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Article

# Zero-Emission Truck Powertrains for Regional and Long-Haul Missions

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**Abstract:** Zero-emission trucks for regional and long haul missions are an option for fossil-free freight. The viability of such powertrains and system solutions was studied conceptually in project ESCALATE for trucks with GVW of 40 tonnes and beyond through various prime mover combinations. The study covers battery and fuel cell power sources with different degrees of battery electric as well as H<sub>2</sub> and fuel cell operation. As a design basis, two different missions with a single-charge/H<sub>2</sub> refill were analysed. The first mission was the VECTO long haul profile repeated up to 750 km, whereas the second was a real 520 km on-road mission in Finland. Based on the simulated energy consumption on the driving cycle, on-board energy demand was estimated, and the initial single-charge operational scenarios were analysed with five different power source topologies. The traction motors of the tractor were dimensioned so that a secondary mission of GVW up to 76 tons on a shorter route can be operated. Based on the powertrain and vehicle model, various infrastructure options for charging and H<sub>2</sub> refuelling strategy as well as various operative scenarios with indicative total cost of ownership (TCO) were analysed.

**Keywords:** electric vehicle; battery; fuel cell; charging

## 1. Introduction

The European Green Deal outlines the climate change mitigation targets as follows: “all 27 EU Member States committed to turning the EU into the first climate neutral continent by 2050”. They pledged to reduce emissions by at least 55% by 2030, compared to 1990 levels and reaching out to fossil-free society by 2050 [1]. The transportation sector is responsible for roughly one-quarter of the total greenhouse emissions in the EU with road vehicles contributing to over 60% of the emissions. Lorries, buses and coaches are responsible for about a quarter of carbon dioxide (CO<sub>2</sub>) emissions from road transport in the EU and for some 6% of total EU emissions. Despite some improvements in fuel consumption efficiency in recent years, these emissions are still rising, mainly due to increasing road freight traffic. This requires tremendous efforts in the coming years to introduce zero-emission powertrains and energy infrastructure into regional and long haul trucking operations. Vehicle emission regulations and other policy measures will pave the way the transition towards zero-emission transport curbing the total EU emissions of CO<sub>2</sub>, although for heavy-duty vehicles the current regulation is still quite mild: -15% from 2025 onwards and -30% from 2030 onwards, compared with 2019/2020 level [2].

Even the electrification is only one tool among others to reduce the vehicle emission it appears to be the most efficient and feasible technology. Only that there is dilemma between uptake of electric heavy-duty vehicles (e-HDV) and the building-up of the charging infrastructure. To resolve the chicken-and-egg problem of e-mobility, three largest truck manufacturers have joined in the project for establishing charging infrastructure for electric long-distance freight transport [3]. The uptake of e-HDVs has been most feasible in conventional city deliveries that typically, like e-Buses, drive pre-defined work cycles, their energy consumption can be estimated quite accurately, and they can be charged overnight in their dedicated parking depots, while their daily driving range vary only a little. However, if there are more variables in the logistics assignment there should be flexibility in the

system so that in exceptional cases it could be possible to use opportunity charging (fast charging, high power charging, HPC) in addition to depot charging. Driving in multiple shifts create the demand for HPC instead of slow depot charging. Ad-hoc assignments (e.g. courier service, construction transports, maintenance and utility vehicles), logistics in greater metropolitan areas, long-haul transportation, etc. can be based on the depot but additionally would require the HPC. Roughly put, the heavier the (articulated) vehicle is, the more the demand for HPC during the work shift will be.

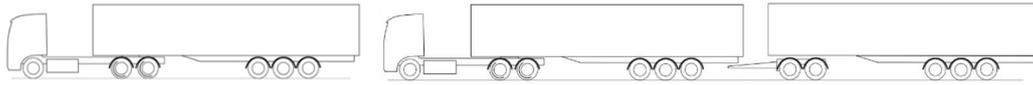
In Nordic countries the long-haul trucks are typically in heavier weight class that is up to GVW 76 tons. These national regulations make Nordics a small and specific market area so that the newest innovations would rather need to be implemented by national or joint activities. Combining the harsh weather conditions with the higher vehicle masses makes the Nordics an ideal location for piloting new innovations. In 2021-22 piloting case examples in electrification of heavy transports were reported in Sweden that High Capacity Transport (HCT) articulated vehicles of 64 and 80 GVW-tons can be electrified in certain routes and drive cycles [4,5]. Also, that the transportation safety norms for dangerous goods (ADR) can be fulfilled using e-HDVs [6].

The strict definition of zero-emission road transport requires the prime mover to be electricity (battery electric vehicle, BEV) or hydrogen (fuel cell vehicle, FCV). The present paper deals with conceptualizing and designing modular zero-emission powertrains suitable for regional and long-haul missions using trucks with GVW of 40 tonnes and beyond. In Europe this relates to VECTO vehicle groups 4-12, and in the US Class 8 trucks. The conceptual design object is a 6x4 tractor (VECTO 12, [7]) prototype with a modular zero-emission powertrain capable of multiple zero-emission missions in regional and long haul operations. The powertrain has an intermediate-sized traction battery for electric operation, fuel cell system capable of providing average power for selected missions, and a strategy for battery-fuel cell hybrid operations. The modular powertrain therefore enables three energy and operation strategies to be analysed in one demonstration setting: BEV operation, FCV operation, and fuel cell range extended BEV (FCRE) operation.

In line with the European 2050 goals, the present paper has been produced through the project ESCALATE, which aims to demonstrate high-efficiency zHDV powertrains (up to 10% increase) for long-haul applications that will provide a range of 800 km without refueling/recharging and cover at least 500 km average daily operation (6+ months) in real conditions. ESCALATE is built on the novel concepts around 3 main innovation areas, which are: i) Standardized well-designed, cost effective modular and scalable multi-powertrain components; ii) Fast Fueling & Grid-friendly charging solutions; and iii) Digital Twin (DT) & AI-based management tools considering capacity, availability, speed, and nature of the charging infrastructures as well as the fleet structures. Throughout the project lifetime, 5 pilots, 5 DTs and 5 case studies on TCO (with the target of 10% reduction), together with their environmental performance via LCA will be performed.

## 2. Materials and Methods

Two design bases driving cycles for the GVW 40-ton prototype tractor demonstrator were used, vehicle configuration as in Figure 1 (left). The first driving cycle is a single charge & refill mission of 750 km based on the long-haul mission profile of the VECTO tool, and the second one a real round-trip mission in Finland of 520 km exposed to various Nordic road conditions. The real route runs between the port of Helsinki in the south of Finland up to Jyväskylä in central parts of Finland, along the TEN-T core corridor. Modular powertrain and vehicle model was constructed to support the conceptual design, and driving cycles for both the VECTO long haul and the real mission were constructed, utilizing open road network and speed limit data. Charging and H<sub>2</sub> refuelling sites were planned to support the missions. Energy consumption on the said driving cycles and loading were estimated through simulation and this information was used for preliminary dimensioning of the powertrain. The electric drives of the tractor were dimensioned so that a secondary mission of GVW up to 76 tons configuration, Figure 1 (right) on a shorter route can be operated. The basic parameters of the powertrain and the vehicle combinations used in the simulation are given in Table 1.



**Figure 1.** Tractor and semitrailer (prototype) with the nominal GVW 40t configuration (left) and a HCT configuration of tractor, semitrailer, dolly and another semitrailer with GVW of 76t (right).

**Table 1.** Main vehicle and powertrain parameters of the simulated vehicle combinations (GVW 40t tractor and semitrailer, GVW 76t tractor, semitrailer, dolly and semitrailer).

Parameter	
Total mass	40 t / 76 t
Empty mass	16 t / 26 t
Tractor axle configuration	6x4
Motor nominal power	430 kW
Motor nominal speed	1200 rpm
Number of gears	5
Battery efficiency	97%
Inverter efficiency	98%
Driveline efficiency	93%
Aerodynamic factor $C_dA$	7.96 m <sup>2</sup> / 12.0 m <sup>2</sup>
Rolling resistance factor	0.0065
Maximum speed	80 km/h

In the piloting phase the electric truck (in BEV and/or FCEV configuration) will operate on a flexible time schedule. The vehicle will be depot charged in Jyväskylä. It is possible to drive directly to Vuosaari port in Helsinki without need for opportunity charging on the road. The driver's resting hours will be well enough to make each leg without additional breaks due to possible charging events. The time schedule allows the driver to unload the cargo plus having the lawful break in port before heading to second leg. Meanwhile the truck can be opportunity charged (high-power charging, HPC).

While the work cycle in the planned piloting phase offers high flexibility it is crucial to design and validate the configuration also in work cycles of heavier gross vehicle weights. Typically, the long-haul trucks drive in three-shift work only by changing the driver by the road. The EC regulations for driver's rest times require one 45 min break after each 4.5 h period of driving [8]. The 45 min break can be split into 15+30 min of which the 30 min need to take place after each 4.5h of driving. Thus, it is important that the vehicle supports HPC in a way that enough energy can be charged for at least 2-2.5 h of driving. The validation of the functionality of the charging and terminal operations during the fast charging will be covered in other phases of the project.

The energy consumption of electric trucks was evaluated by means of simulations. For this purpose, the simulation platform VTT Smart eFleet, originally developed for urban buses [9] and validated based on measurements in [10] was utilised. The simulation platform models the longitudinal dynamics of a vehicle travelling on a specific route. The route is in the simulations divided into short segments, of which each includes data on the topology, traffic lights, road curvature, speed limit and length obtained from open data sources. In the simulation, a speed reference is formed for each vehicle based on the characteristics of the route, i.e. the speed limit and the road curvature. In addition to this, a traffic component can be included to model the impact of congestion. The speed of the vehicle is controlled by a PI-controller. As the power flow of the simulation model is forward-facing, the powertrain design parameters automatically set limits on the acceleration, and the simulation model is well suited for cases where no speed measurement data is yet available.

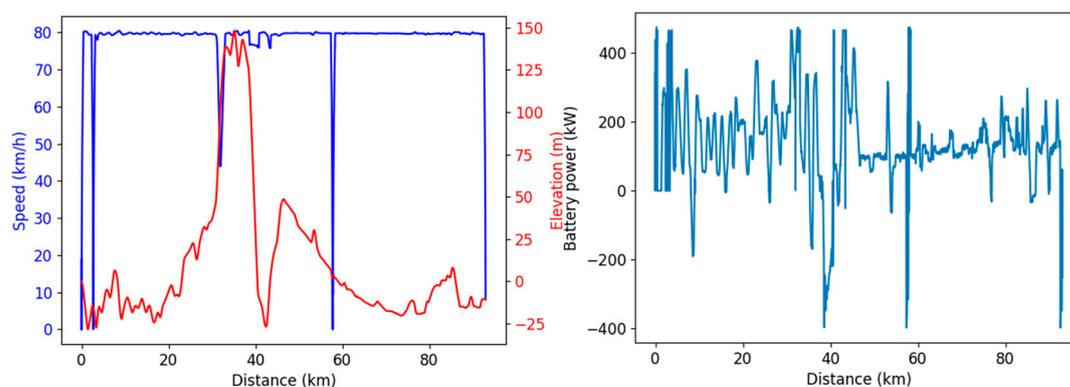
Two different powertrain options for the zero-emission truck were modelled, a pure battery-electric powertrain and a battery-electric with a fuel cell acting as a range extender. The electric motor is modelled as an efficiency look-up table dependent on the rotational speed and the torque. The efficiencies of the gearbox, the battery and the inverter are assumed to be constant. The power rating of the electric drive was dimensioned to enable operation with GVW of 76 t and to meet the power requirement of 5kW/GVW-ton. A simple efficiency curve was implemented for the fuel cell, also the power of the fuel cell system will be scaled based on the degree of FC hybridisation. Estimated mass of the power source components will be taken into account as well. For battery use, a simple limitation of available output power on battery state of charge was implemented.

To ensure the traction performance of the vehicle combination, the mechanical driveline includes a 5-speed gearbox. The gear change logic uses fixed traction motor speeds for up and down shifting keeping the traction motor speed in a range with sufficient power output capability and the highest possible efficiency. The traction power is delivered to the road using tandem driven bogie axles. For the operation with 40 t GVW the tandem driven axles would not be needed, but this selection is made to enable also the operation with 76 t GVW. Losses in the mechanical driveline are taken into account using efficiency factors for the gearbox and driving axles. The road load model includes the gravity force due to slope and driving resistance forces for tire rolling resistance and aerodynamic drag.

### 3. Results

The results from the simulations are shown in Figure 2 for the VECTO long haul mission profile and in Figure 3 for the actual long-haul mission. In the synthesised results, the VECTO profile (Figure 2) is repeated until the design basis of 750 km mission is reached. The average energy consumption for the VECTO long haul driving cycle was 1.83 kWh/km, resulting in a total energy of 1373 kWh drawn from the battery in pure battery electric mode. Six different power source combinations to fulfil the 750 km mission are shown in Table 2 and the corresponding simulation results for each variation are shown in Figure 3. The fuel cell has been selected individually for each powertrain combination. The maximum power and the average power on the VECTO profile are included in Table 2. The H2 tank indicates the minimum amount of hydrogen required for the VECTO long haul mission whereas the fuel cell is selected to be able to provide enough power also for a truck with maximum weight 76 tons. Therefore, the fuel cell does not operate at maximum power in the first three options, and the fuel cell efficiency is relatively good. The efficiency of the fuel cell system including all auxiliary devices and cooling of the fuel cell is shown in Figure 4.

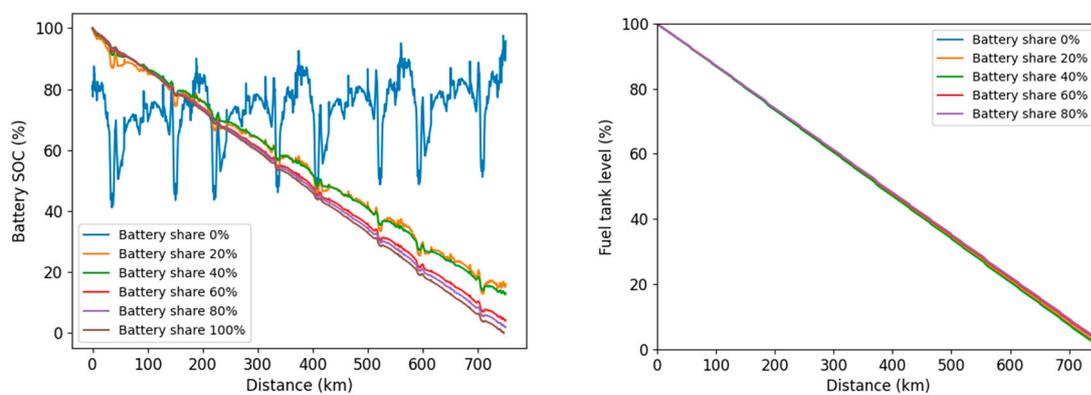
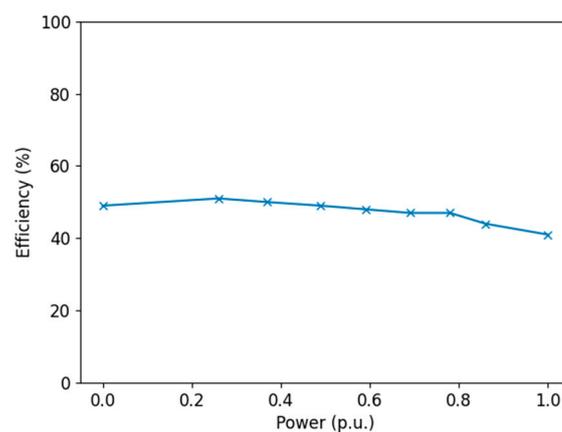
Conceptual powertrain design configurations for the power source capacities are given in Table 2 for the VECTO long haul profile. The design basis analysis assumes that the entire mission is carried out without intermediate or opportunity charging or H2 refilling, in other words, energy storages are full at the start of the mission and will be depleted at the end.



**Figure 2.** VECTO long haul driving cycle with elevation and driving speed (left) and battery power (right).

**Table 2.** Power source combinations for 750 km VECTO long haul mission.

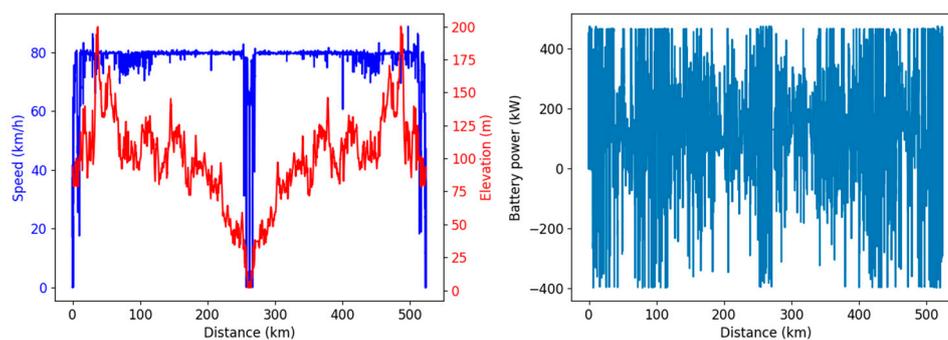
Share of battery electric operation	Battery size	H2 tank	Fuel cell maximum power	Average fuel cell power	Weight (fuel cell, hydrogen storage, battery)
0%	50 kWh	85 kg	230 kW	133 kW	2500 kg
20%	275 kWh	71 kg	180 kW	110 kW	3210 kg
40%	549 kWh	58 kg	110 kW	86 kW	4120 kg
60%	824 kWh	42 kg	57 kW	57 kW	5030 kg
80%	1098 kWh	21 kg	29 kW	29 kW	5950 kg
100%	1373 kWh	0 kg	-	-	6860 kg

**Figure 3.** Battery state of charge (SOC) and hydrogen tank level during the VECTO 750 km long haul mission for the different powertrain variants.**Figure 4.** Efficiency of the fuel cell system. The fuel cell output power is expressed relative to the maximum power.

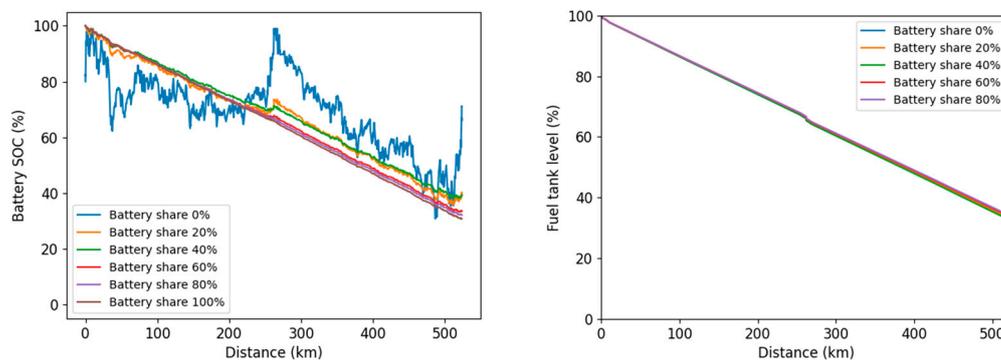
For the second use case, the driving cycle consist of a round-trip shown in Figure 5 (520 km). The route was simulated with the same powertrain configurations as in Table 2 and the resulting energy consumption for the nominal GVW 40t configuration in pure battery electric mode was 1.82 kWh/km. The consumption in the direction Vuosaari – Jyväskylä was 1.85 kWh/km and in the

opposite direction 1.78 kWh/km. The battery state of charge and fuel tank level are illustrated in Figure 6. An additional vehicle configuration was analysed based on a GVW of 76 t as shown in the right side of Figure 1 and using the same powertrain as previously described. The energy consumptions stated above can be considered to be slightly on the conservative side to provide sufficient margins at the preliminary design phase.

The results with the 76 t configuration are illustrated in Figure 7. The battery was charged in Vuosaari for roughly 45 minutes with a charging power of maximum 1 MW, and the fuel cell power was raised to the maximum level for all powertrain configurations. In addition, a larger H<sub>2</sub> tank was used for the first two powertrain configurations operating with 0% and 20% battery share, respectively. H<sub>2</sub> refilling in Vuosaari could be an option to minimize the H<sub>2</sub> tank. The resulting total energy consumption levels on the Jyväskylä – Vuosaari route are shown in Table 3. It is to be noted that these consumption numbers are not fully optimized. The energy management strategy could be tuned based on the mission to prioritize battery electric energy and minimize the use of hydrogen especially in the case that it is more expensive than charged electricity. The fuel cell efficiency varied in the range 48% - 53% in the simulations, while the battery efficiency was 97%. In other words, 1 kg of hydrogen corresponds to 16 – 17 kWh of usable energy. The energy management strategy should be selected based on the available recharging infrastructure. The strategy chosen here allows the vehicle to operate on long distances on the expense of high energy consumption when relying heavily on the fuel cell.



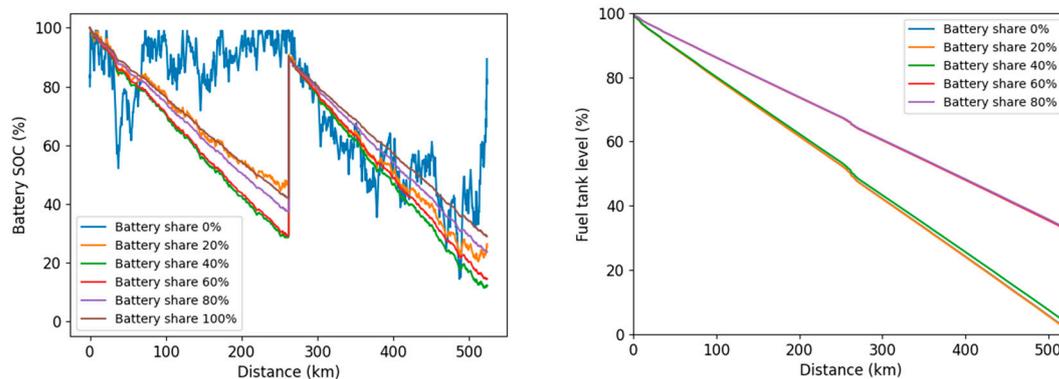
**Figure 5.** Speed and elevation of the Jyväskylä - Vuosaari roundtrip (left) and corresponding battery power in pure BEV mode (right).



**Figure 6.** Simulated battery state of charge (SOC) and hydrogen fuel tank level on the Jyväskylä - Vuosaari route (roundtrip).

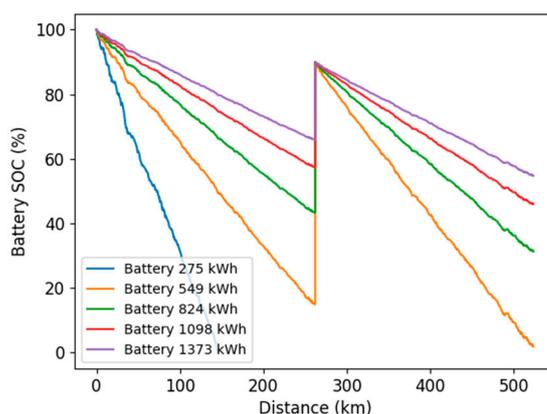
**Table 3.** Energy consumption for the 520 km on-road roundtrip long haul mission for 40 t and 76 t configurations. An intermediate recharge/refuelling during at the turning point the mission assumed for the 76 t configuration.

Share of battery electric operation	GVW 40t nominal case				GVW 76t HCT case			
	Jyväskylä – Vuosaari		Vuosaari – Jyväskylä		Jyväskylä – Vuosaari		Vuosaari – Jyväskylä	
	Battery electric energy (kWh/km)	Hydrogen energy (kWh/km)	Battery electric energy (kWh/km)	Hydrogen energy (kWh/km)	Battery electric energy (kWh/km)	Hydrogen energy (kWh/km)	Battery electric energy (kWh/km)	Hydrogen energy (kWh/km)
0%	-0.04	3.72	0.05	3.70	-0.04	7.59	0.02	7.52
20%	0.30	3.10	0.35	3.09	0.47	5.94	0.67	5.89
40%	0.62	2.52	0.67	2.51	1.42	3.63	1.63	3.60
60%	1.02	1.84	1.08	1.83	2.20	1.88	2.38	1.86
80%	1.39	0.94	1.46	0.93	2.60	0.96	2.78	0.95
100%	1.78	0.00	1.85	0.00	2.99	0.00	3.21	0.00



**Figure 7.** Battery state of charge (left) and hydrogen tank level (right) when operating on the Jyväskylä – Vuosaari route with 76t configuration. The battery is charged in Jyväskylä for about 45 minutes with a maximum power of 1 MW.

Further simulations were performed on the Vuosaari – Jyväskylä route. Operation in pure battery electric mode is possible with intermittent charging halfway. The simulated results when charging at a power of 1 MW is available in Jyväskylä are shown in Figure 8. The charging break is assumed to be roughly 45 minutes with a couple of minutes reserved for connecting and disconnecting. The smallest batteries are obviously not enough for this case, while a battery of minimum 549 kWh battery is sufficient.



**Figure 8.** Operation in pure battery electric mode with charging in Vuosaari on the Jyväskylä – Vuosaari roundtrip.

#### 4. Discussion and conclusions

Approach and methodology for conceptual design of zero-emission truck powertrains intended for regional and long haul missions is presented. Various scenarios with the developed vehicle and powertrains models were analysed, taking into account infrastructure and charging/refuelling all along the missions, as well as their impact on the operative planning.

The approach starts from the design basis of an uninterrupted 750 km mission in the VECTO long haul profile, and secondly a 520 km mission on a real route in Southern Finland. The powertrain designed is capable for vehicle combinations flexibly from GVW of 40 t all the way up to 76 t. The energy infrastructure analysed included overnight depot charging to start the driving missions with a 100% charged battery, and an intermediate fast charging halfway the roundtrip. Energy use for two truck configurations has been estimated through simulation for both use cases.

Six different conceptual powertrain designs with varying degree of charged electric fuel cell operation were presented. For fully electric operation, the estimated battery capacity required 1373 kWh of traction battery capacity, whereas the other extreme of power source design with H<sub>2</sub> as prime mover gives a hydrogen storage capacity of 83 kg. The four intermediate powertrain options combine battery and H<sub>2</sub> tank capacities in various ways. In terms of total energy consumption (tank to wheel) the smallest overall mission energy consumption is with fully electric operation – this depends on the relative efficiencies of battery electric and fuel cell electric powertrains.

The final and optimal choice for the power source and prime mover split depends on additional factors such as infrastructure availability, electricity and hydrogen prices, required payload capacity, and system level availability and productivity. These data will become available when the final design of the demonstrator vehicle as the fuel cell range extended electric truck is manufactured and put in trial operation. The final prototype design is expected to have battery and fuel cell capacities in mid-area, between the 40-60% rows of Tables 2 and 3. The testing and data from the piloting operations will include operation in both purely electric and fuel cell mode as well as their various combinations.

As part of this subsequent analysis, an additional element of the research approach will be to assess and compare the system-level techno-economics of the powertrain and system configurations in the said use cases and missions. The analysis is upcoming based on the results of the vehicle and mission simulations and related technical and operational data. The methodology is based on earlier total cost of ownership (TCO) analysis on electric city buses [11] and related literature. This research has been presented at the EVS36 Symposium in Sacramento, USA, June 2023.

**Author Contributions:** Conceptualization, M.P., R.Å.; methodology, M.P., M.R. and P.R.; software, M.R.; validation, M.R. and P.R.; formal analysis, M.P., M.R.; investigation, M.R., M.P.; resources, M.P., R.Å.; data curation, M.R.; writing—original draft preparation, M.R, M.P.; writing—review and editing, All.; visualization, All.; supervision, M.P.; project administration, M.P.; funding acquisition, M.P. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data related to the present research is owned by VTT and other relevant ESCALATE partners and cannot be shared at the point of publication.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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