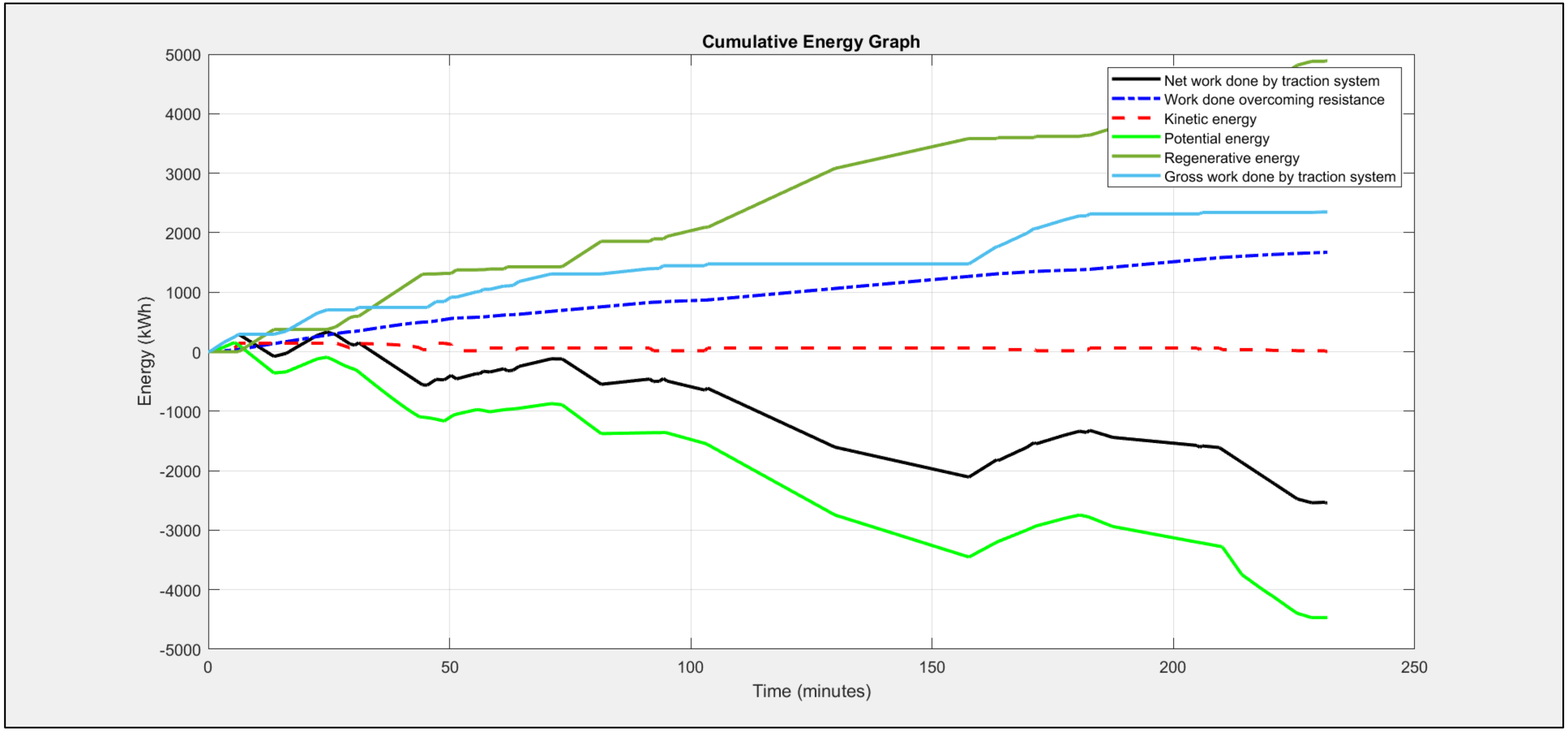
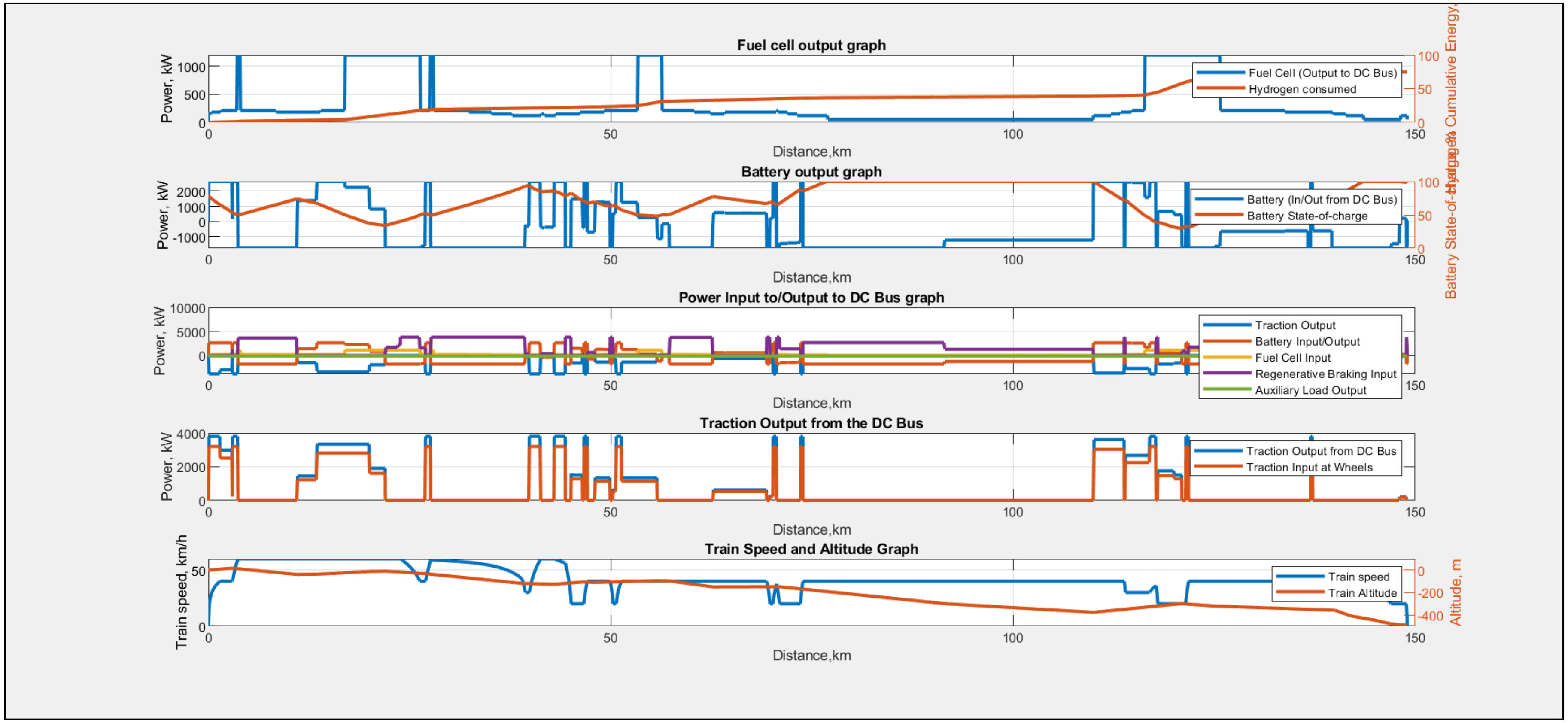
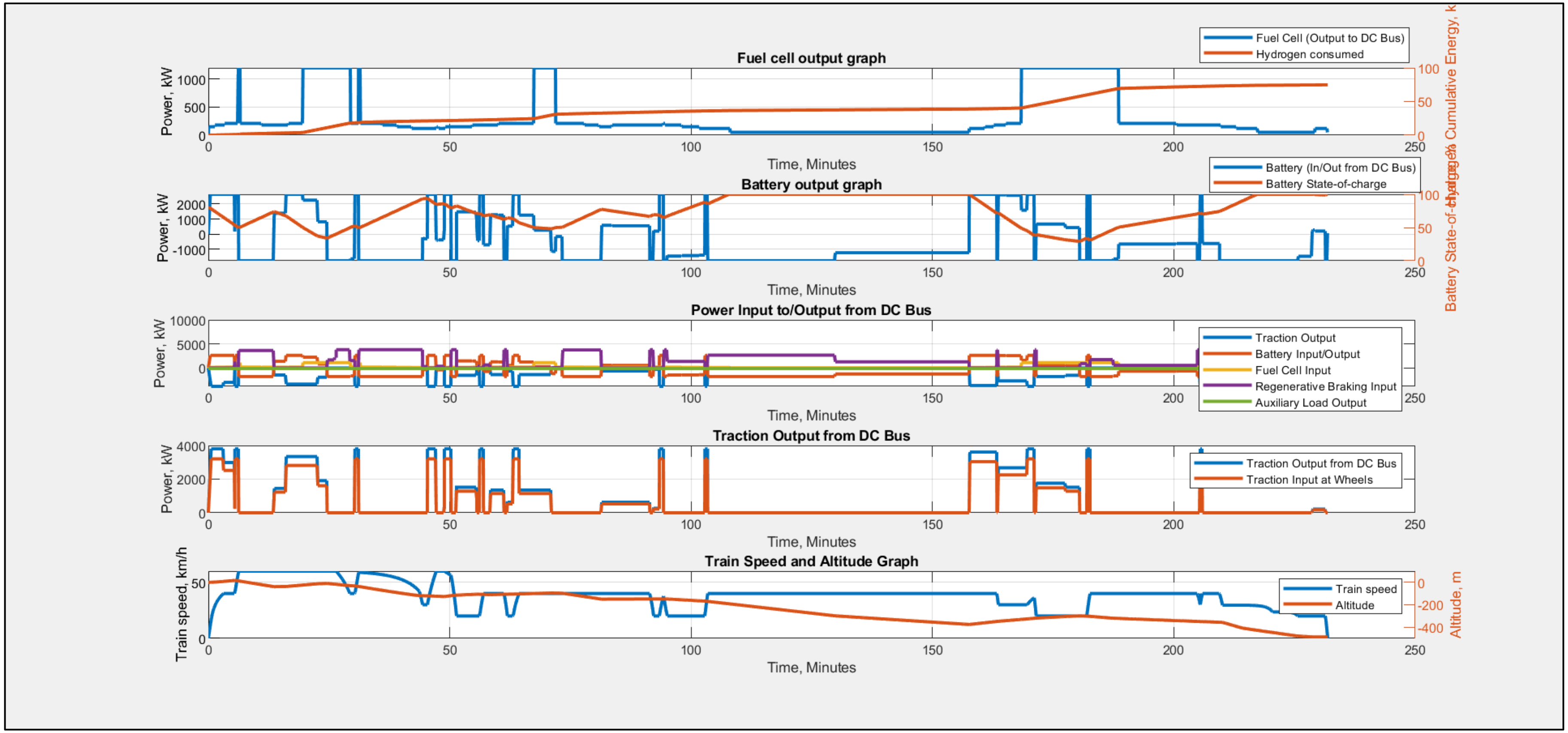
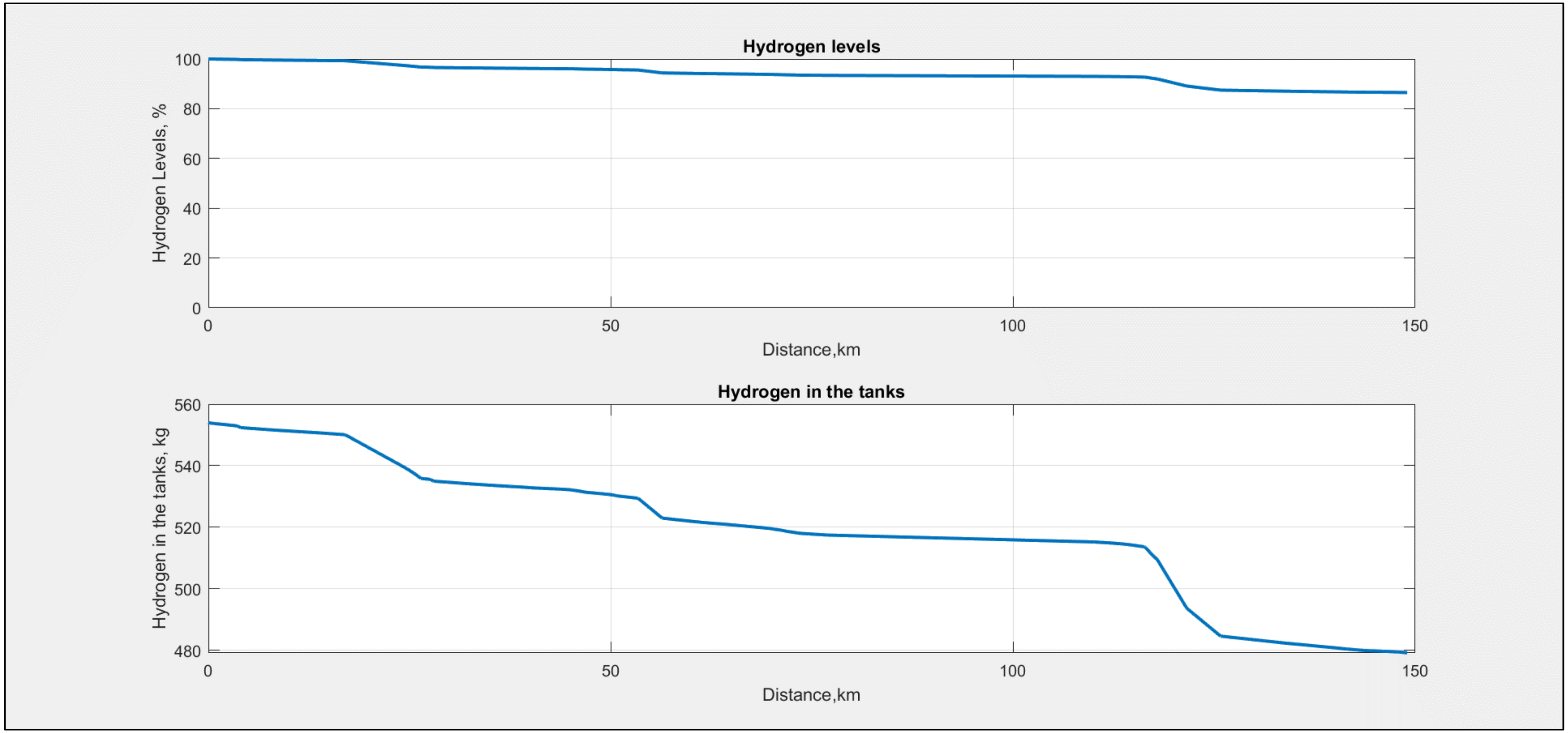
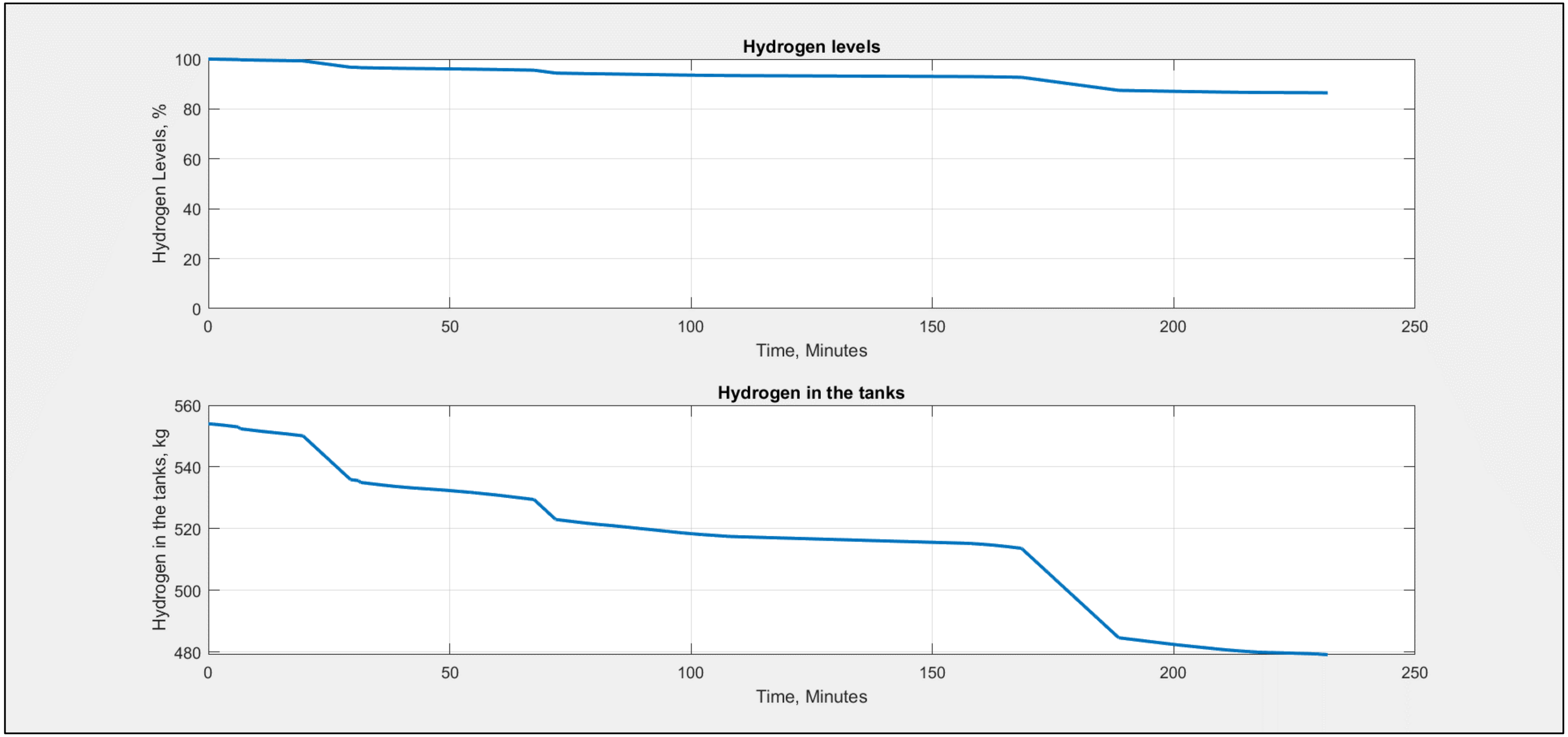



Cumulative Energy Graph
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system
Energy (kWh)
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
0
50
100
150
200
250
Time (minutes)

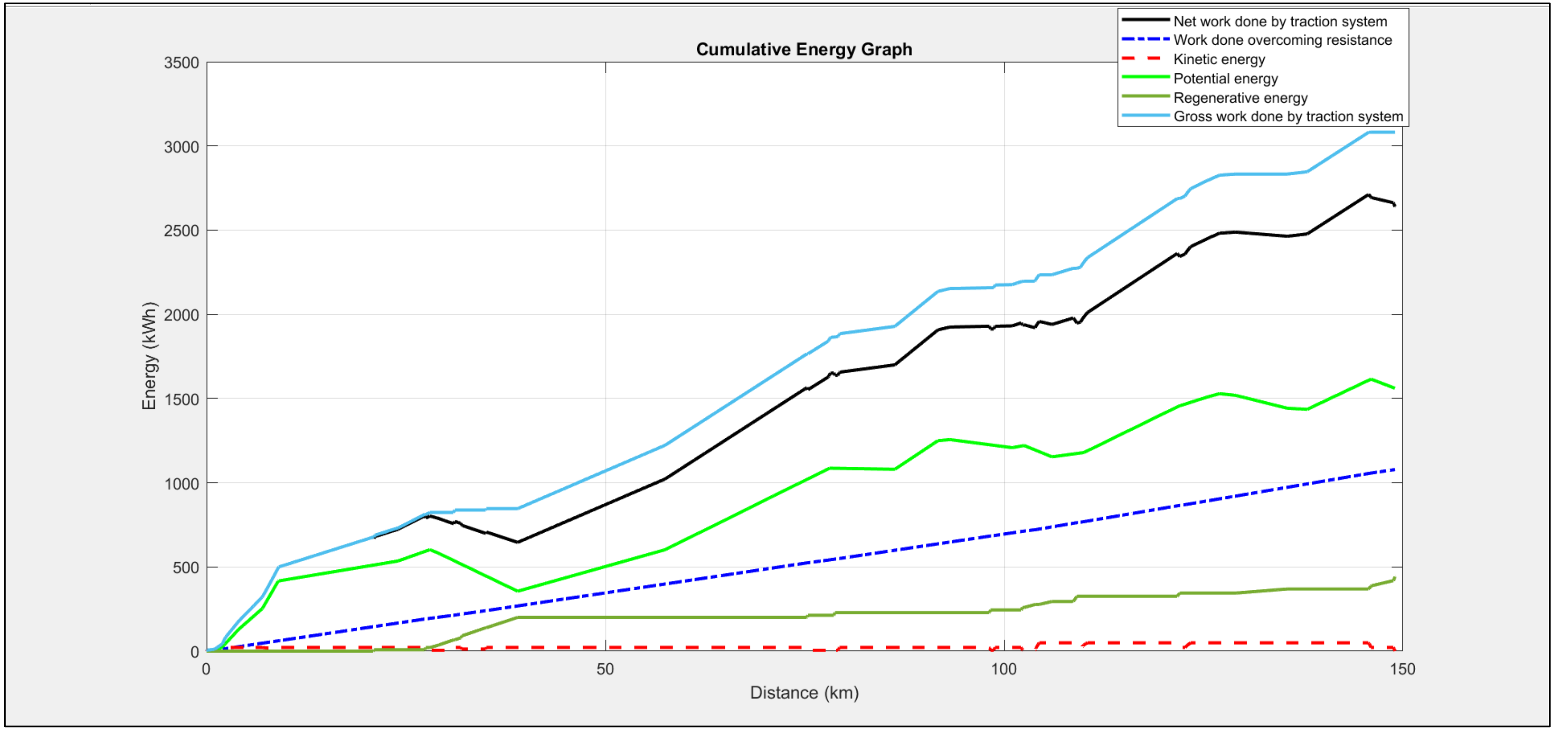

Fuel cell output graph
Power, kW
Distance,km
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Hydrogen % Cumulative Energy
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge %
Power Input to/Output to DC Bus graph
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from the DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Altitude, m
Train speed
Train Altitude

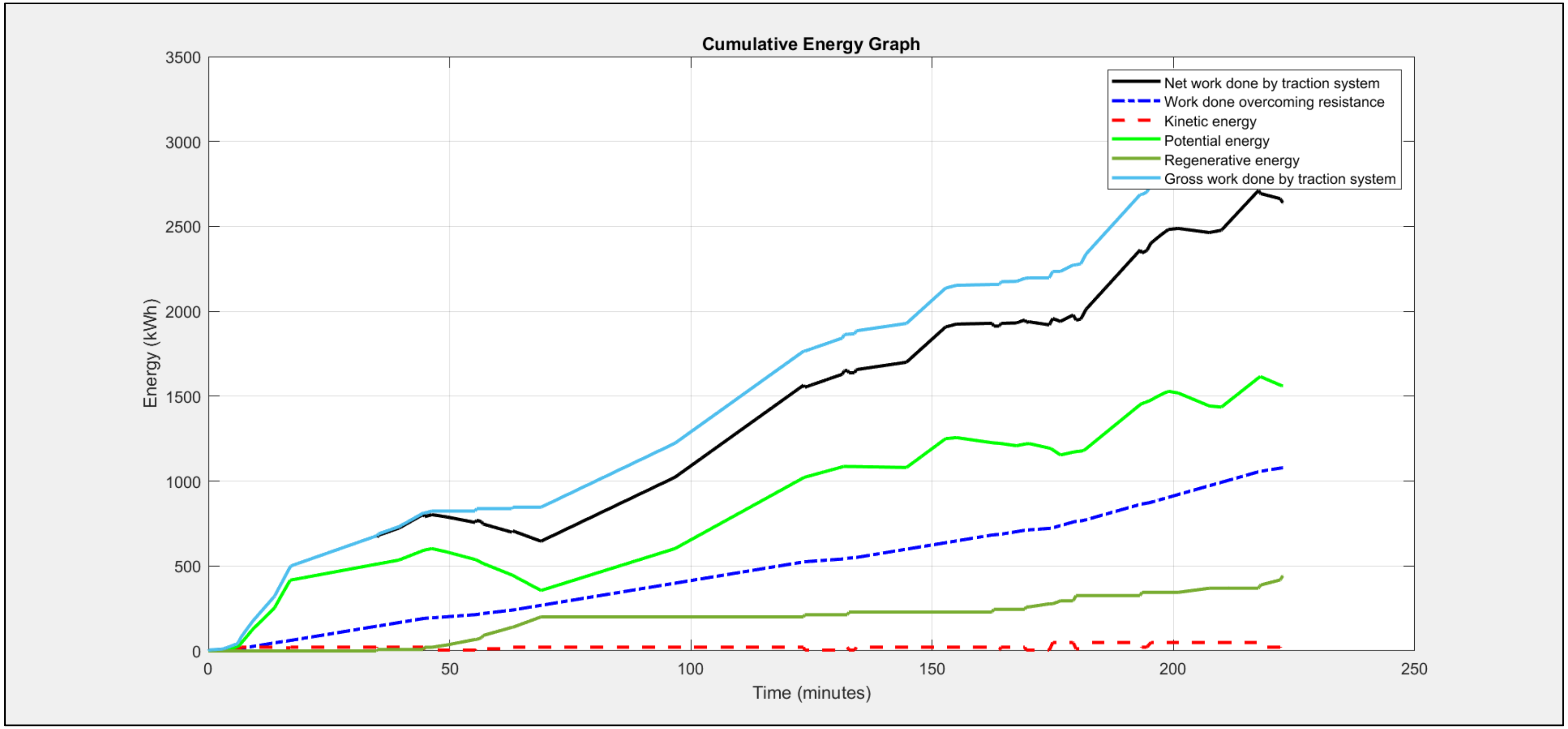

Fuel cell output graph
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Power, kW
Time, Minutes
Hydrogen Cumulative Energy, k
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output from DC Bus
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed
Altitude
Train speed, km/h
Altitude, m

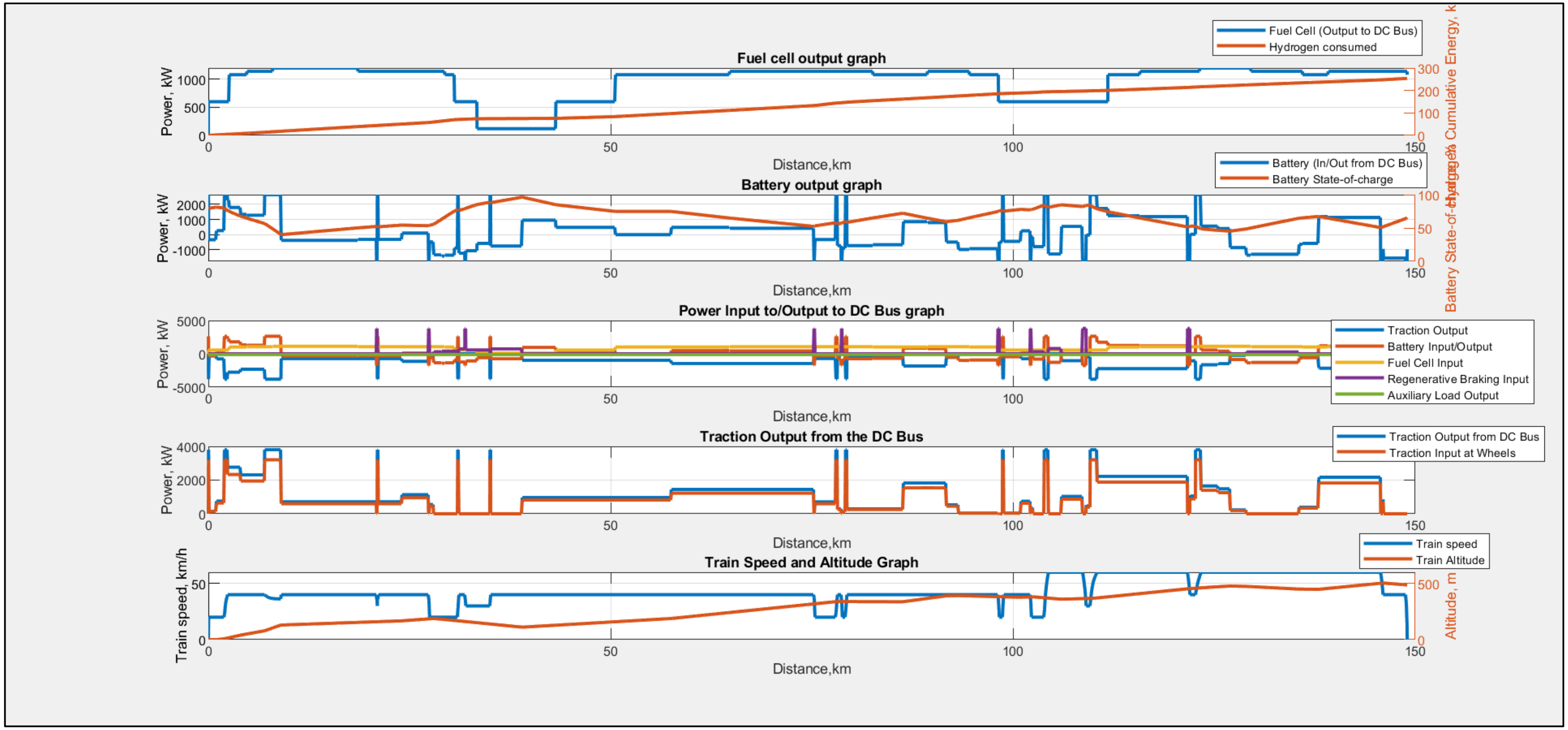

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
Distance,km
Hydrogen in the tanks
Hydrogen in the tanks, kg
560
540
520
500
480
0
50
100
150
Distance,km

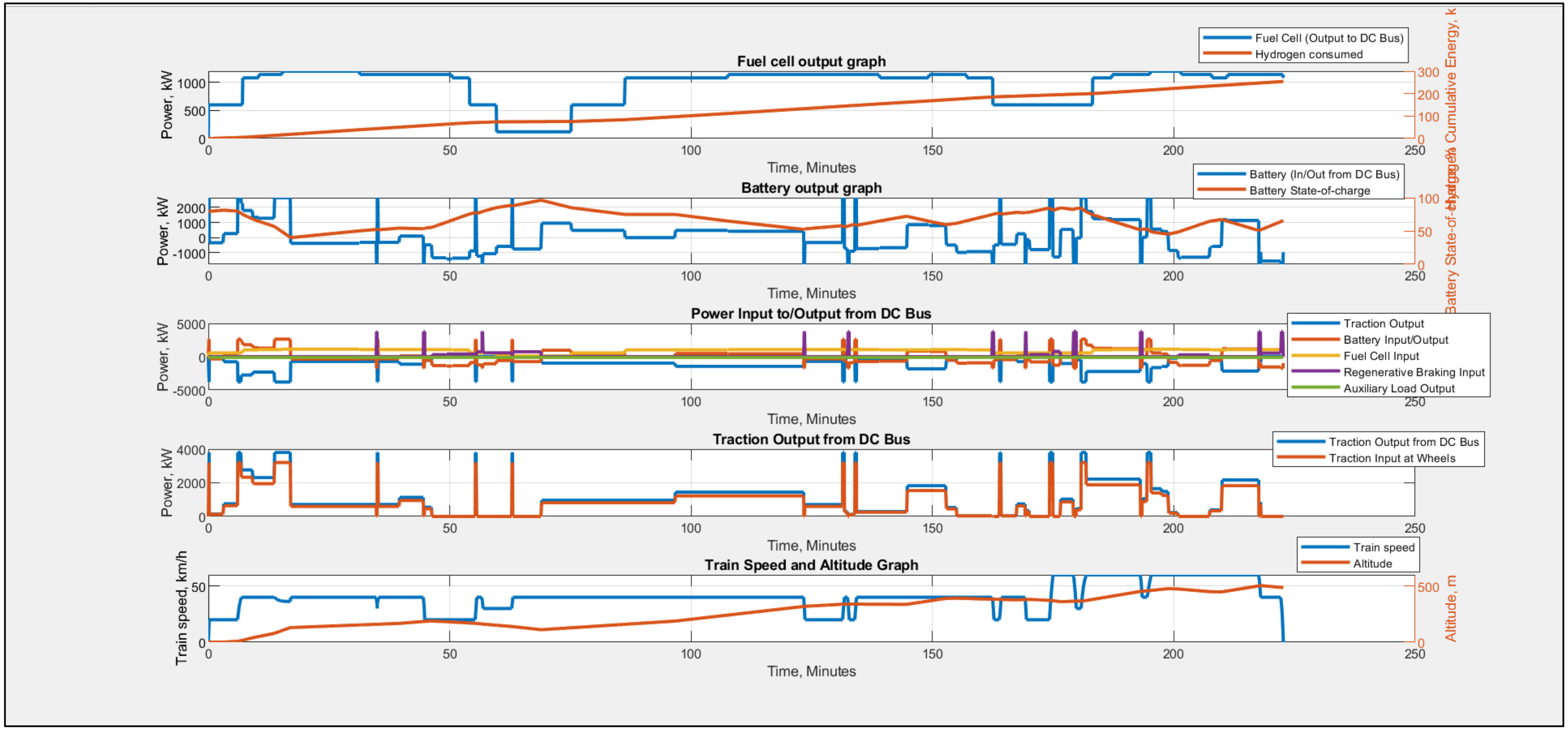

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
200
250
Time, Minutes
Hydrogen in the tanks
Hydrogen in the tanks, kg
560
540
520
500
480
0
50
100
150
200
250
Time, Minutes

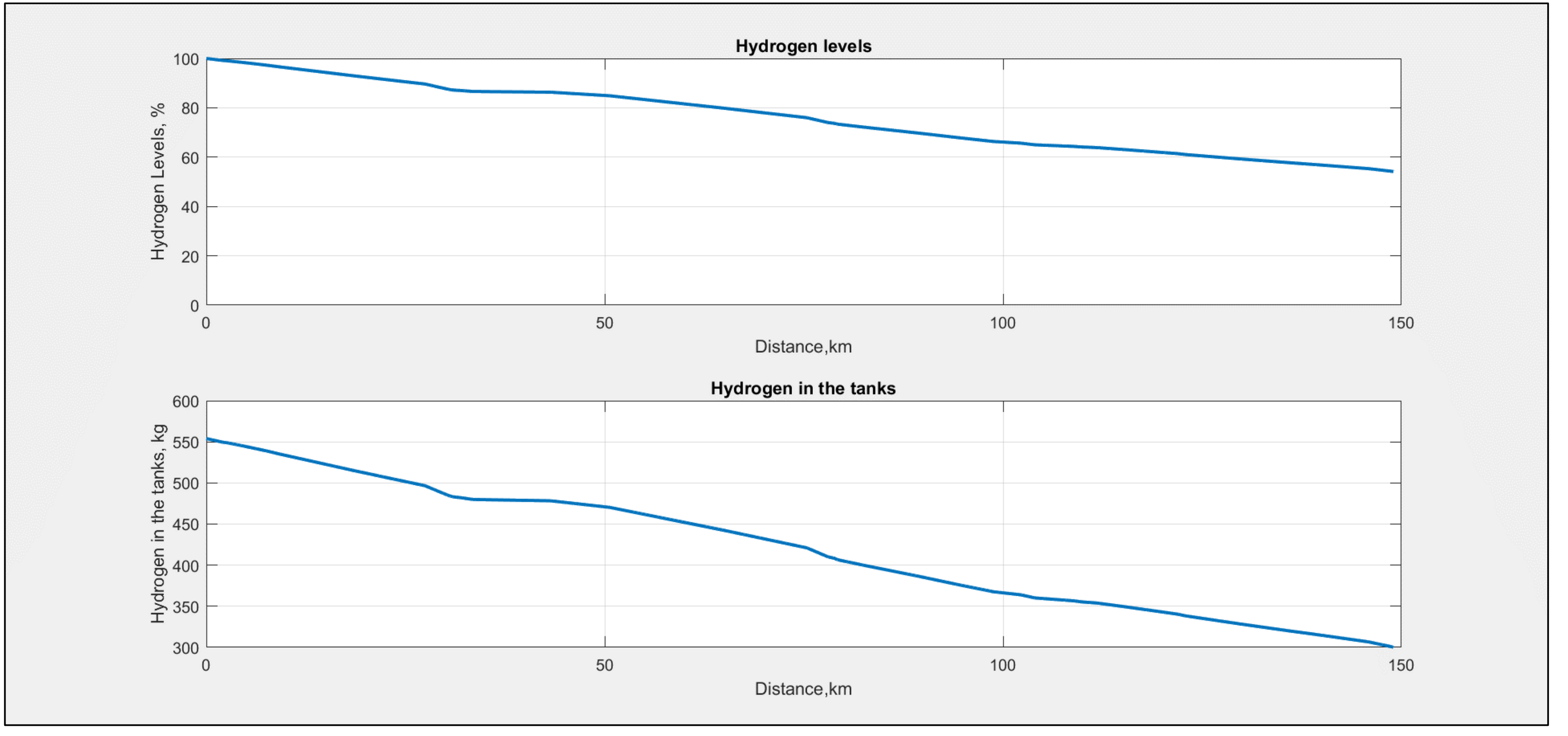
APPENDIX B: DESTINATION TO ORIGIN OF THE CENTRAL ZONE ROUTE RESULTS

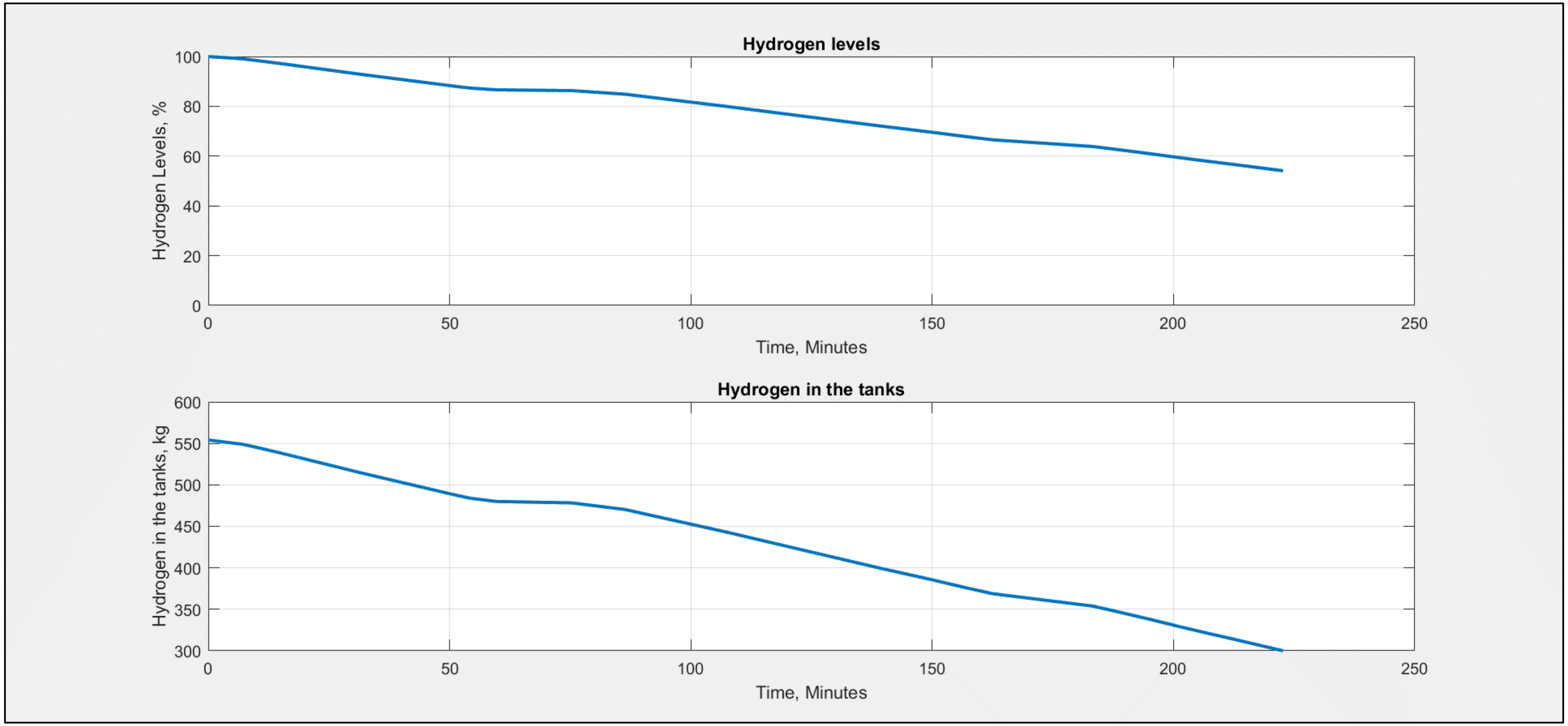

Cumulative Energy Graph
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system
Energy (kWh)
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
Distance (km)


Cumulative Energy Graph
Energy (kWh)
Time (minutes)
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system

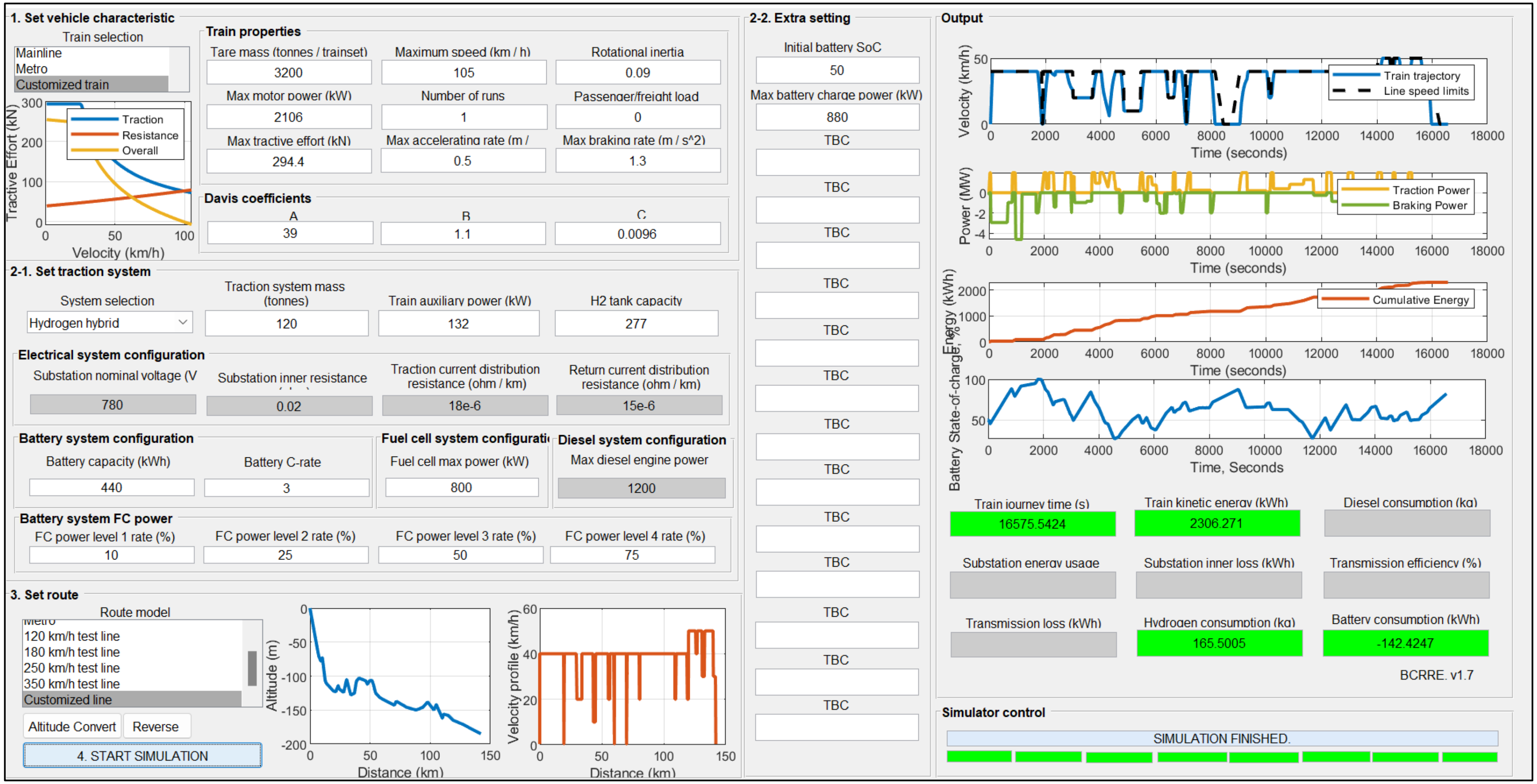

Fuel cell output graph
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Power, kW
Distance,km
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output to DC Bus graph
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from the DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed
Train Altitude
Train speed, km/h
Altitude, m

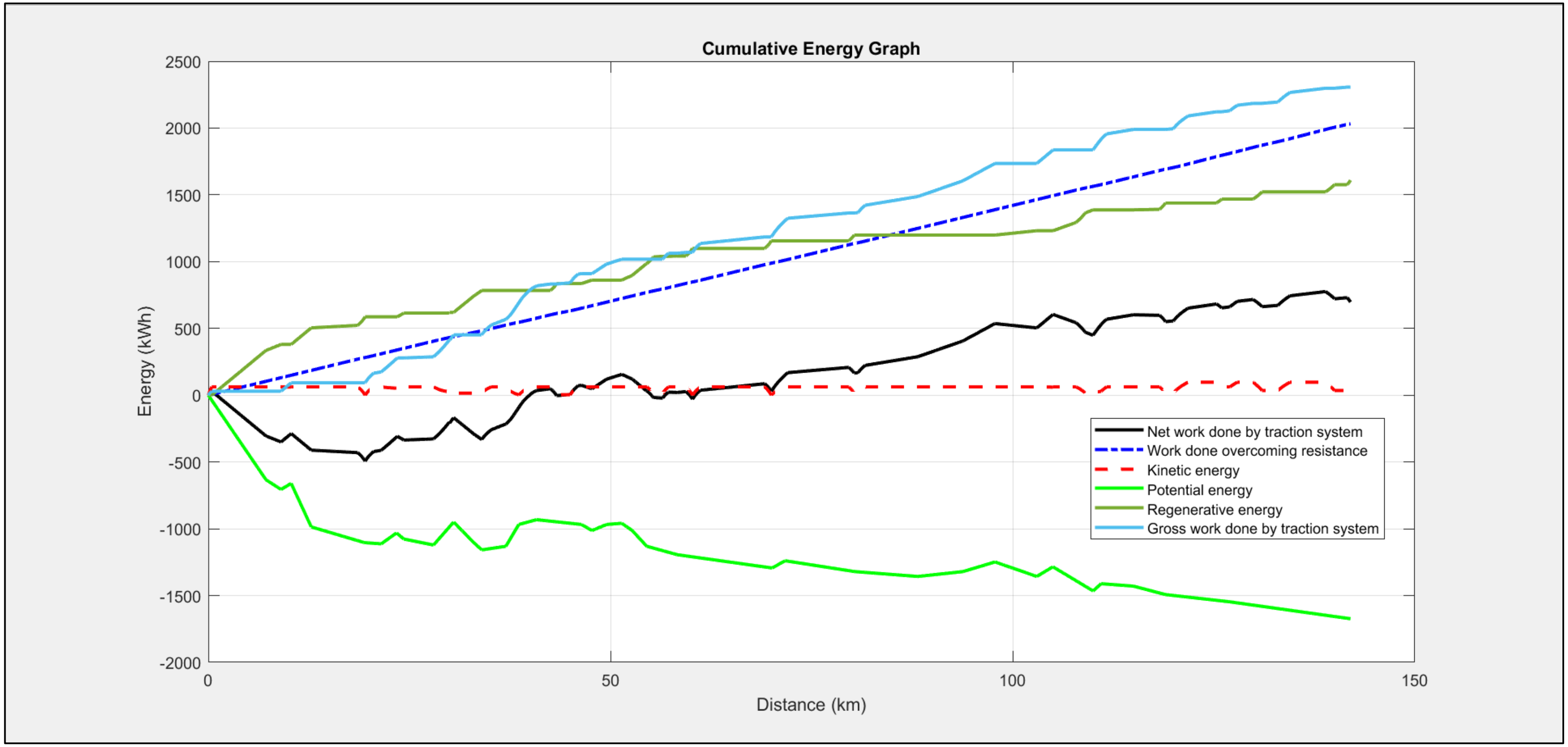

Fuel cell output graph
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Power, kW
Time, Minutes
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Power, kW
Time, Minutes
Power Input to/Output from DC Bus
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Power, kW
Time, Minutes
Traction Output from DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Power, kW
Time, Minutes
Train Speed and Altitude Graph
Train speed
Altitude
Train speed, km/h
Altitude, m
Time, Minutes

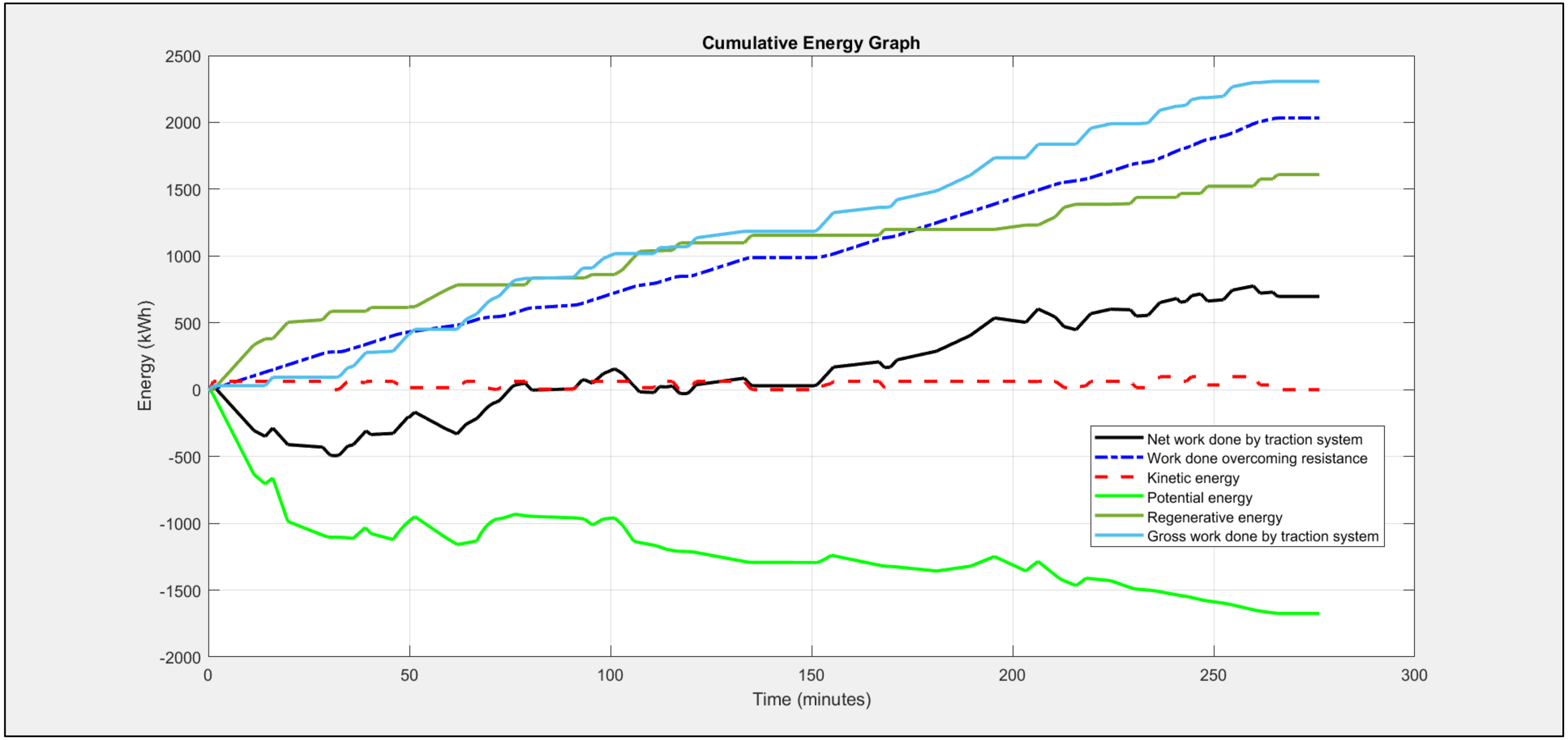

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
Distance,km
Hydrogen in the tanks
Hydrogen in the tanks, kg
600
550
500
450
400
350
300
0
50
100
150
Distance,km

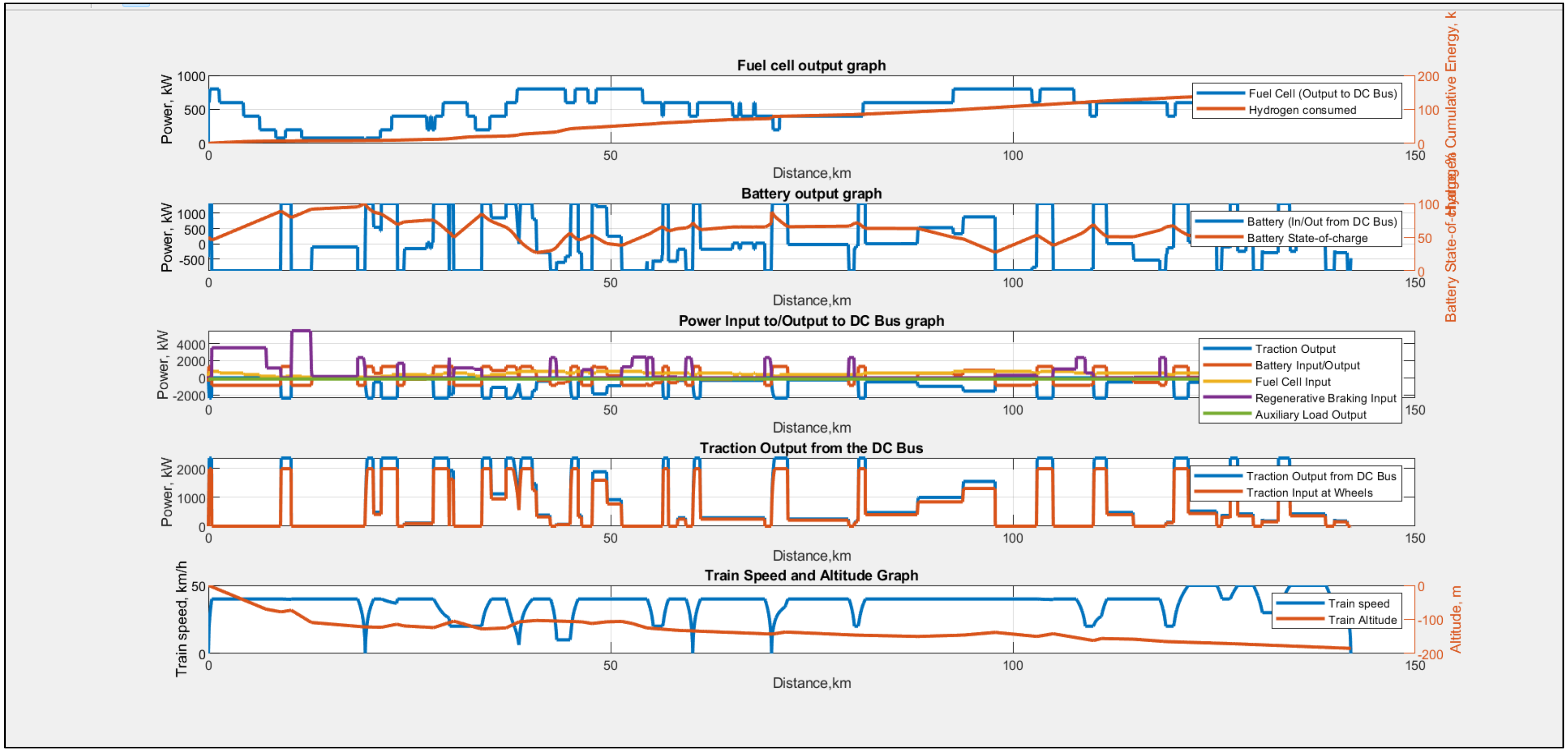

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
200
250
Time, Minutes
Hydrogen in the tanks
Hydrogen in the tanks, kg
600
550
500
450
400
350
300
0
50
100
150
200
250
Time, Minutes

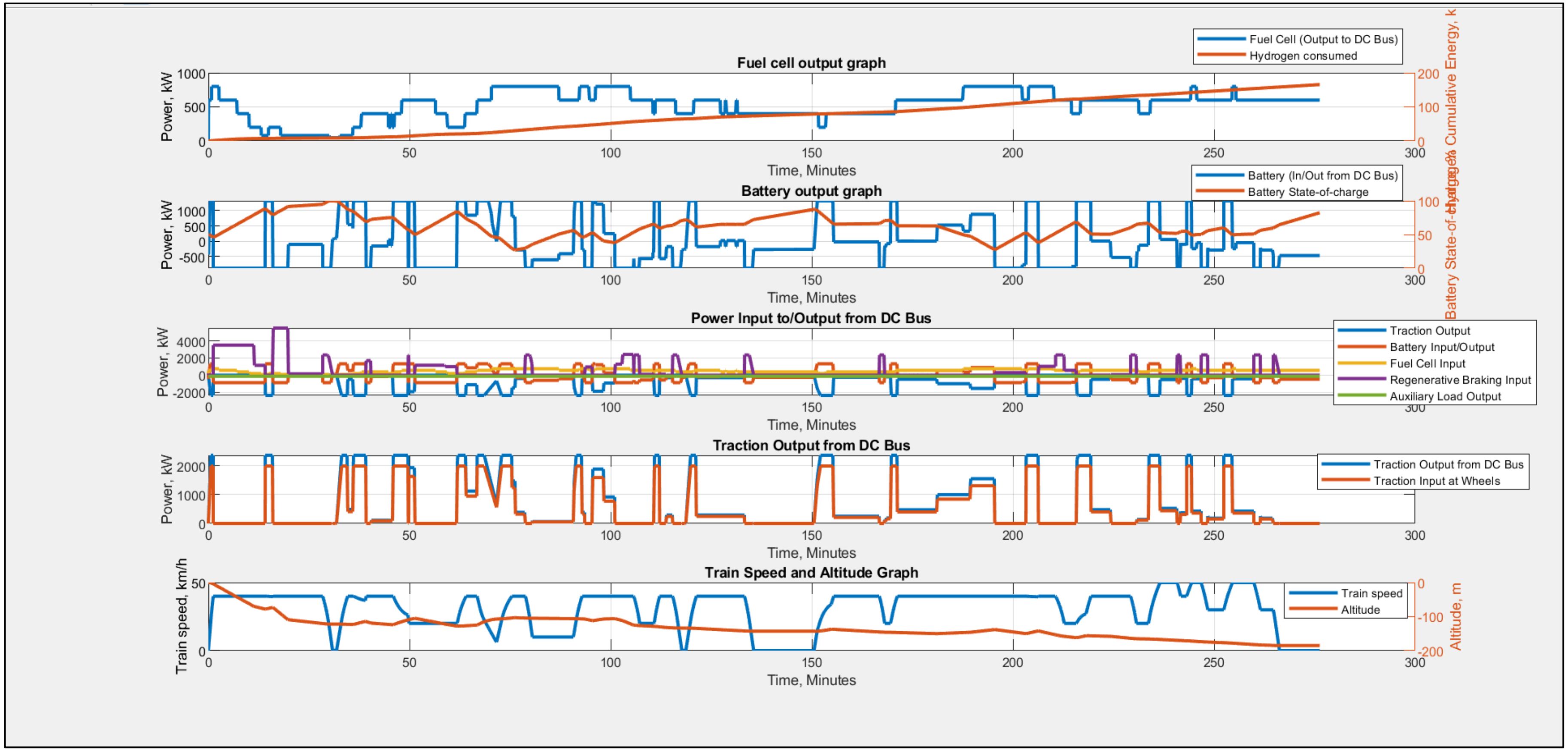
APPENDIX C: ORIGIN TO INTERMEDIATE POINT OF THE CENTRAL – SOUTH ZONE ROUTE RESULTS

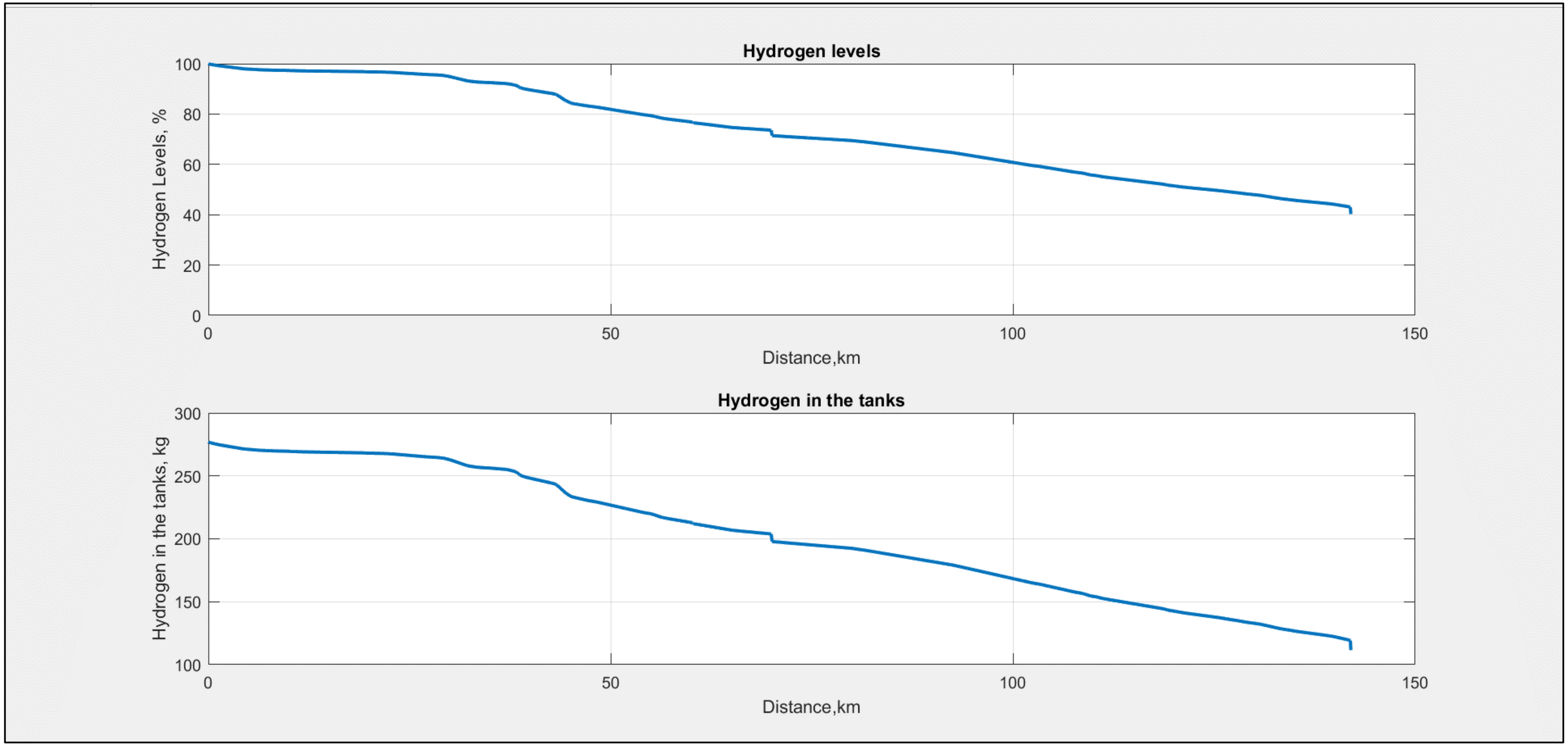


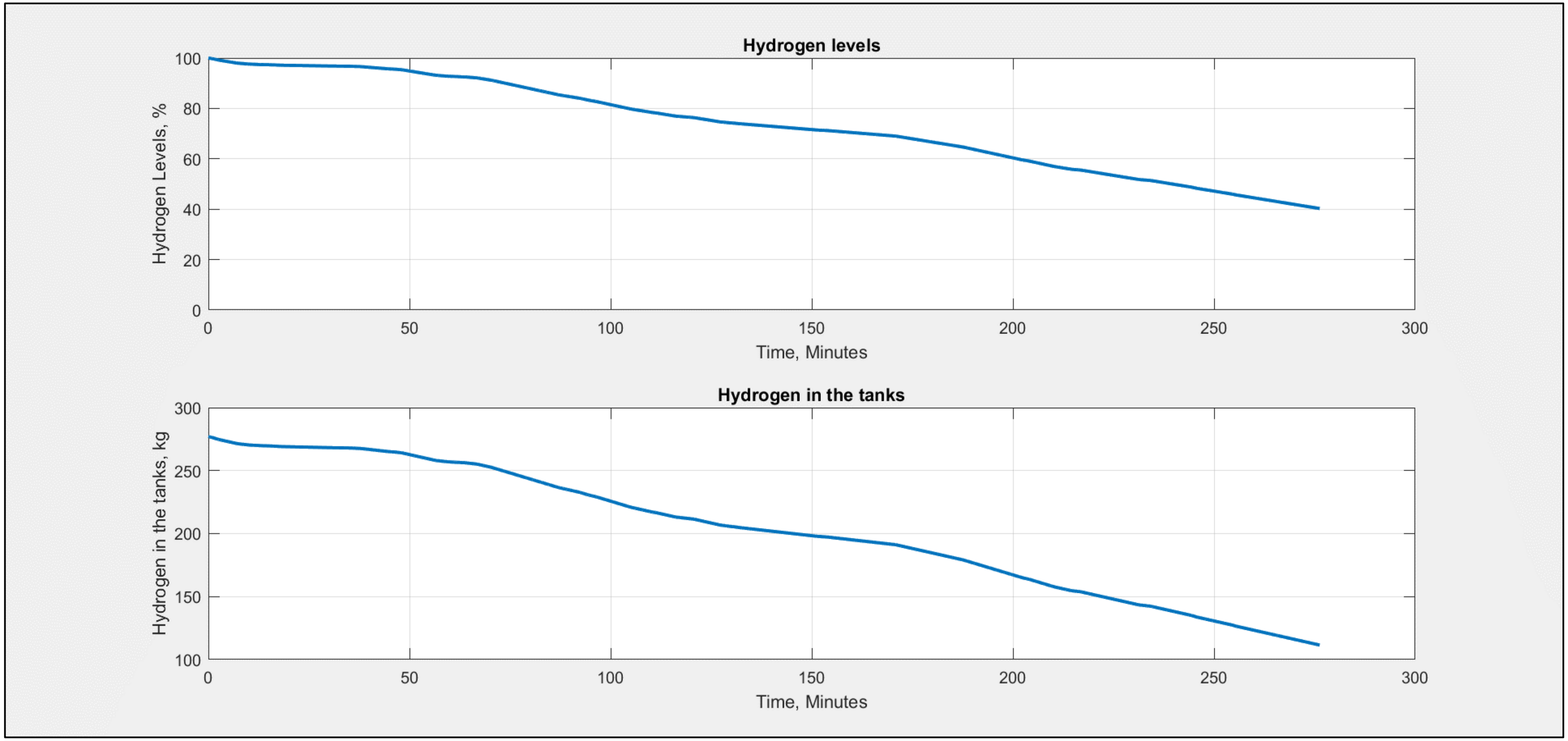

Cumulative Energy Graph
Energy (kWh)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
50
100
150
Distance (km)
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system


Cumulative Energy Graph
Energy (kWh)
Time (minutes)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
50
100
150
200
250
300
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system

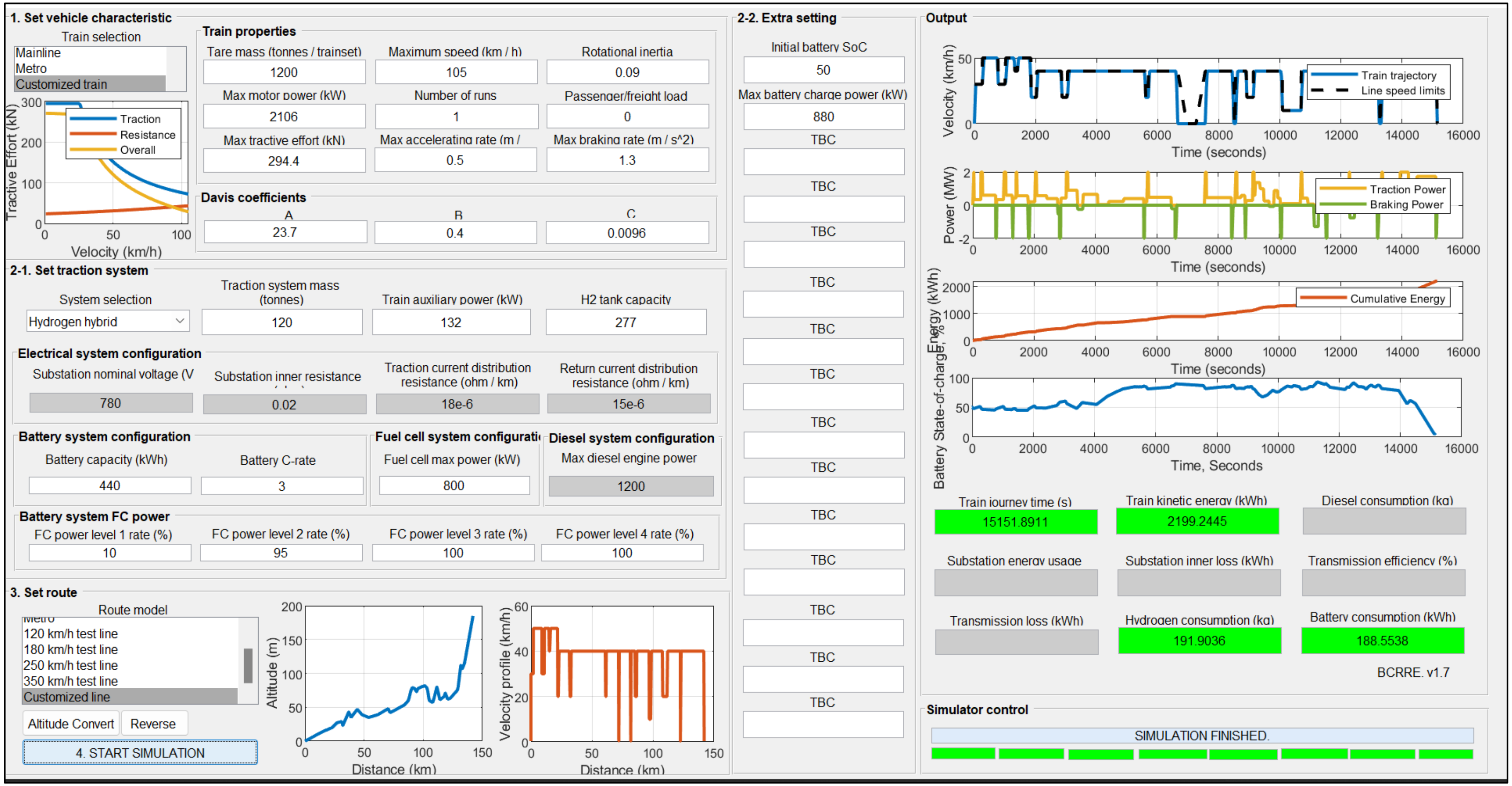

Fuel cell output graph
Power, kW
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Cumulative Energy, k
Distance,km
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output to DC Bus graph
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from the DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Train speed
Train Altitude
Altitude, m

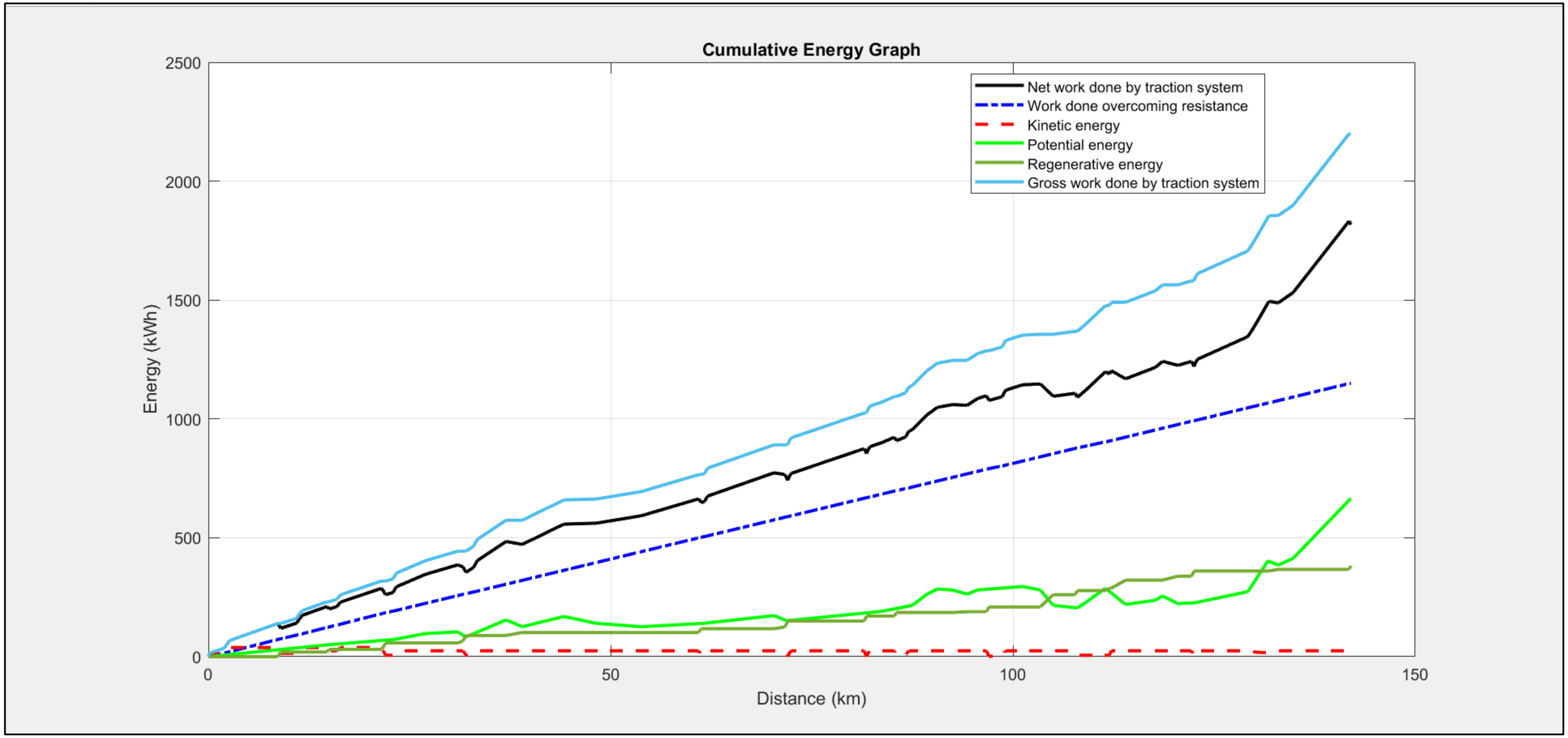

Fuel cell output graph
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Power, kW
Time, Minutes
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Power Input to/Output from DC Bus
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed
Altitude
Train speed, km/h
Altitude, m

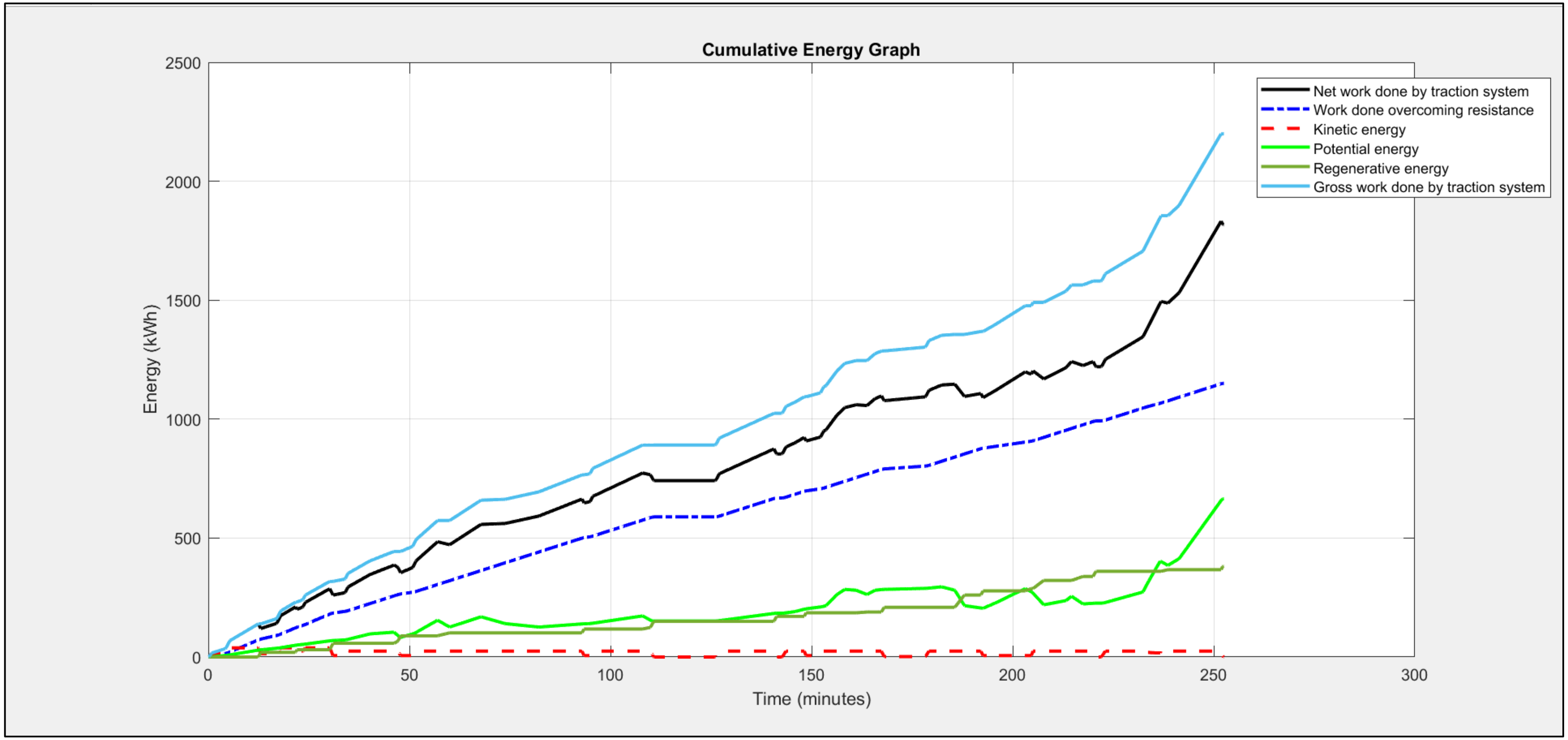

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
Distance,km
Hydrogen in the tanks
Hydrogen in the tanks, kg
300
250
200
150
100
0
50
100
150
Distance,km

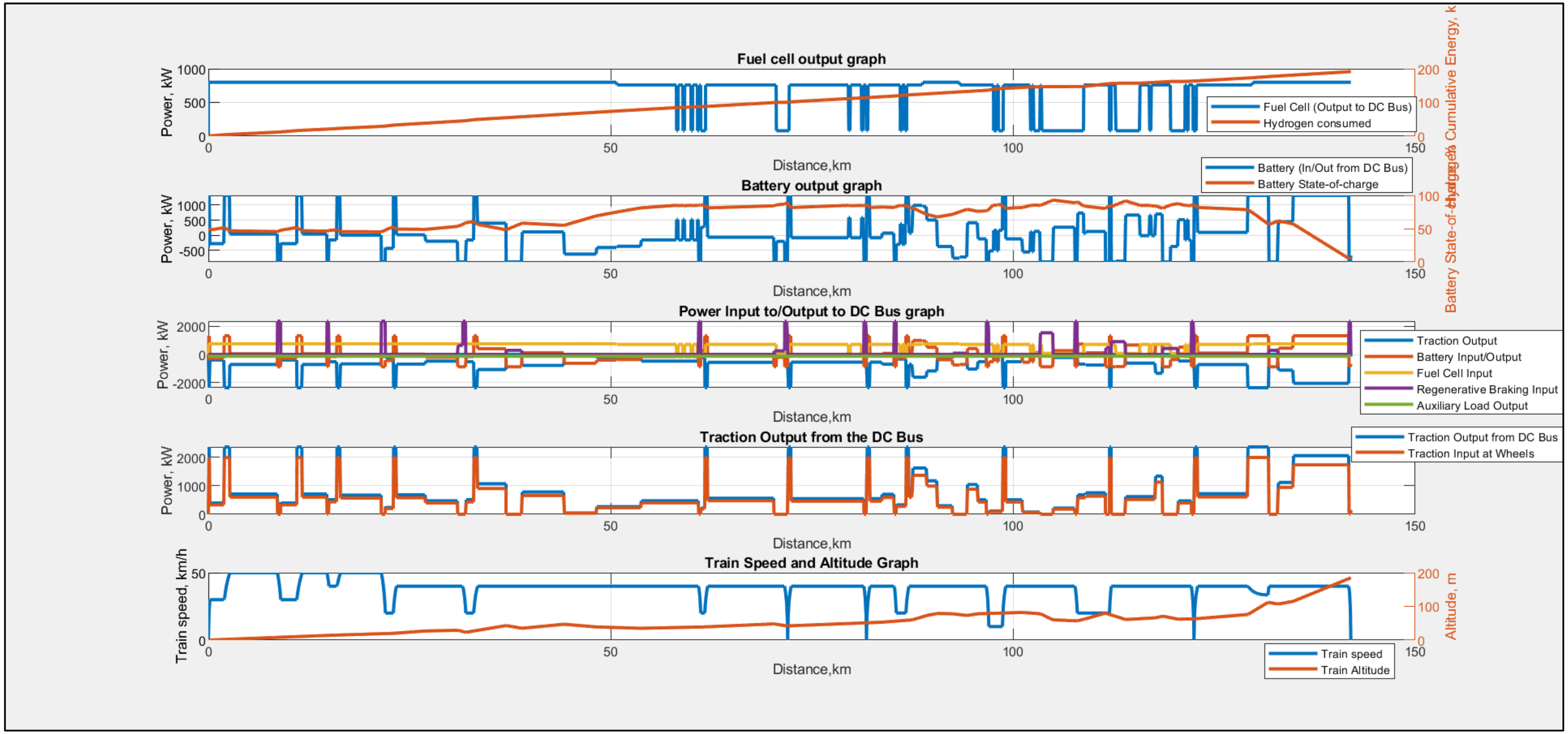

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
200
250
300
Time, Minutes
Hydrogen in the tanks
Hydrogen in the tanks, kg
300
250
200
150
100
0
50
100
150
200
250
300
Time, Minutes

APPENDIX D: INTERMEDIATE POINT TO ORIGIN OF THE CENTRAL – SOUTH ZONE ROUTE RESULTS

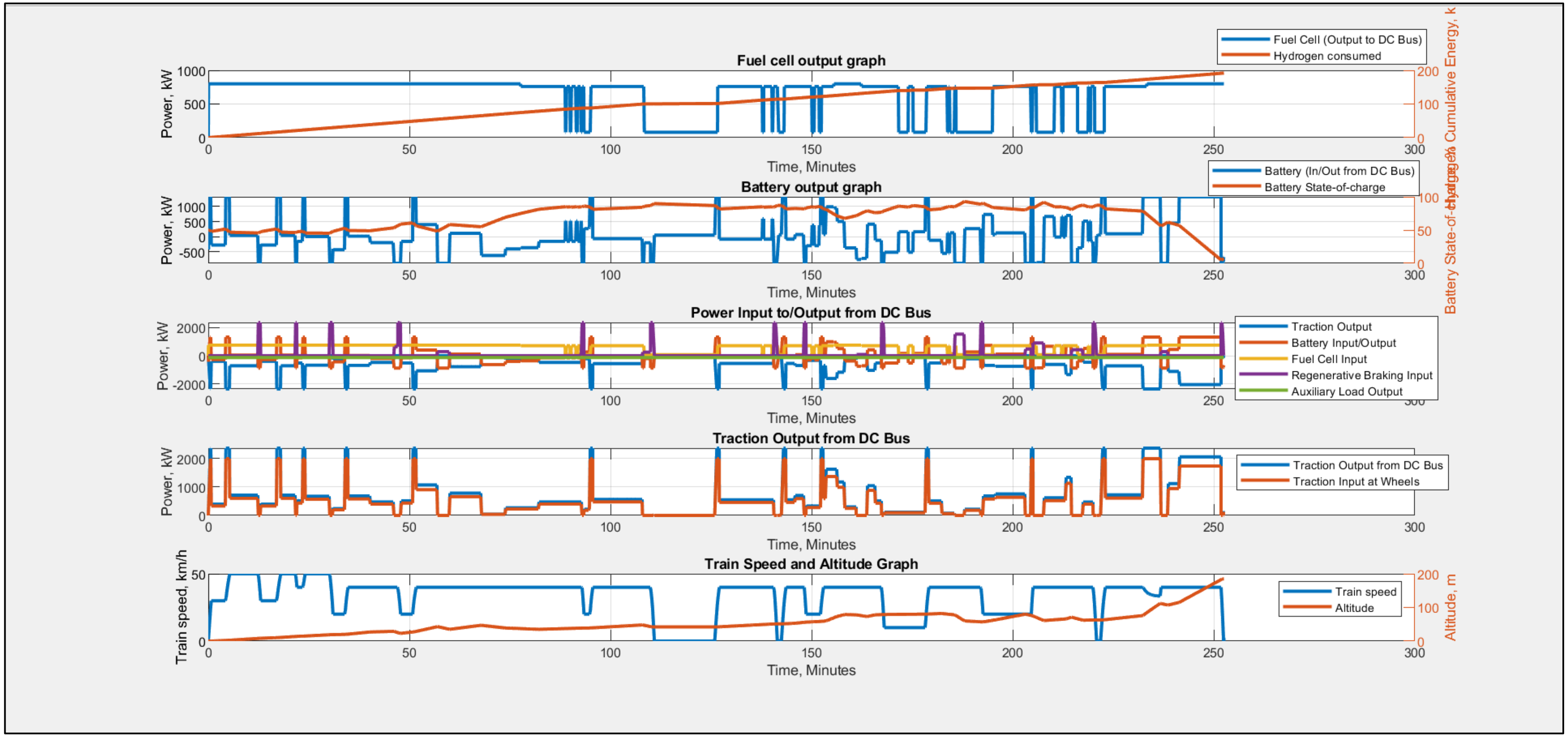


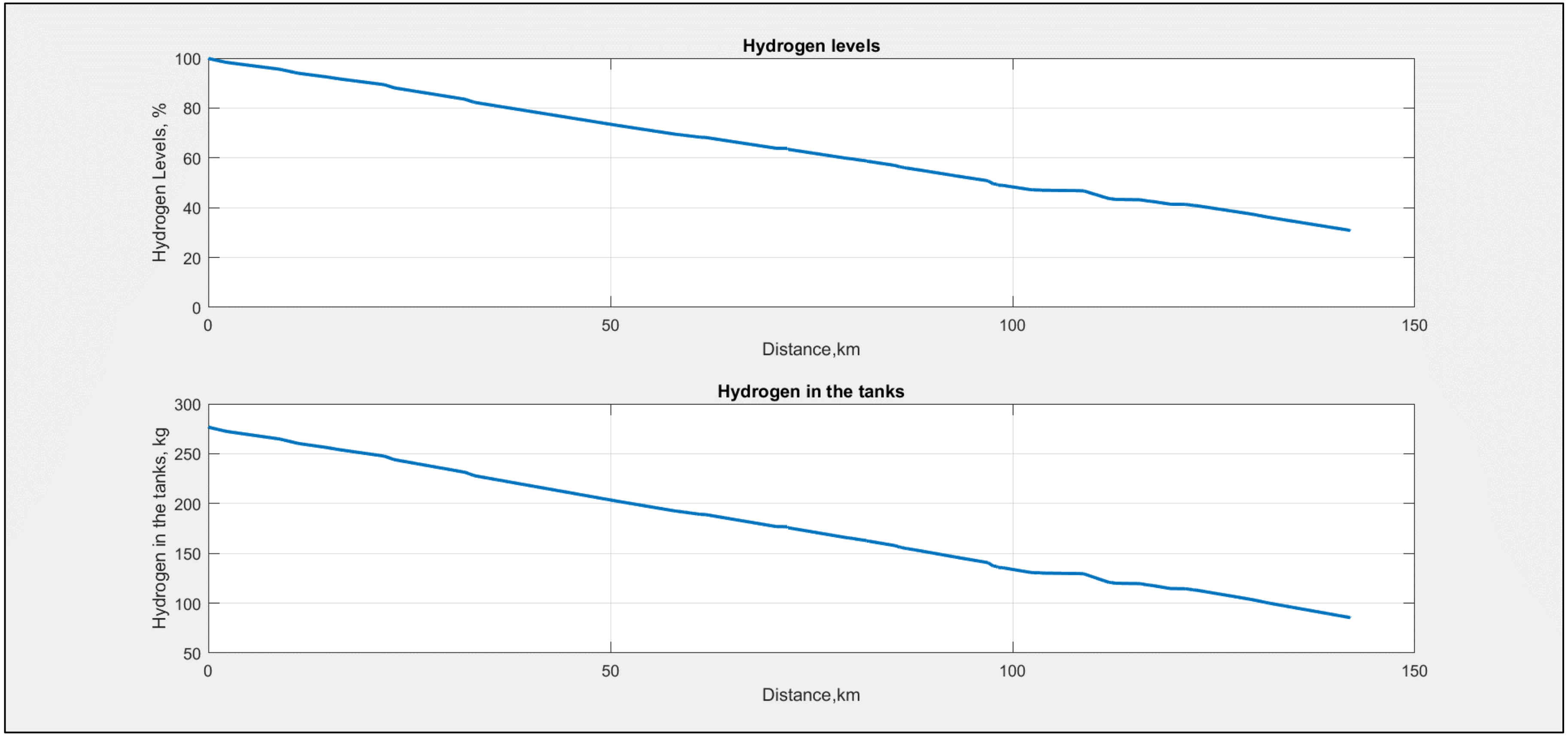

Cumulative Energy Graph
Energy (kWh)
2500
2000
1500
1000
500
0
0
50
100
150
Distance (km)
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system

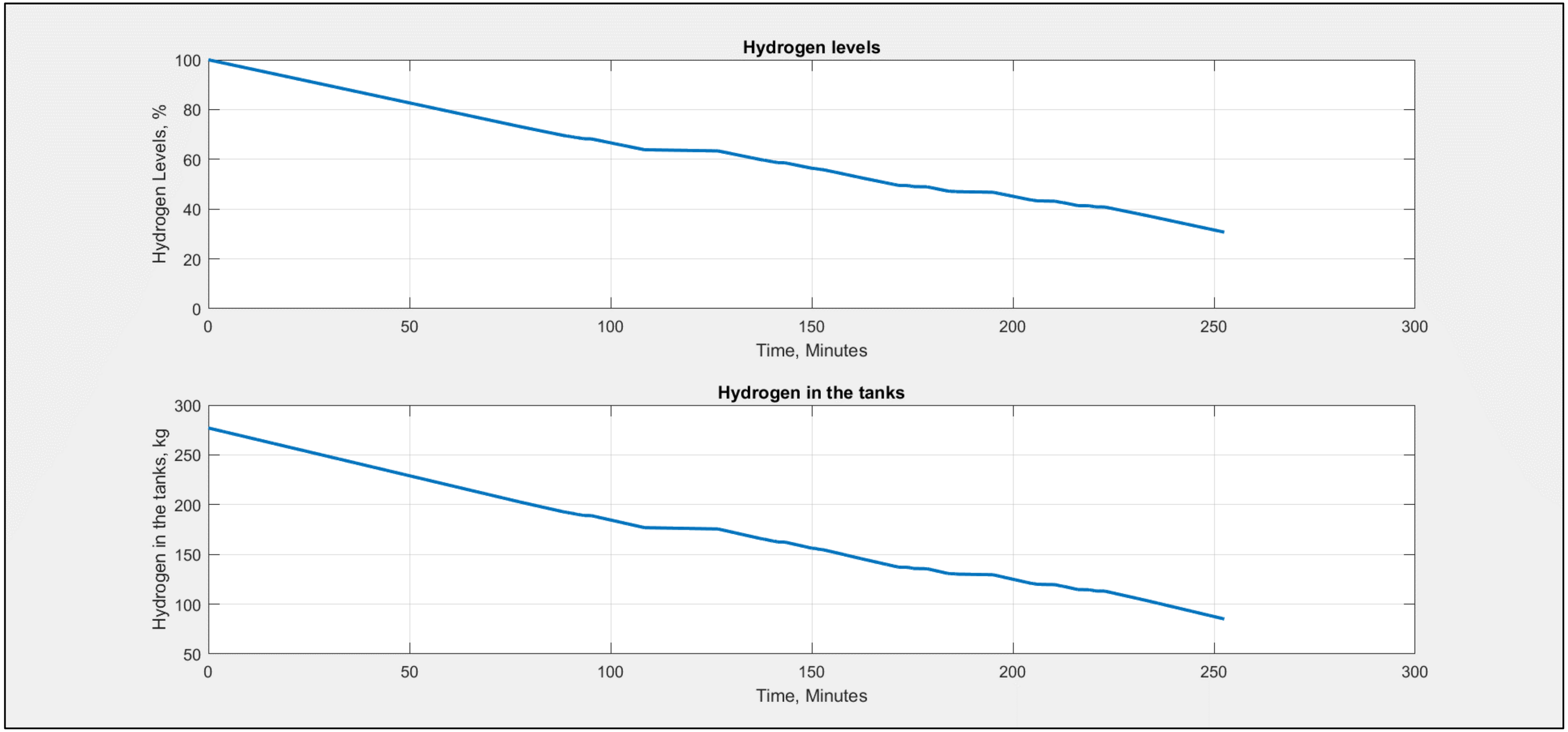

Cumulative Energy Graph
Energy (kWh)
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Time (minutes)
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system



Fuel cell output graph
Power, kW
Distance,km
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Power Input to/Output to DC Bus graph
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from the DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Altitude, m
Train speed
Train Altitude


Fuel cell output graph
Power, kW
Time, Minutes
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Hydrogen Cumulative Energy, k
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output from DC Bus
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Altitude, m
Train speed
Altitude


Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
Distance,km
Hydrogen in the tanks
Hydrogen in the tanks, kg
300
250
200
150
100
50
0
50
100
150
Distance,km


Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
50
100
150
200
250
300
Time, Minutes
Hydrogen in the tanks
Hydrogen in the tanks, kg
300
250
200
150
100
50
0
50
100
150
200
250
300
Time, Minutes

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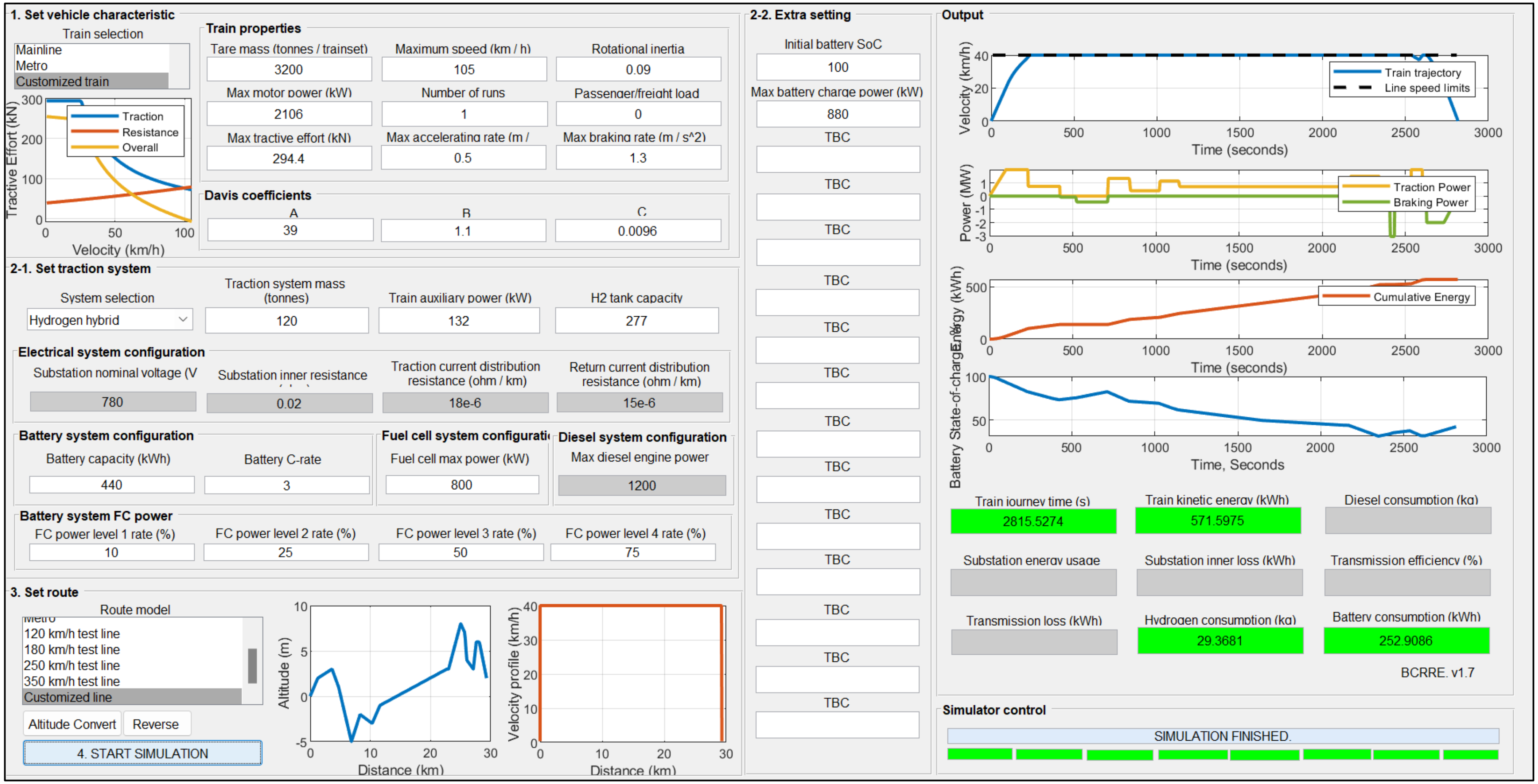
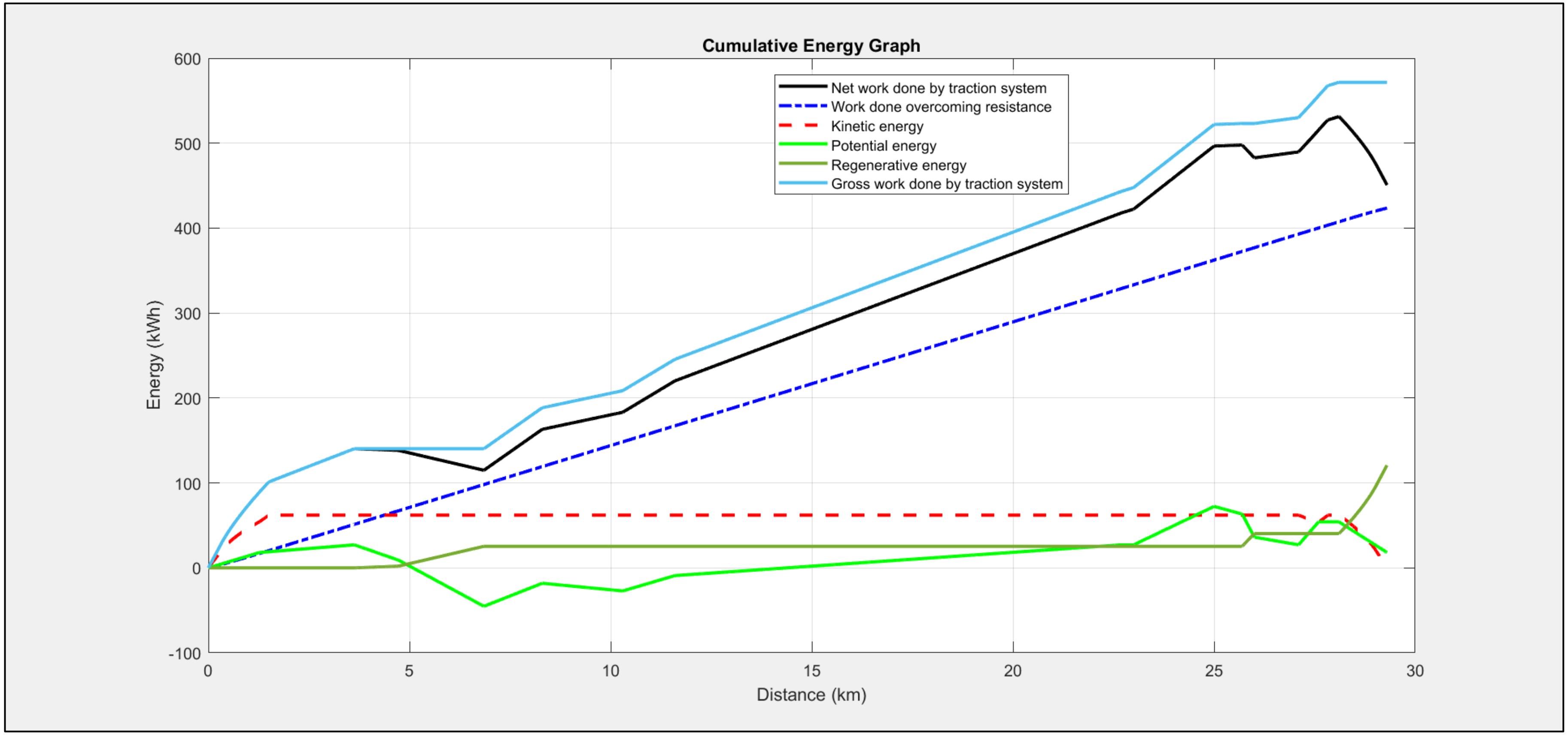
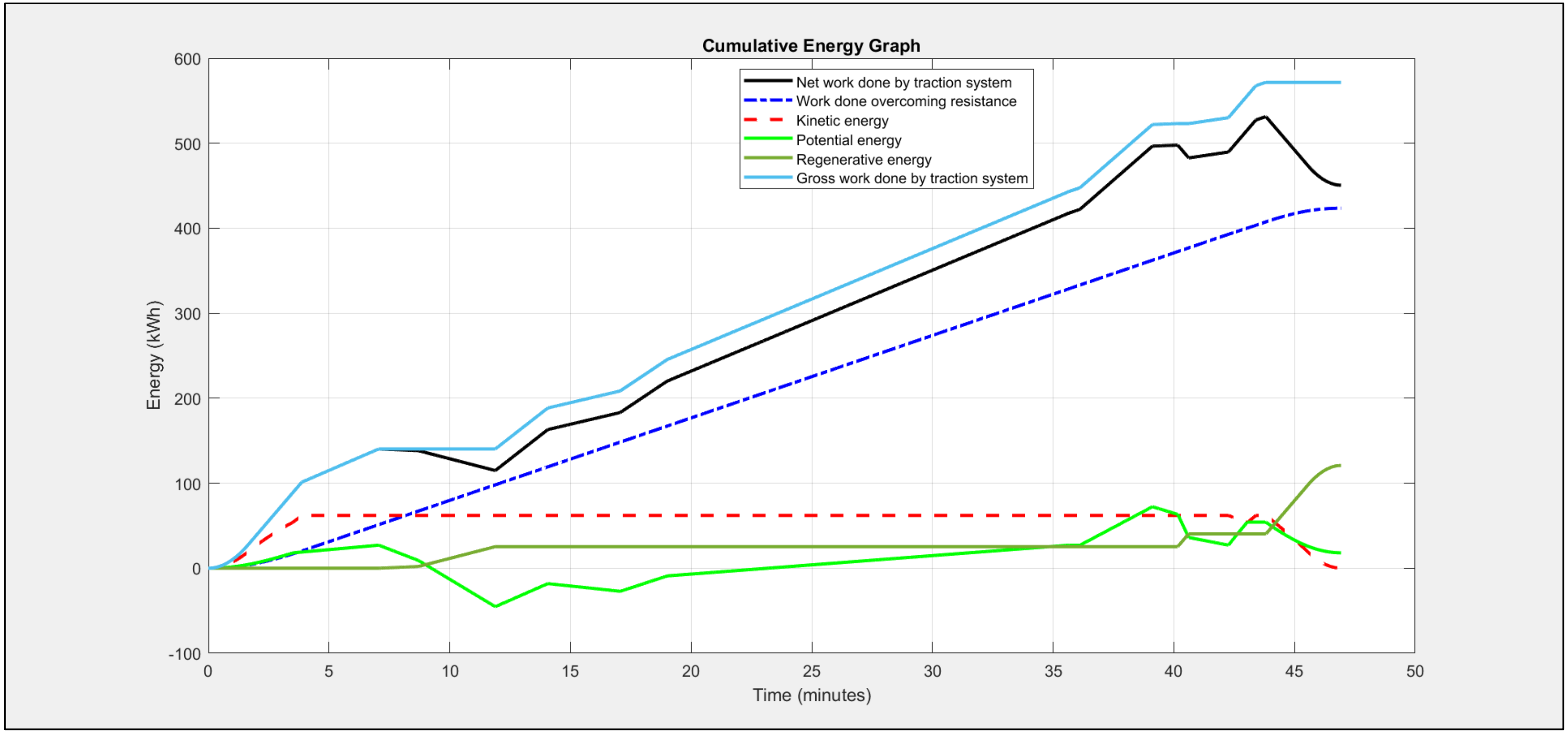
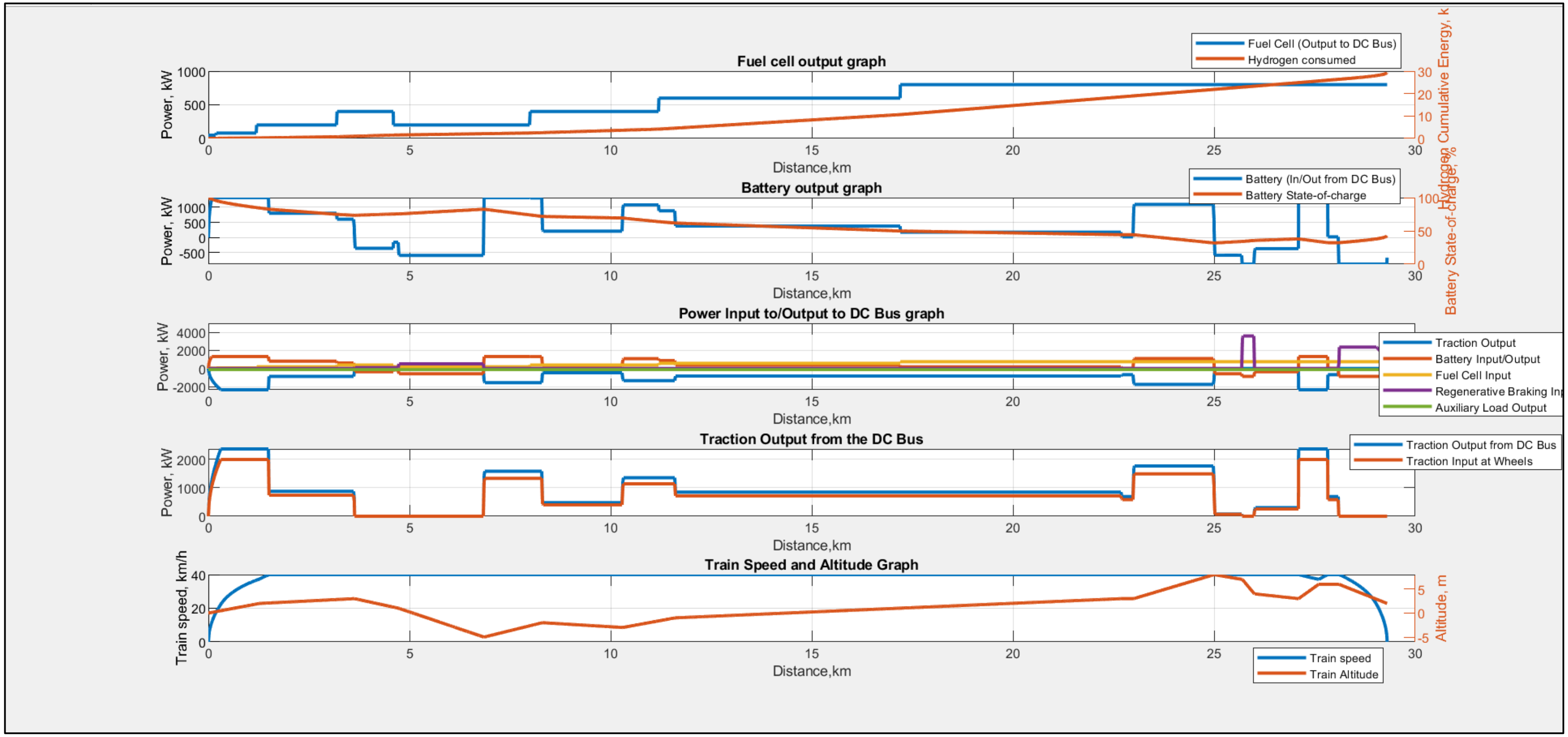
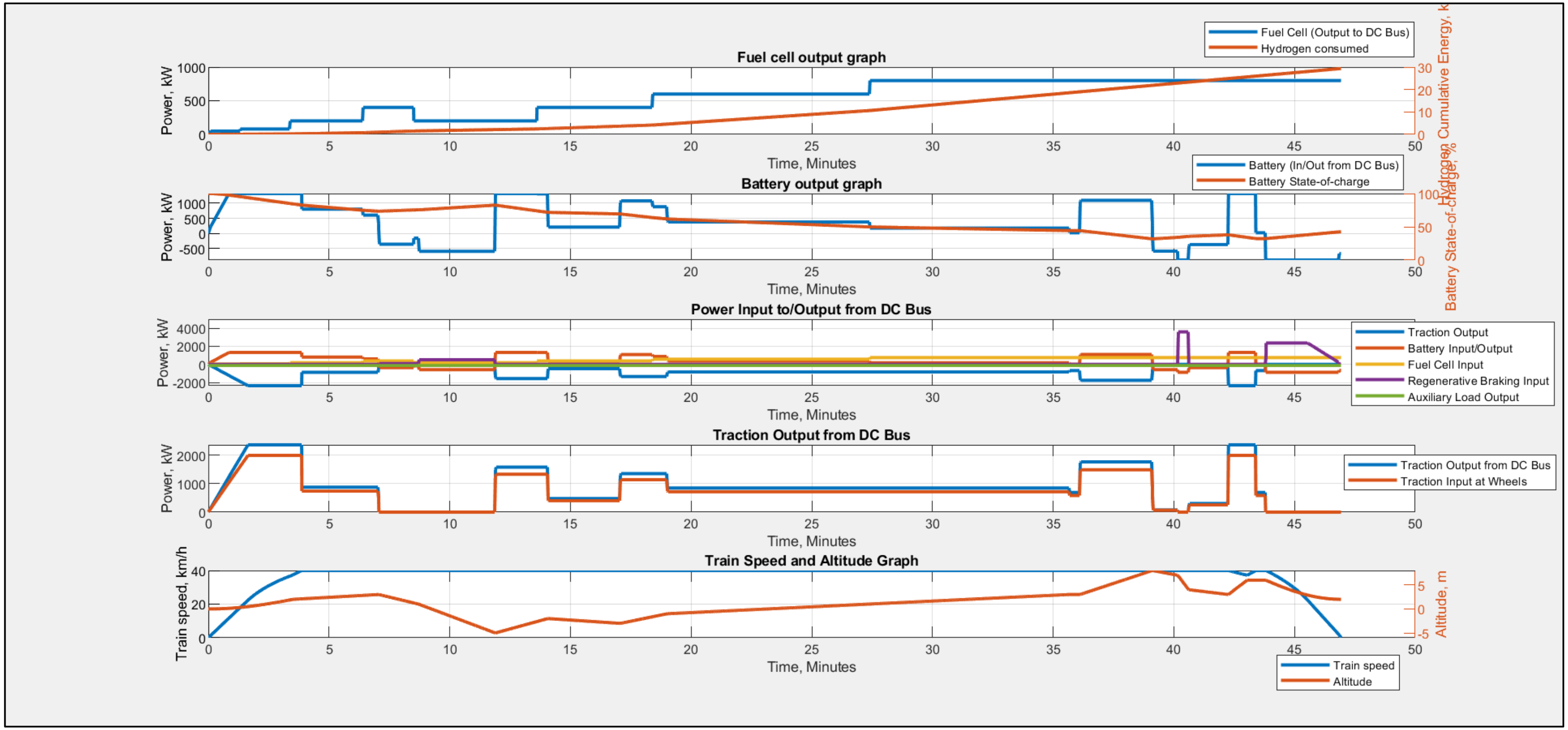
APPENDIX E: INTERMEDIATE POINT TO DESTINATION OF THE CENTRAL – SOUTH ZONE ROUTE RESULTS

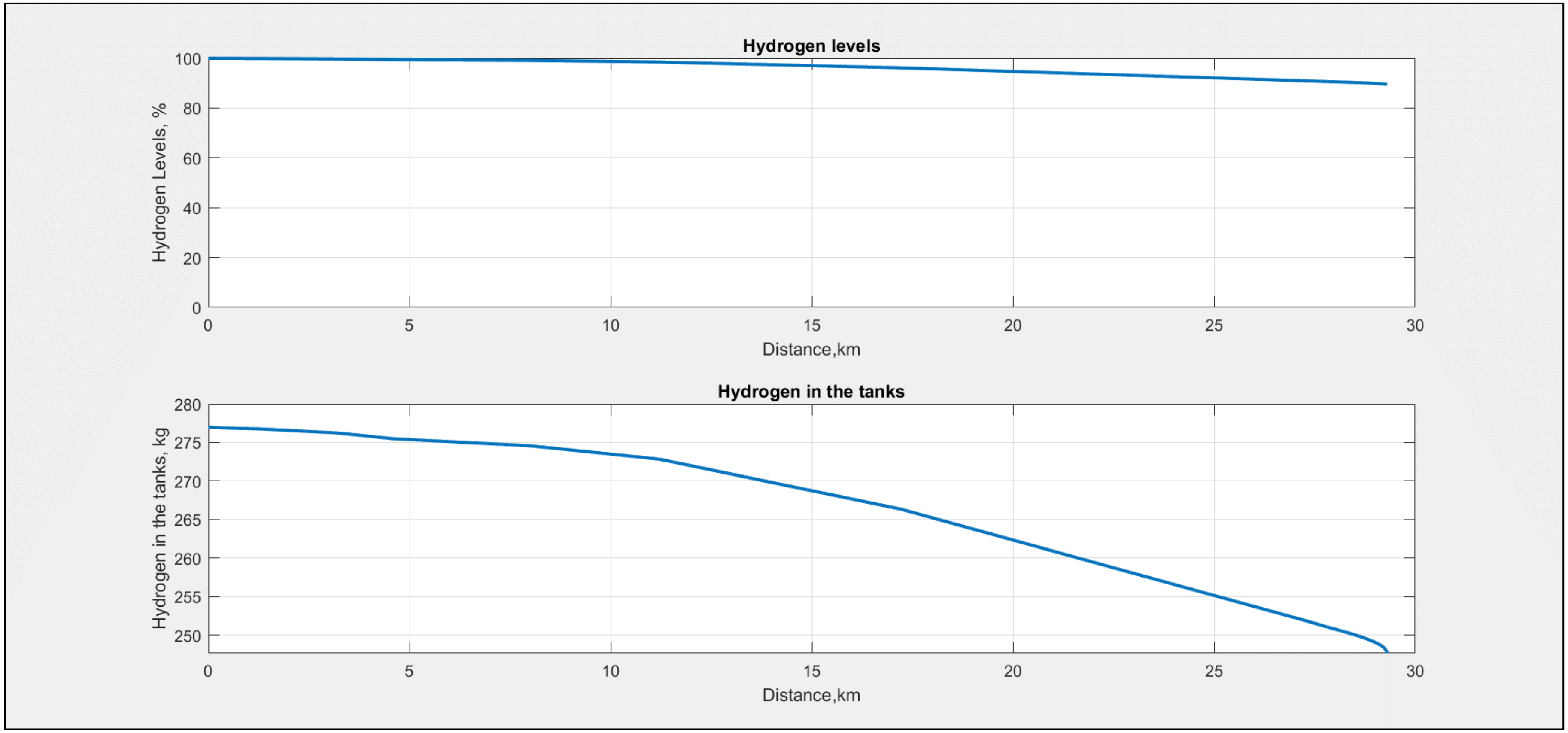


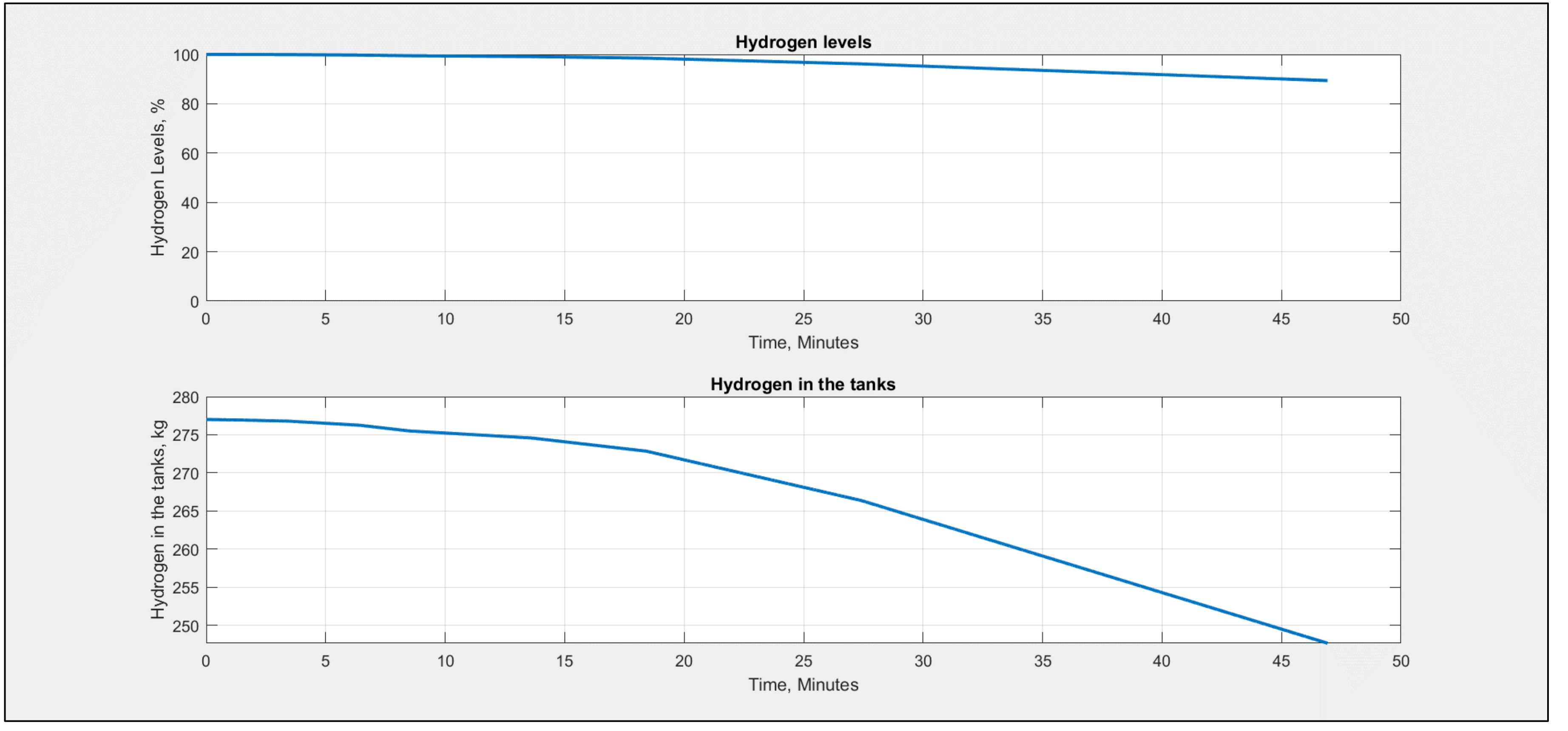

Cumulative Energy Graph
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system
Energy (kWh)
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
Distance (km)


Cumulative Energy Graph
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system
Energy (kWh)
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)

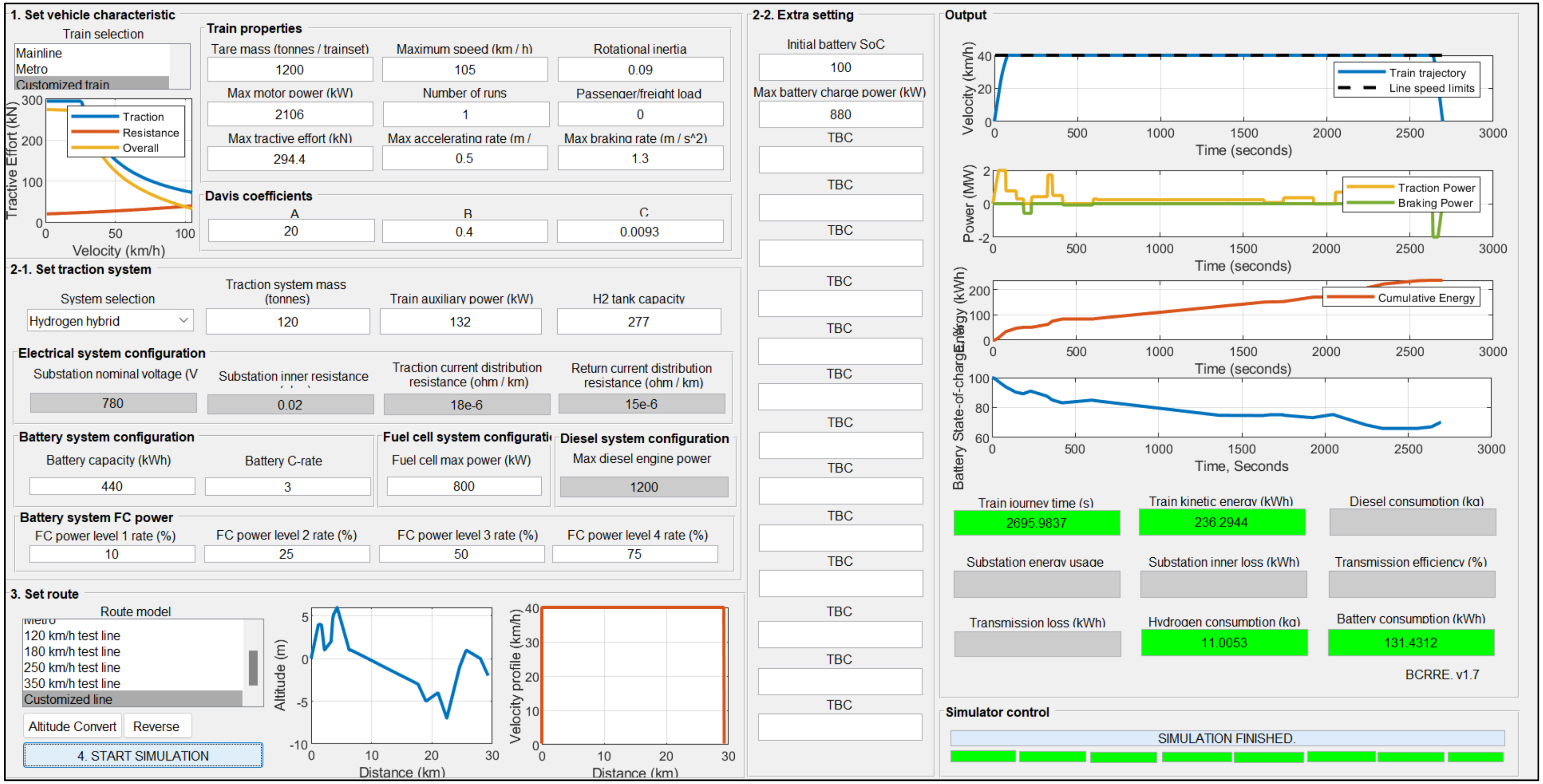

Fuel cell output graph
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Power, kW
Hydrogen Cumulative Energy, k
Distance,km
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output to DC Bus graph
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking In
Auxiliary Load Output
Traction Output from the DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Altitude, m
Train speed
Train Altitude

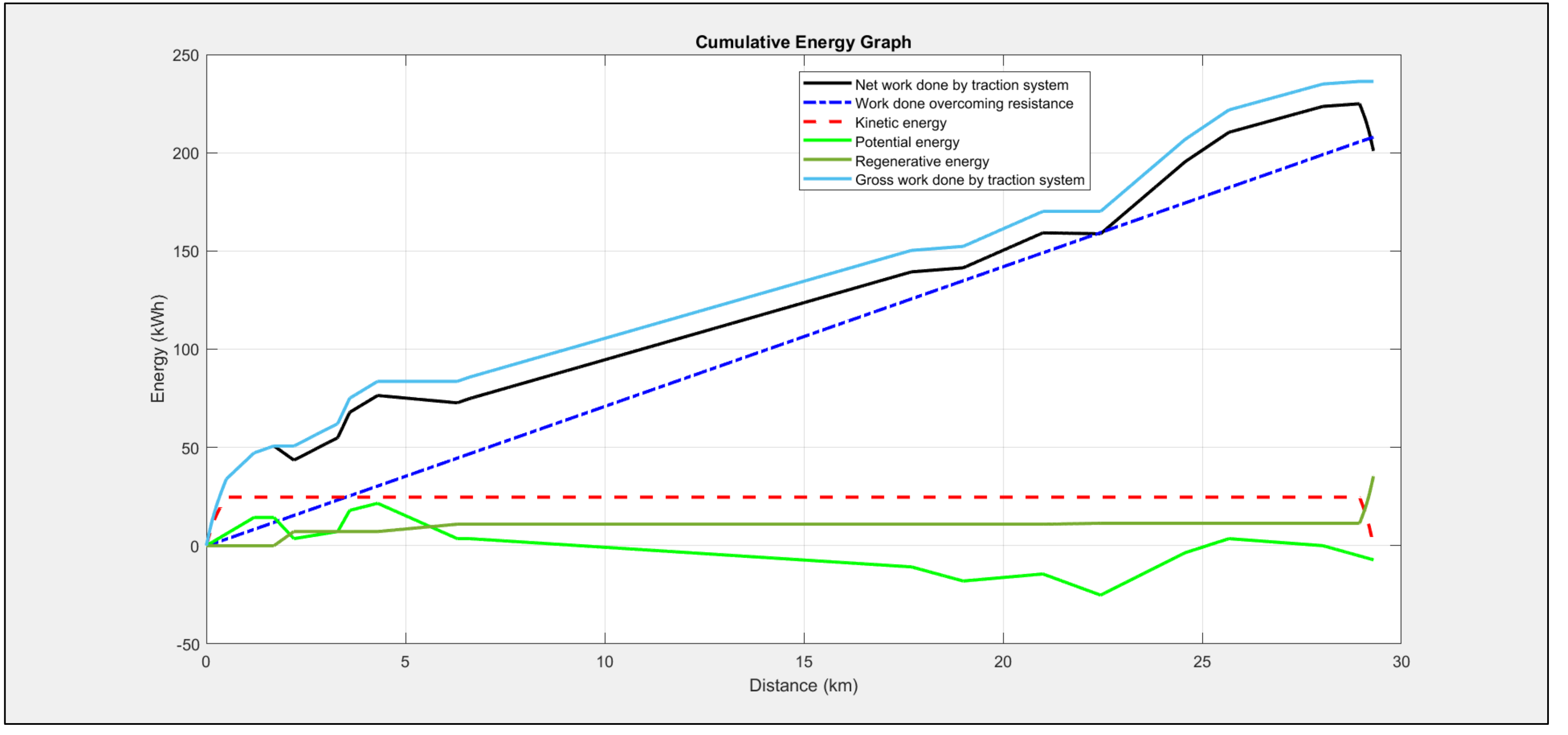

Fuel cell output graph
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Power, kW
Hydrogen Cumulative Energy, k
Time, Minutes
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output from DC Bus
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Altitude, m
Train speed
Altitude

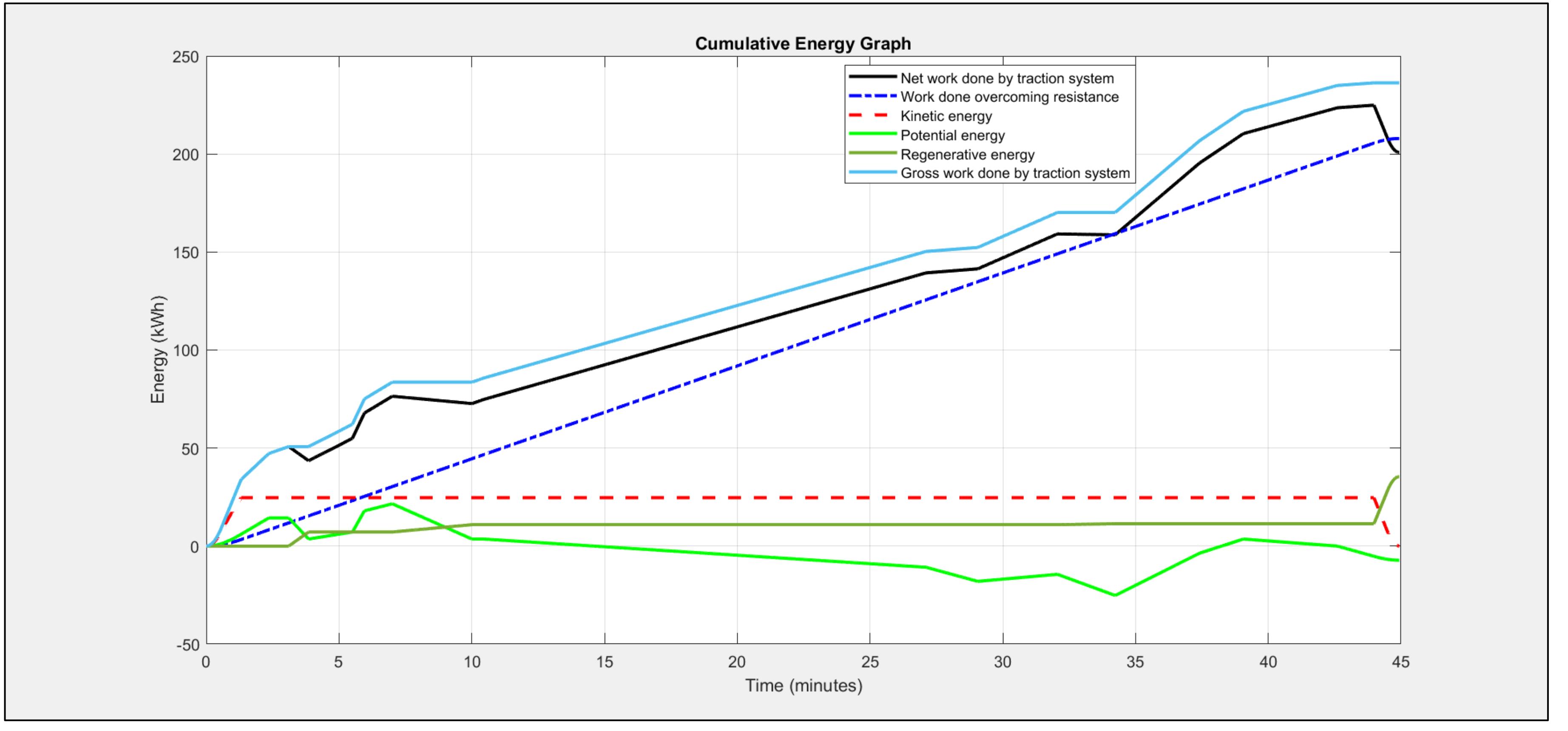

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
5
10
15
20
25
30
Distance,km
Hydrogen in the tanks
Hydrogen in the tanks, kg
280
275
270
265
260
255
250
0
5
10
15
20
25
30
Distance,km

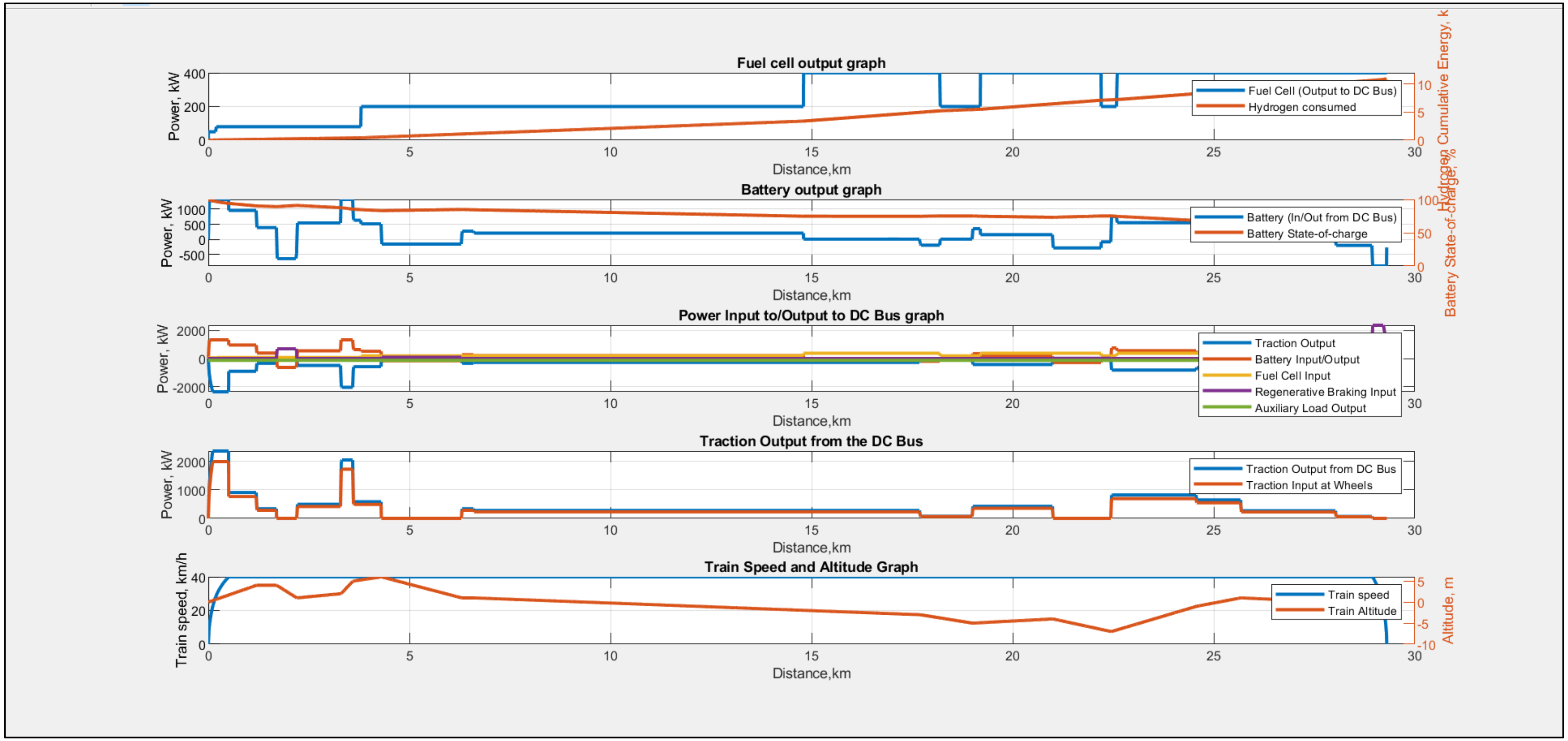

Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
50
Time, Minutes
Hydrogen in the tanks
Hydrogen in the tanks, kg
280
275
270
265
260
255
250
0
5
10
15
20
25
30
35
40
45
50
Time, Minutes

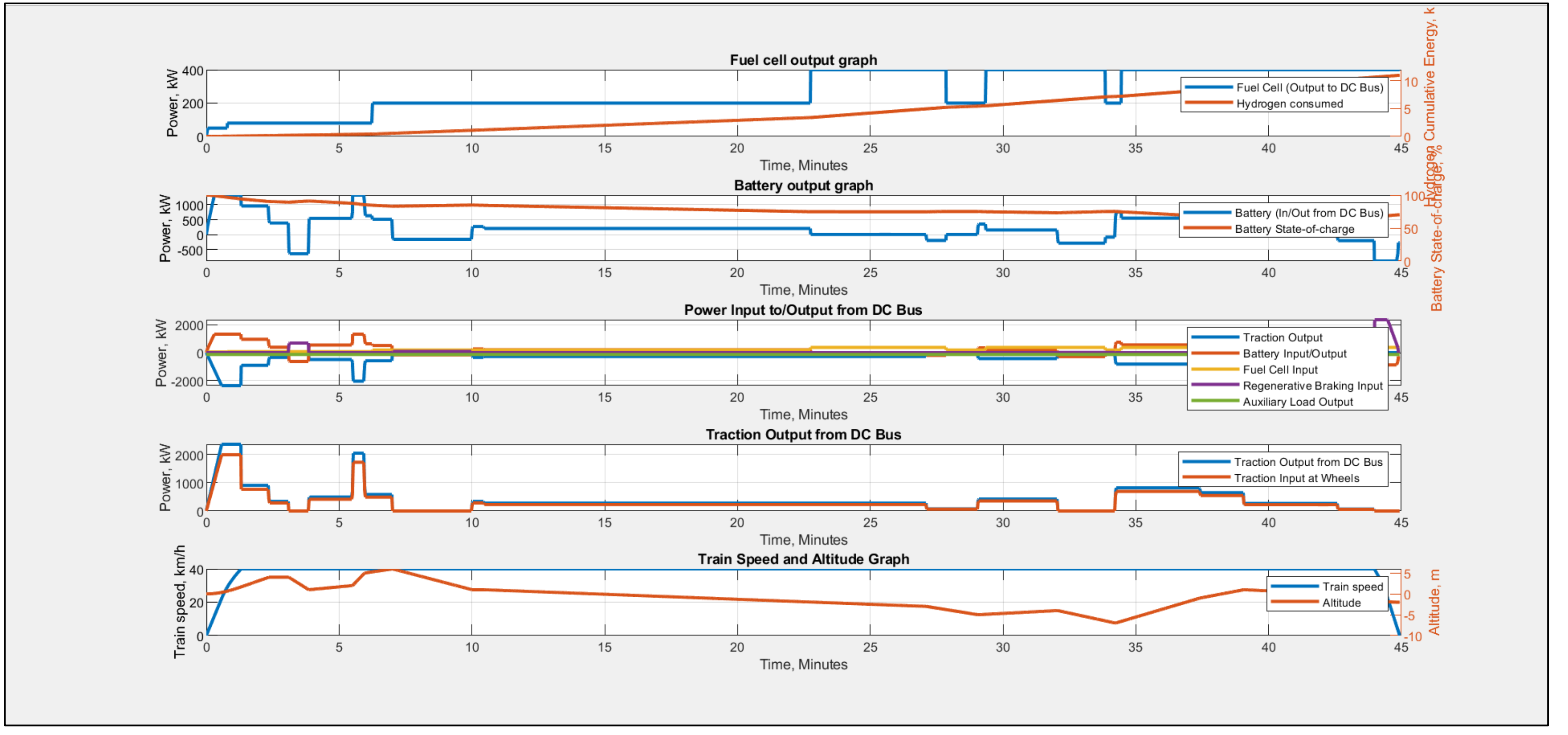
APPENDIX F: DESTINATION TO INTERMEDIATE POINT OF THE CENTRAL – SOUTH ZONE ROUTE RESULTS

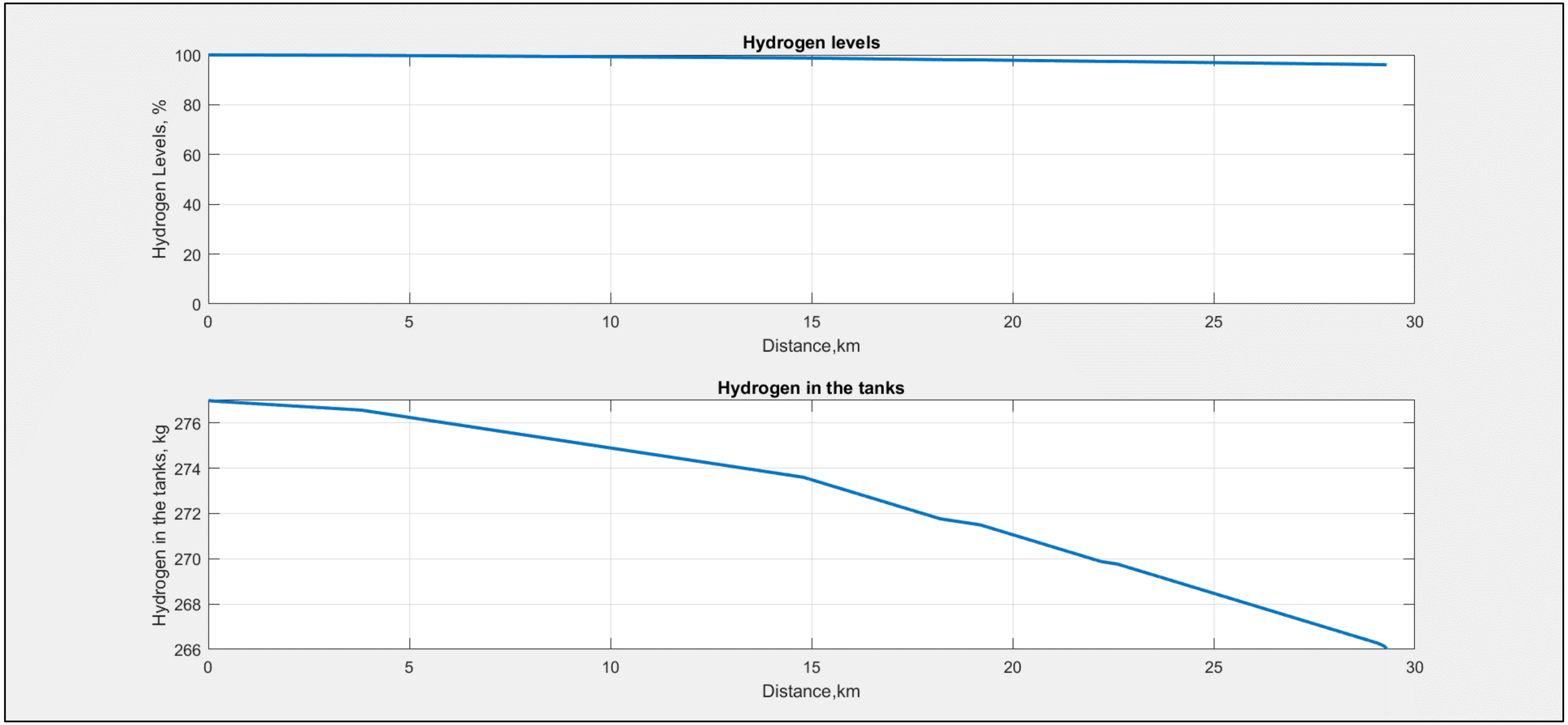


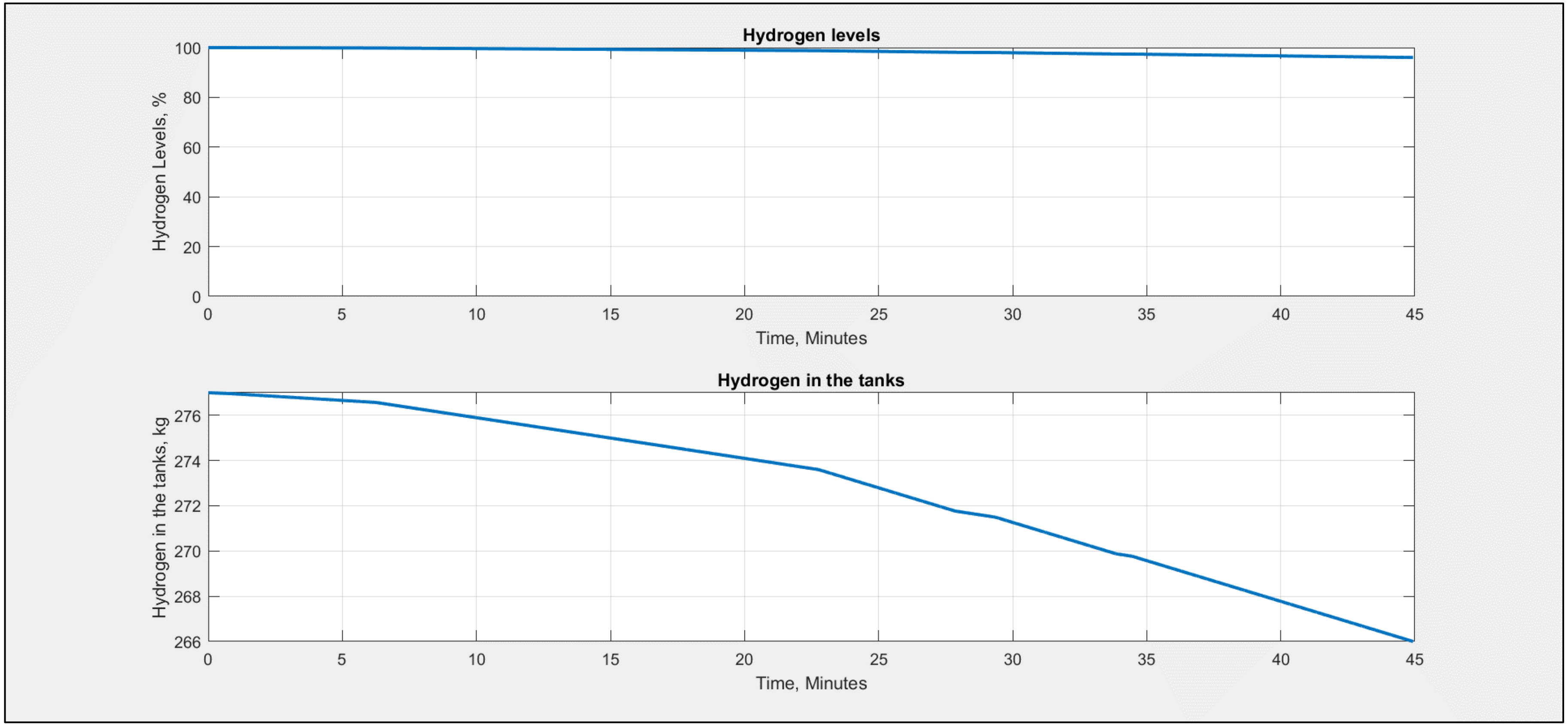

Cumulative Energy Graph
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system
Energy (kWh)
Distance (km)
250
200
150
100
50
0
-50
0
5
10
15
20
25
30


Cumulative Energy Graph
Net work done by traction system
Work done overcoming resistance
Kinetic energy
Potential energy
Regenerative energy
Gross work done by traction system
Energy (kWh)
250
200
150
100
50
0
-50
0
5
10
15
20
25
30
35
40
45
Time (minutes)

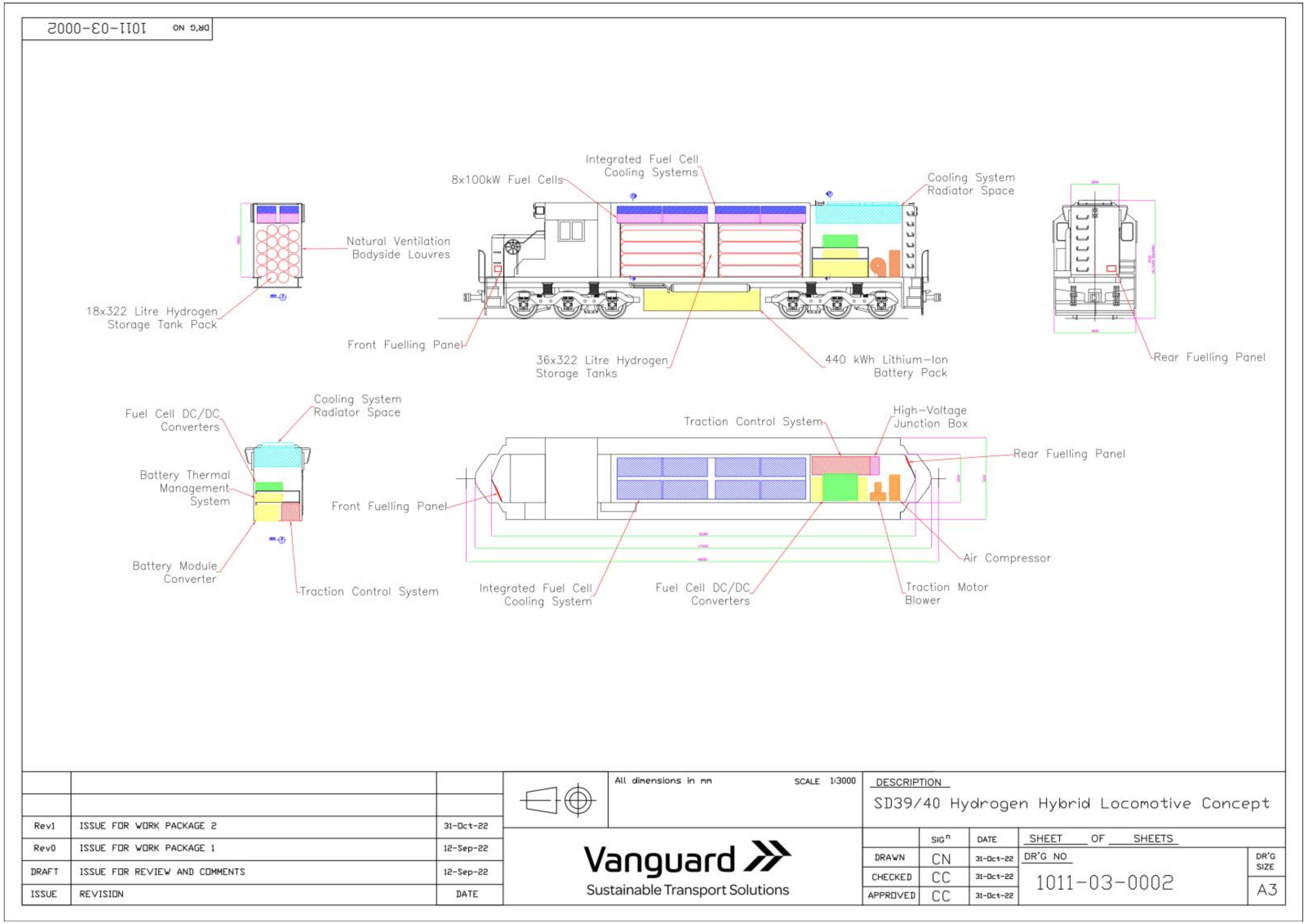

Fuel cell output graph
Power, kW
Distance,km
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Hydrogen Cumulative Energy, k
Battery output graph
Battery (In/Out from DC Bus)
Battery State-of-charge
Battery State-of-charge, %
Power Input to/Output to DC Bus graph
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from the DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Train speed
Train Altitude
Altitude, m


Fuel cell output graph
Power, kW
Hydrogen Cumulative Energy, k
Fuel Cell (Output to DC Bus)
Hydrogen consumed
Time, Minutes
Battery output graph
Battery State-of-charge, %
Battery (In/Out from DC Bus)
Battery State-of-charge
Power Input to/Output from DC Bus
Traction Output
Battery Input/Output
Fuel Cell Input
Regenerative Braking Input
Auxiliary Load Output
Traction Output from DC Bus
Traction Output from DC Bus
Traction Input at Wheels
Train Speed and Altitude Graph
Train speed, km/h
Altitude, m
Train speed
Altitude


Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
5
10
15
20
25
30
Distance,km
Hydrogen in the tanks
Hydrogen in the tanks, kg
276
274
272
270
268
266
0
5
10
15
20
25
30
Distance,km


Hydrogen levels
Hydrogen Levels, %
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
Time, Minutes
Hydrogen in the tanks
Hydrogen in the tanks, kg
276
274
272
270
268
266
Time, Minutes

APPENDIX G: SD-39/SD-40 BENCHMARK CONCEPT LEVEL DESIGN DRAWING



APPENDIX H: SINGLE TRAIN SIMULATOR ROUTE DATA

Central south zone route data

Location, km	Gradient, x/1000	Gradient (Percentage)
0	-9,76	-0,98
7,17	-4,28	-0,43
9,04	3,97	0,40
10,3	-14,40	-1,44
12,8	-1,97	-0,20
19,4	-0,48	-0,05
21,5	4,74	0,47
23,4	-5,56	-0,56
24,3	-1,35	-0,14
28	7,60	0,76
30,5	-6,80	-0,68
33	-6,00	-0,60
34	1,00	0,10
37	11,25	1,13
38,6	1,82	0,18
40,8	-0,71	-0,07
46,4	-3,85	-0,38
47,7	2,78	0,28
49,5	0,53	0,05
51,4	-4,62	-0,46
52,7	-7,22	-0,72
54,5	-1,84	-0,18
58,3	-0,93	-0,09
70,1	3,75	0,38
71,7	-1,03	-0,10
80,4	-0,51	-0,05
88,2	0,71	0,07
93,8	2,00	0,20
97,8	-2,31	-0,23
103	4,00	0,40
105	-4,00	-0,40
106	-4,00	-0,40
110	6,00	0,60
111	-0,50	-0,05
115	-1,75	-0,18
119	-0,75	-0,08
127	-0,93	-0,09
142	0,93	0,09

Speed limit changing location, km	Speed Limits, km/h
0	40
30	20
34	40
43,3	10
45	40
55,3	20
56,5	40
80,3	20
80,8	40
109	20
110	40
119	20
120	50
126	40
127	50
131	30
133	50
140	30
142	30

Station Locations		
Origin	0	0
intermediate point	19,5	60
-	60,2	60
intermediate point	70	900
Destination	142	0

Location, km	Gradient, x/1000	Gradient (Percentage)
0	5,67	0,57
3	-7	-0,70
11	0,8	0,08
13,5	3,69	0,37
20	1,5	0,15
22	-4	-0,40
23,5	-4,72	-0,47
27,1	-7,23	-0,72
39	-2	-0,20
43	6	0,60
46,5	-2,67	-0,27
48	1,92	0,19
55,8	-1,33	-0,13
57,3	-9,81	-0,98
62,7	0,24	0,02
70,9	-7,33	-0,73
91,5	-4,16	-0,42
110	7,1	0,71
120	6	0,60
121	-5,25	-0,53
125	-2,47	-0,25
140	-25,5	-2,55
142	-13	-1,30
145	-16	-1,60
147	-8	-0,80
148	0	0,00
149	0	0,00

Central zone route data

Speed limit changing location, km	Speed Limits, km/h
0	40
3	60
26,3	40
27	60
39,4	30
39,9	60
45,1	20
46,7	40
50,3	20
50,7	40
69,8	20
70,2	40
71	20
73,6	40
114	30
117	40
118	20
121,5	40
137	30
128	40
147	20
149	0

Station Location	Station location, km	Dwell, seconds
Origin	0	0
Destination	149	0

Central - south zone route data

Location, km	Elevation ASL (m)
0	10
1,27	12
3,63	13
4,73	11
6,85	5
8,3	8
10,3	7
11,6	9
22,7	13
23	13
25	18
25,7	17
26	14
27,1	13
27,6	16
28,1	16
29,3	12

Speed limit changing location, km	Speed Limits, km/h
0	40
29,3	0

Station Location	Station location, km	Dwell, seconds
Intermediate point	0	0
Destination	29,3	0