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BEV duty cycle energy consumption simulation to assess charging power needs over the shift - preliminary results

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October 8th, 2025

CMIN-2026-653-PP

Canada

Outline

- Objectives
- Methodology
- Results
- Next steps

Objectives

- Couple vehicle class with duty cycle and charging strategy to estimate electrical grid power demand over a shift for an underground mine application of battery electric vehicles
  - Vehicle classes: personnel carriers and prime movers (as they can represent over 80% of the diesel consumption underground)
  - Duty cycles according to vehicle classes (based on mining applications)
  - Charging strategies: battery size and charging strategies according to OEM availability per class of vehicle
- Estimate power grid demand per 12-hour shift per class and then aggregate them using the “example” mine vehicle distribution

Methodology: approach for vehicle energy demand and grid charging power estimate

- Methodology for vehicle energy demand estimate
  - Calibrated energy consumption model: use of the energy consumption model (ECM) for BEVs with calibrated data from field tests or equipment specifications with time schedule applied to assumed duty cycle
  - This approach allows for different duty cycles.
  - Limitation: can only be applied to vehicles with calibrated energy model (prerequisite)

Methodology: approach for vehicle energy demand and grid charging power estimate

- Methodology for power demand:
  - Power profile for the grid can then be estimated based on charging of the battery (charger power and time of charge) for each vehicle class and then can be aggregated over the shift using the time of charge
  - Charging strategies (regular charge or swapping) are applied to each vehicle class according to original equipment manufacturing (OEM) availability
  - Includes charging conditions such as minimum SoC% per vehicle class and maintaining initial SoC% per shift (final SoC% must be equal to initial SoC% during shift)

Vehicle class – BEV Personnel carrier

- Vehicles considered

RELAY

ROKION R400

Vehicle class – BEV Personnel carrier

- Vehicle specifications

Description	Relay	Rokion R400
Payload – Tonnes	1.17	1.80
Operating weight – Tonnes	4.12	5.95
Gross weight – Tonnes	5.29	7.65
Motor power – kW	100	66 x 2 (+3.73)
Battery power – kW	170/100 (peak/continuous)	186 (peak)

Vehicle class – BEV Personnel carrier

- Charging specifications

Description	Relay	Rokion R400
Charger type (options)	On board or off board	On board or off board
Charger power – kW	19	13
Charge range SoC%	20% to 85%	20% to 85%
Time to charge (hh:mm)	2:30	6:00
Battery energy – kWh	48	100

ECM – BEV Personnel carrier

- Energy consumption model (ECM) – calibration parameters*

Description	Relay	Rokion R400
Rolling resistance (%)**	2.5	3.2
Vehicle efficiency (%)	80.5	84.5
Auxiliary power (kW)	0.5	3.03

*Parameters were inferred based on test data (not actually measured)
**Different rolling resistance values result from different road conditions during the test, clear ramp for the Relay and ramp with snow for the Rokion. Rolling resistance is a function of tire deformation while rolling where softer ground results in higher values. Results aligned with ranges published in literature.

Duty cycles and charging strategy – BEV Personnel carrier

- Considered general duty cycles

ID	Class	Duty (schedule)	Duty description	Charger	Charging strategy
1	Personnel carrier	Personnel transport (mechanic)	Start and end of shift	Onboard	end of shift + opportunistic
2	Personnel carrier	Beat personnel (mechanic - electrician)	During shift on/off	Onboard	end of shift + opportunistic
3	Personnel carrier	Shift supervisor	Used as needed during the shift	Onboard	end of shift + opportunistic

- Assess shift supervisor duty cycle as it is the most energy demanding case

Duty cycles and schedule – BEV Personnel carrier

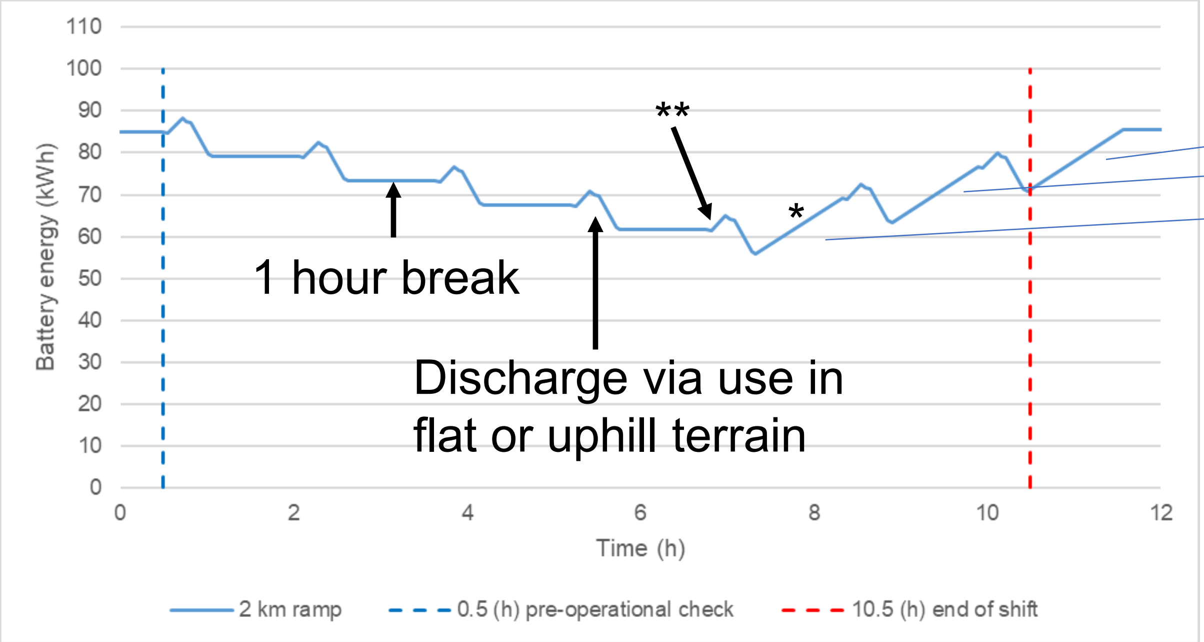
- Proposed duty cycle
  - Travel down fully loaded and travel up empty at 10 km/h
  - Route:
    - 0.5 km from parking to ramp portal
    - Variable ramp distances 2, 4, 6, 8 and 10 km
    - 0.5 km from ramp level access to level destination
    - Ramp grade 15%
    - Surface and level access 2% grade
  - Shift supervisor considers 1 hour stop after each cycle. Alternatively, it allows the supervisor to stop for an hour in total within each cycle.
  - Perform as many complete cycles as possible for a 12-hour shift

Duty cycles and schedule – BEV Personnel carrier

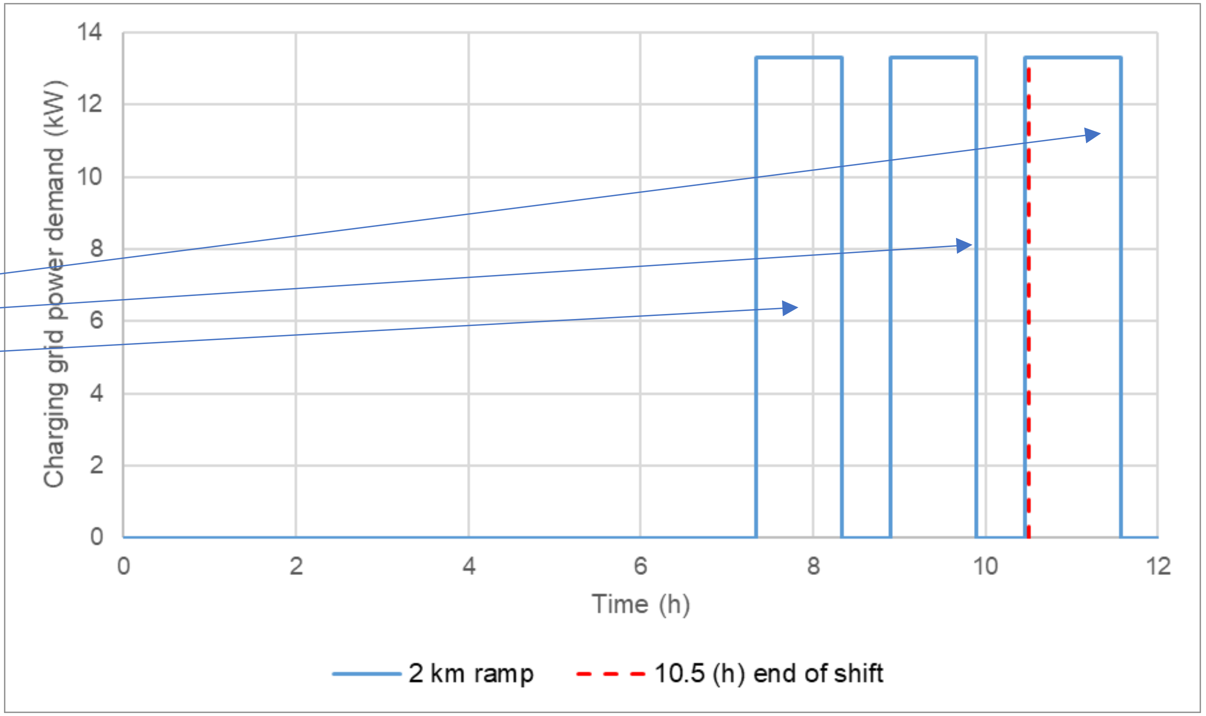
- Work schedule (for all mobile equipment)
  - Shift duration 12 hours
  - 0.5 hours assumed for operator to arrive, do pre-operational check and start equipment
  - 10 hours available to work (per 12-hour shift)
  - 0.5 hours assumed for operator to vacate the mine before blast
  - 1 hour for blast fume clearance and approval to re-enter mine
- Charging strategy:
  - Criteria 1: when next driving cycle would bring the SoC% bellow 20%.
  - Criteria 2 (manually): when SoC% at end of the shift would not match the start of the shift.
  - Criteria 1 and 2 are used to trigger charging of the equipment when it is not working
  - When Criteria 2 is triggered, charges are arbitrarily added during the shift while vehicle is stopped
  - Charging is opportunistic (assuming connectors are available for charging)

Results – observable events in graphs

- During duty cycles, charging occurs at two different rates:
  - *using the charger
  - **charging via regenerative braking



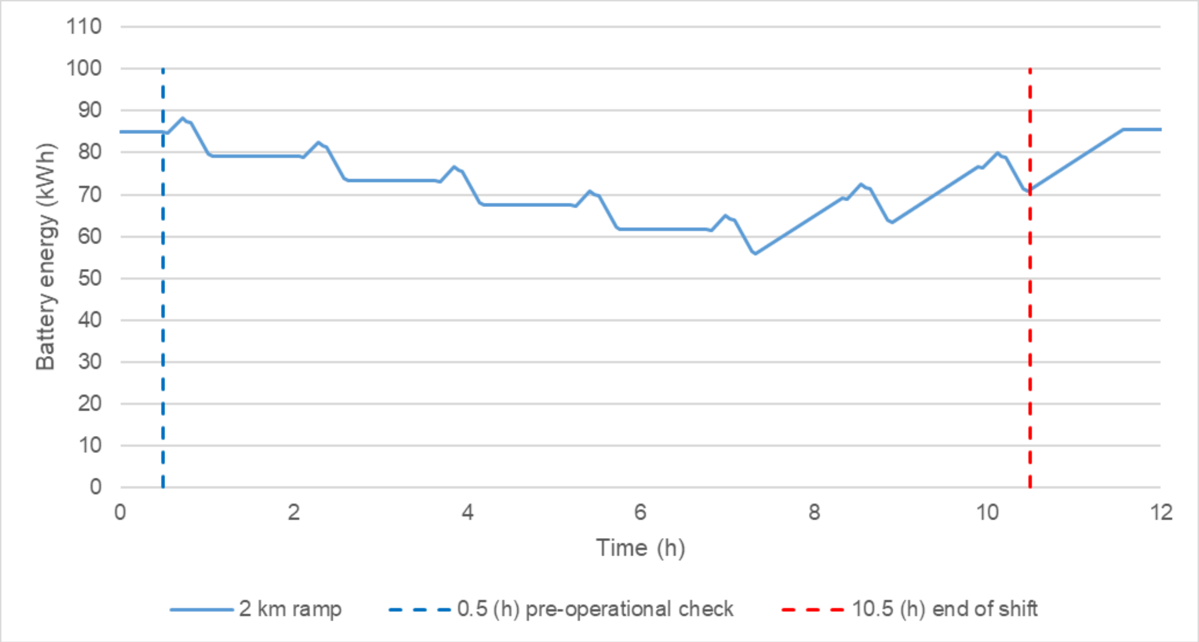
Battery energy graph (consumed and captured)

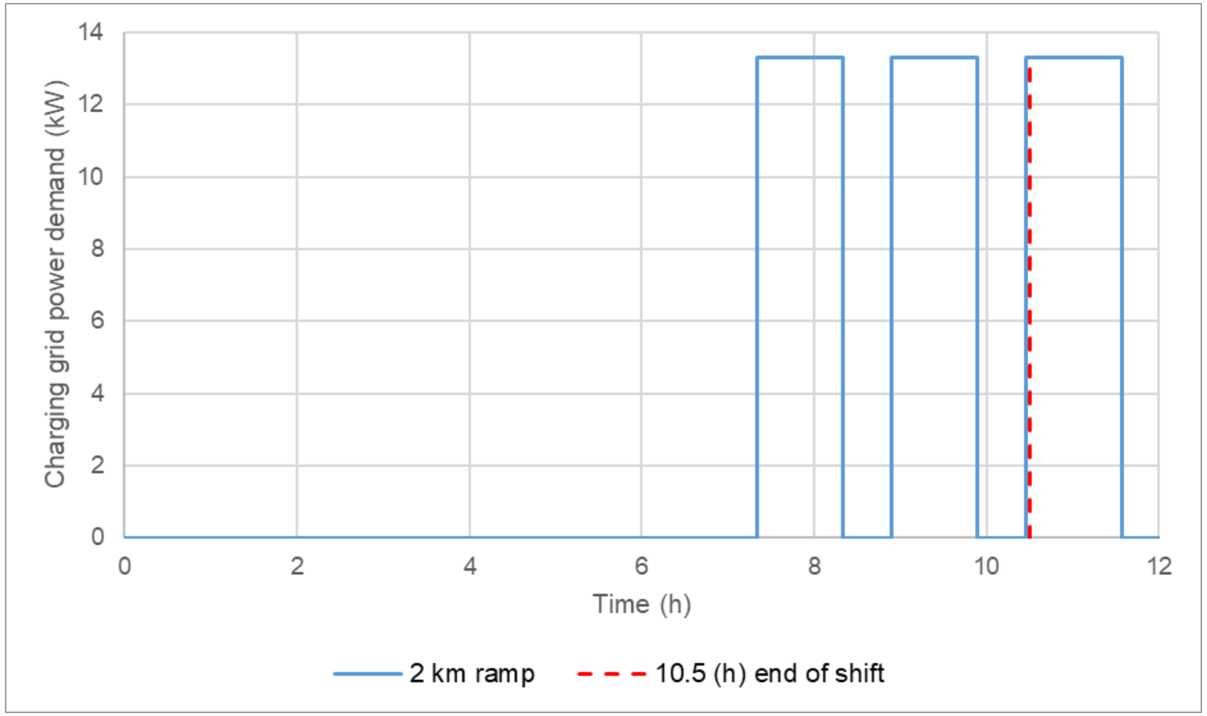


Charger power graph (from electrical grid to battery)

Results – BEV Personnel carrier – Rokion R400

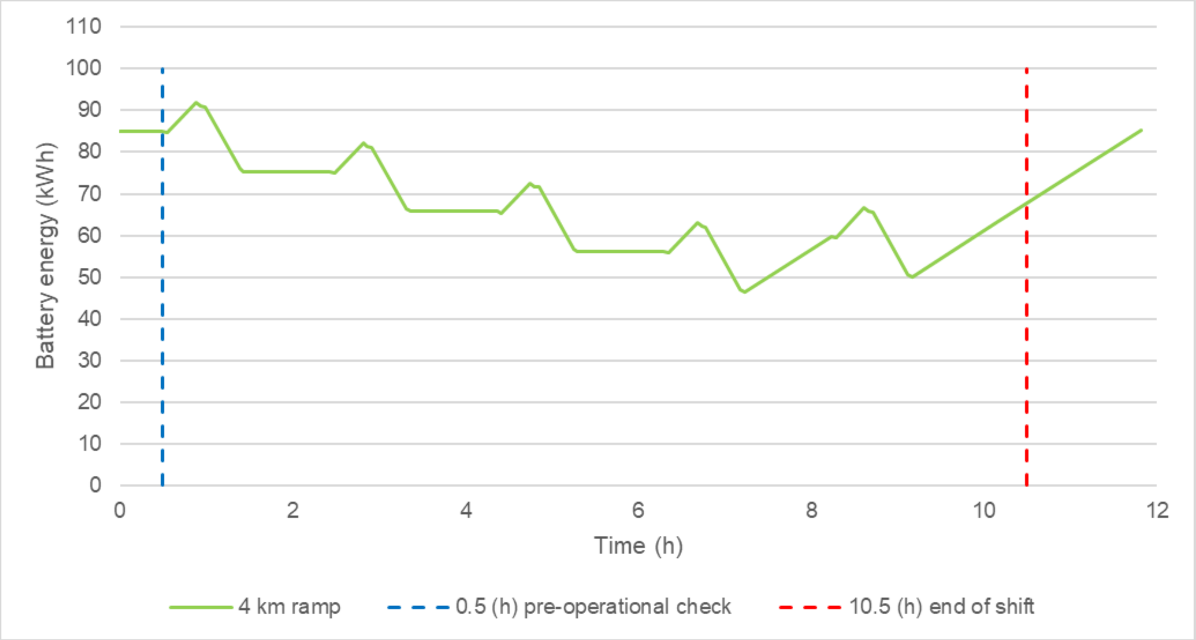
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 2 km ramp)

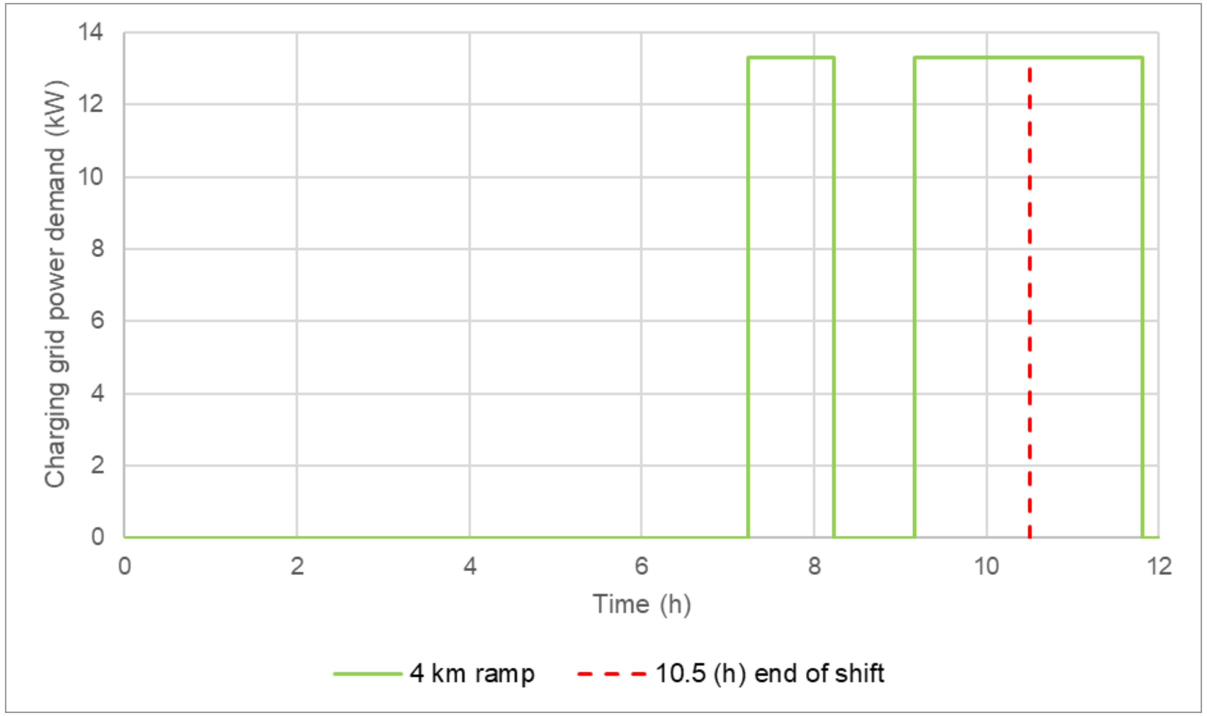




Results – BEV Personnel carrier – Rokion R400

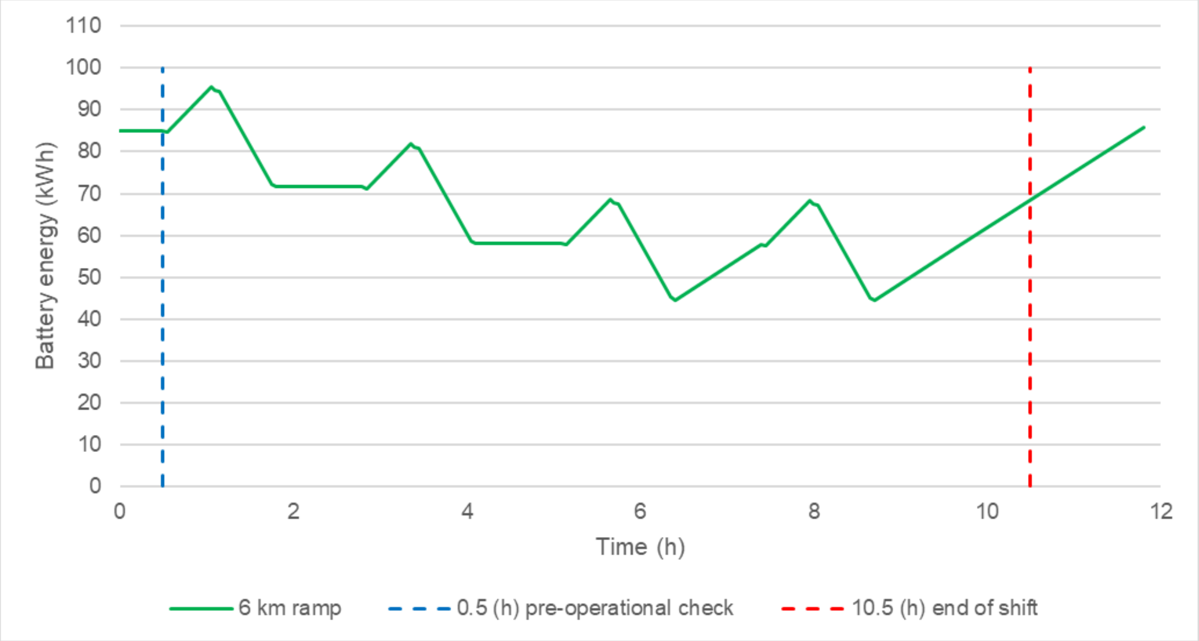
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 4 km ramp)

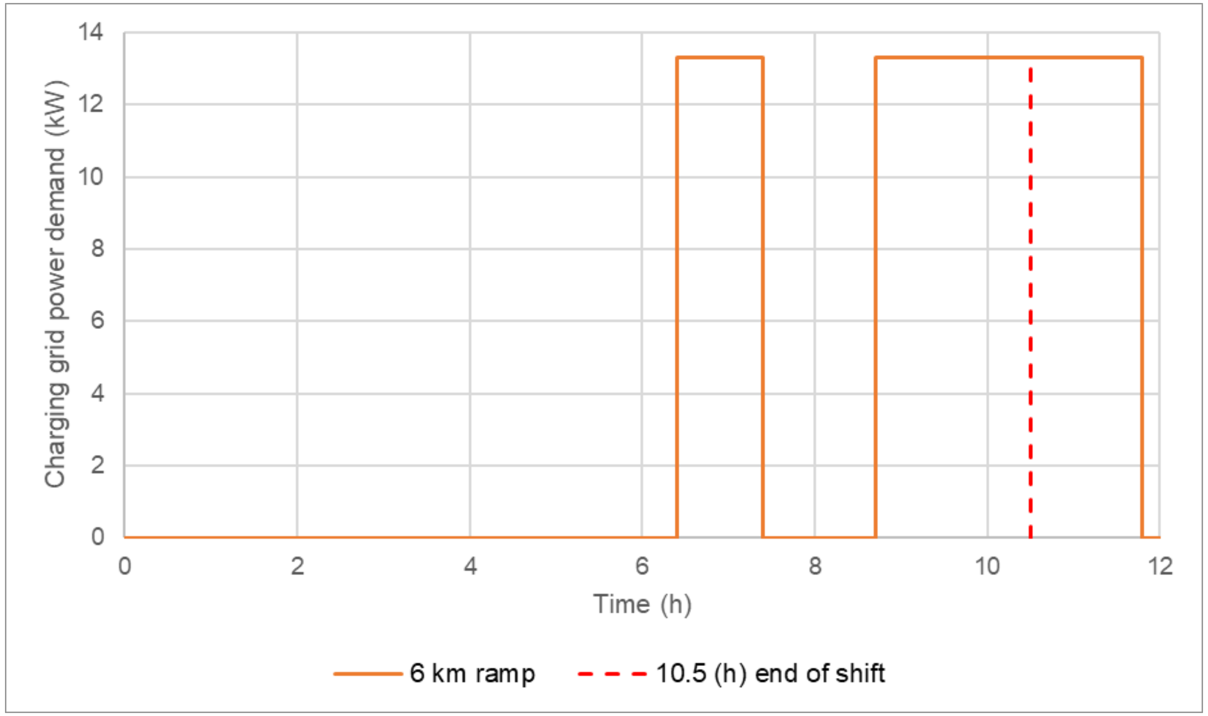




Results – BEV Personnel carrier – Rokion R400

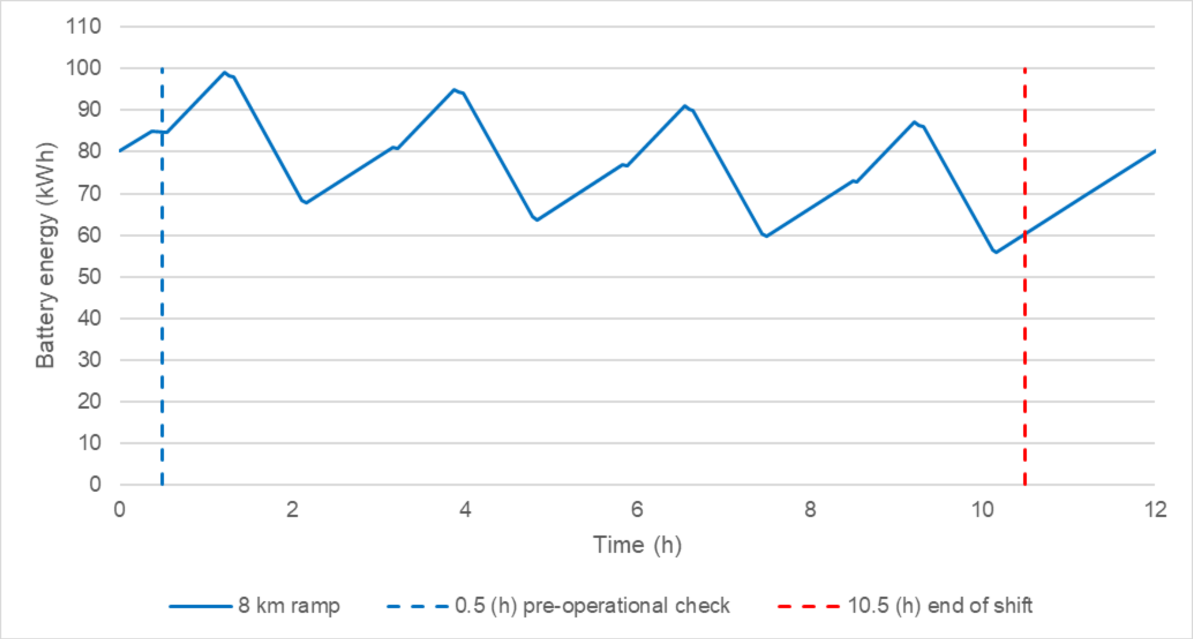
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 6 km ramp)

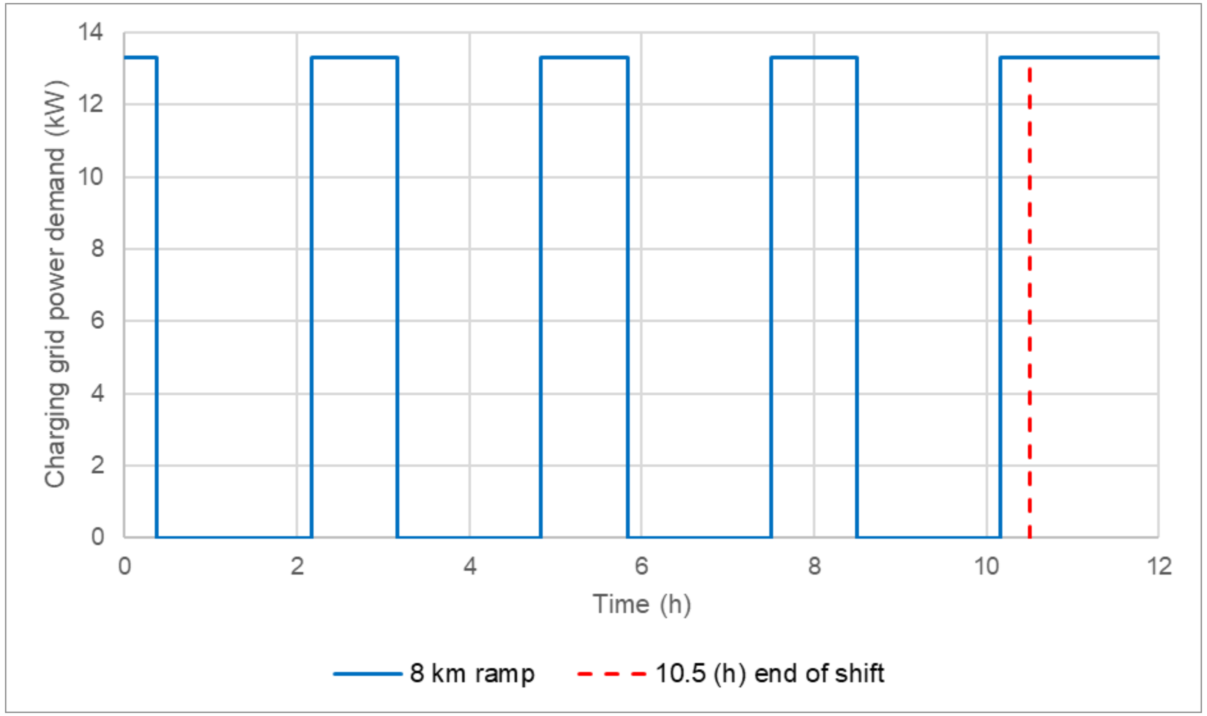




Results – BEV Personnel carrier – Rokion R400

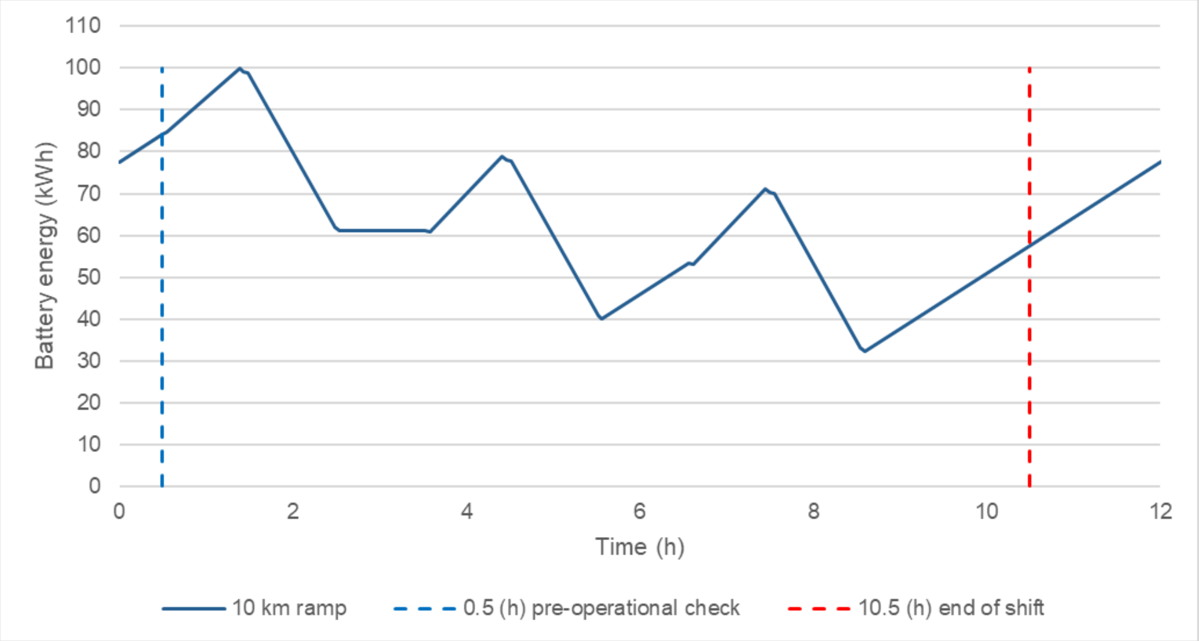
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 8 km ramp)

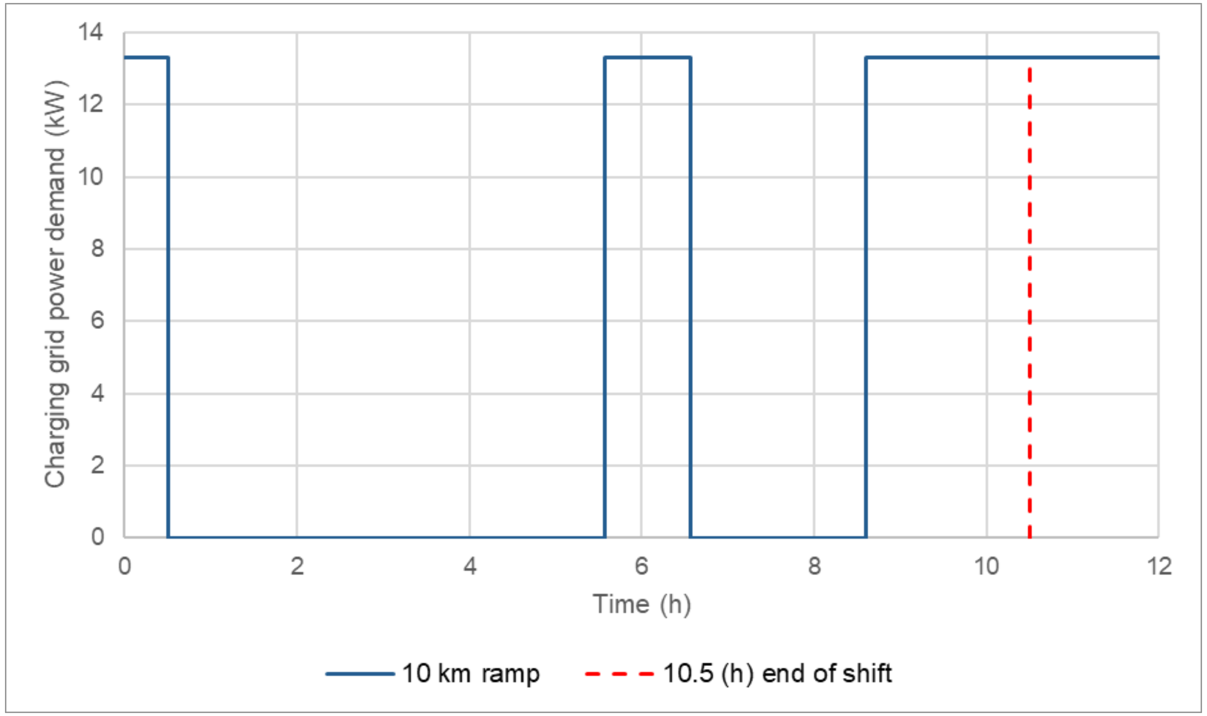




Results – BEV Personnel carrier – Rokion R400

- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 10 km ramp)





Results – BEV Personnel carrier – Rokion R400

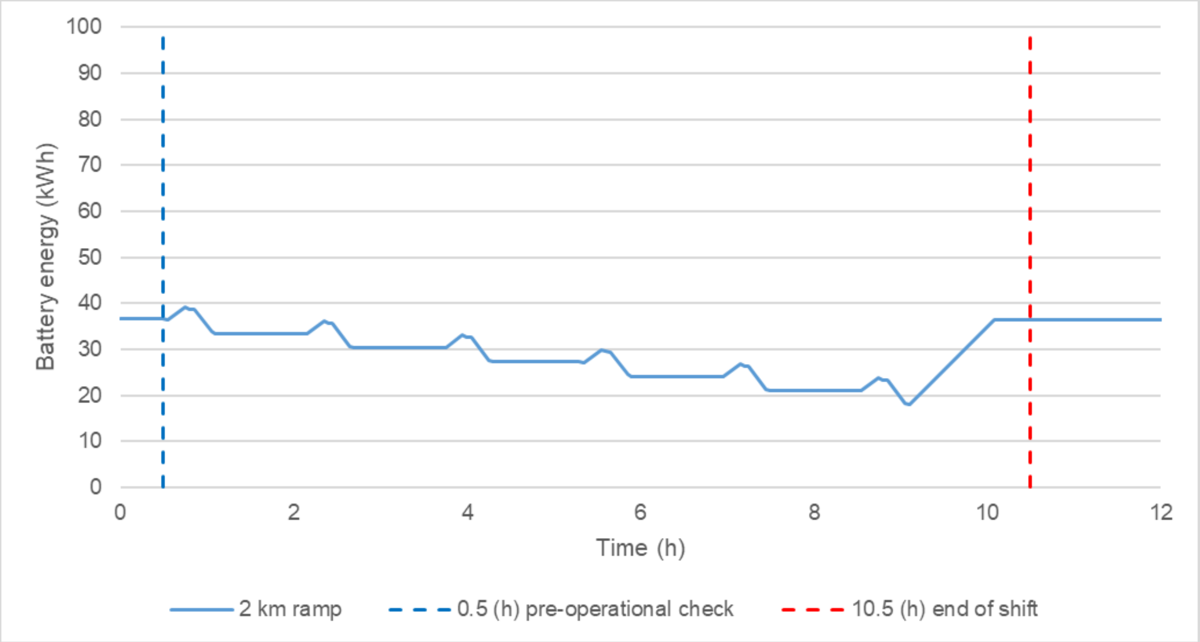
- 12-hour shift (shift supervisor duty cycle) summary
- With the proposed duty cycle, distances between 42 and 66 km can be achieved during the shift
- Energy charged varies from 41 to 69 kWh

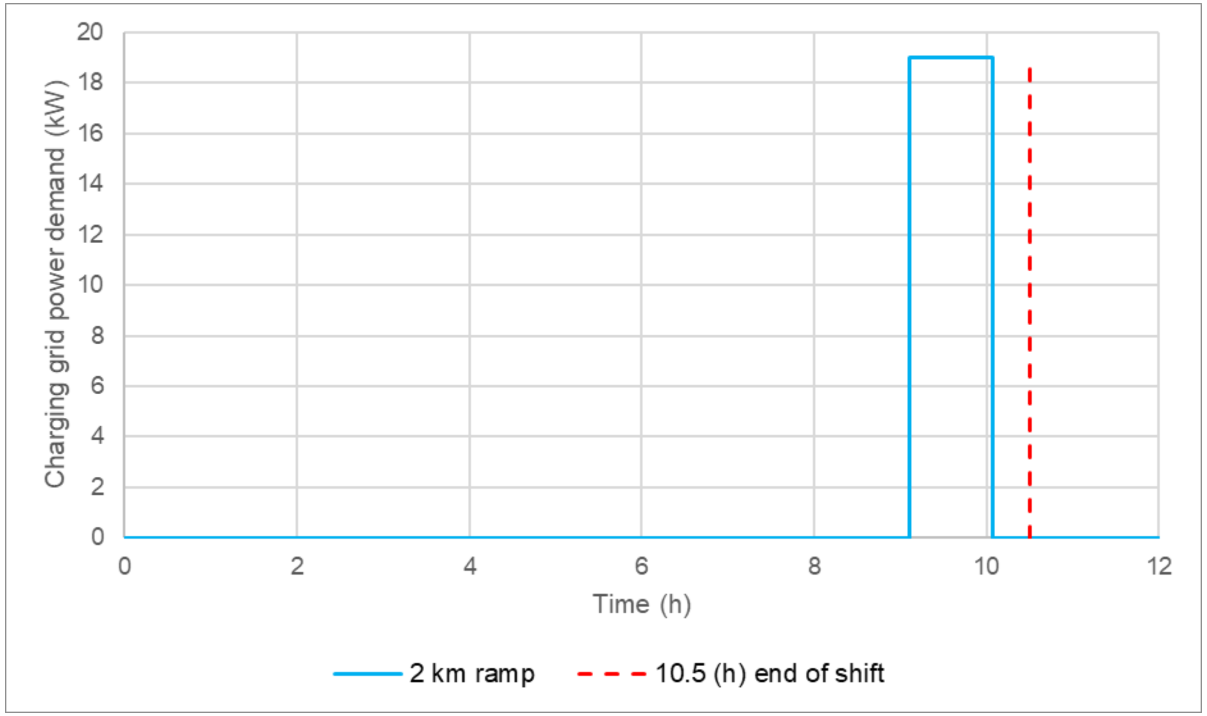
Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)
2 km ramp	6	7	42	41
4 km ramp	10	5	50	49
6 km ramp	14	4	56	55
8 km ramp	18	4	72	69
10 km ramp	22	3	66	65

Maximum distance up 15% ramp loaded is 13.6 km (with 100 kWh battery and energy used from 85% to 20% SoC)

Results – BEV Personnel carrier – Relay

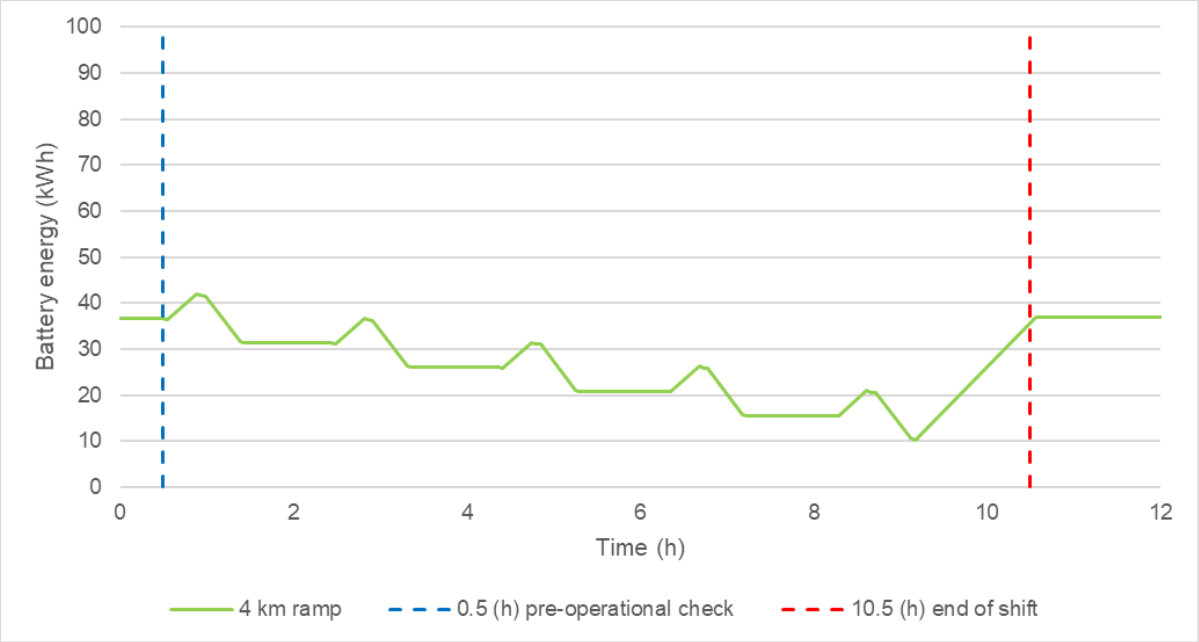
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 2 km ramp)

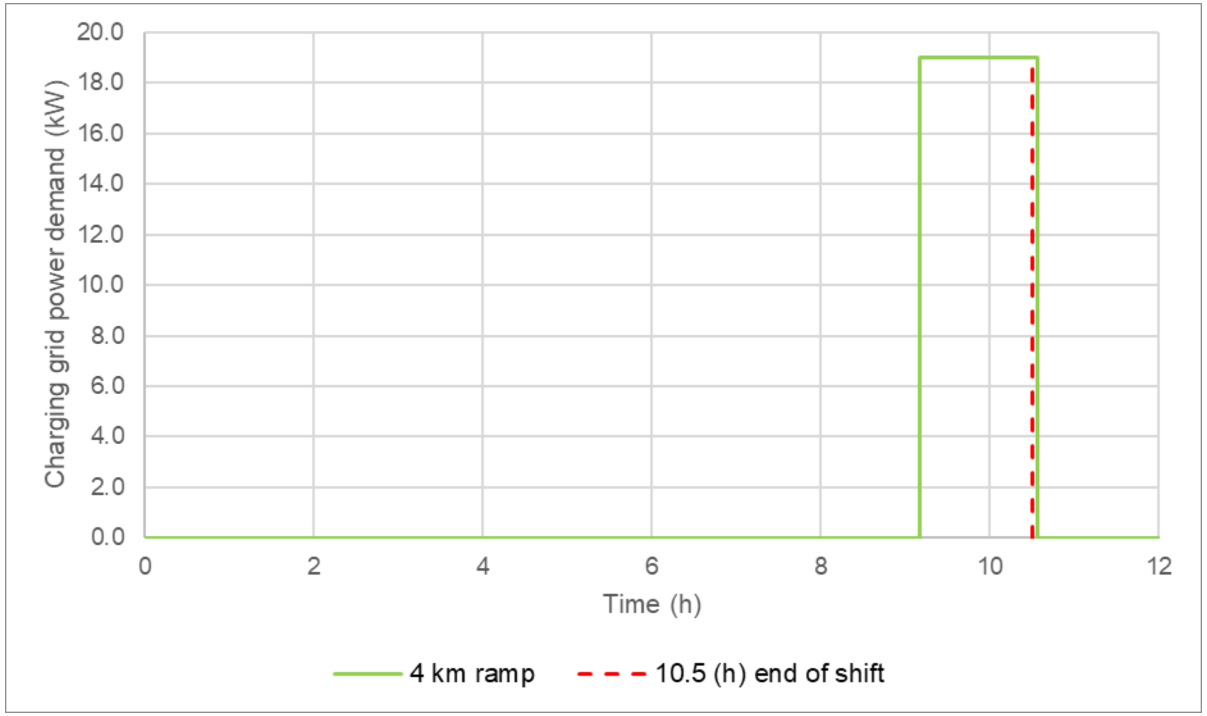




Results – BEV Personnel carrier – Relay

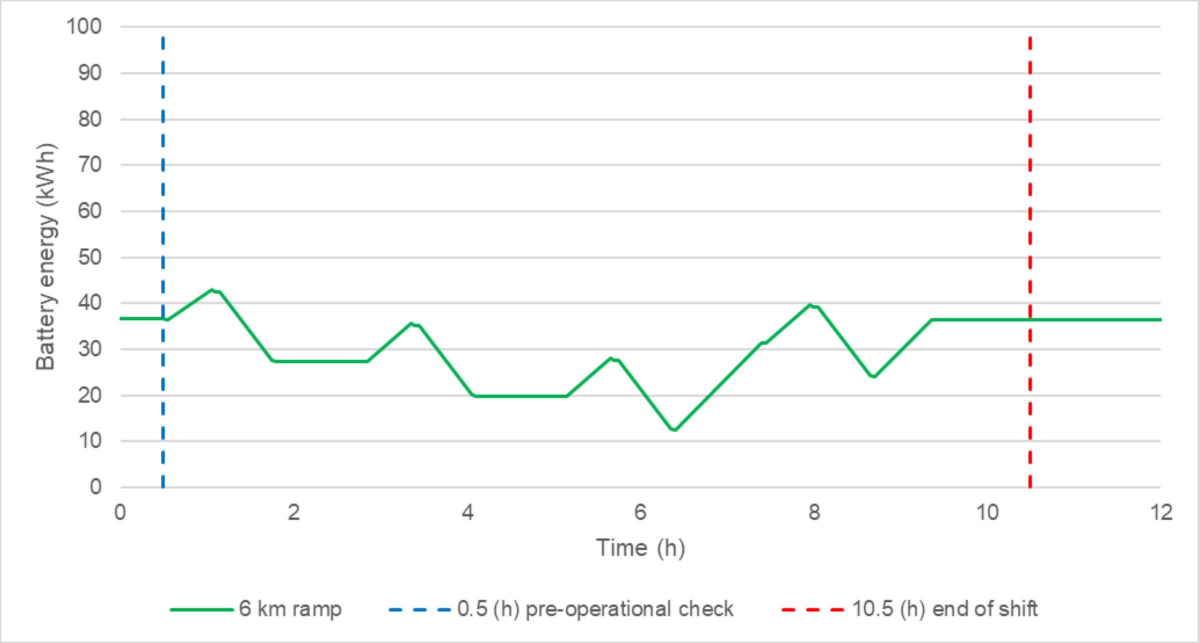
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 4 km ramp)

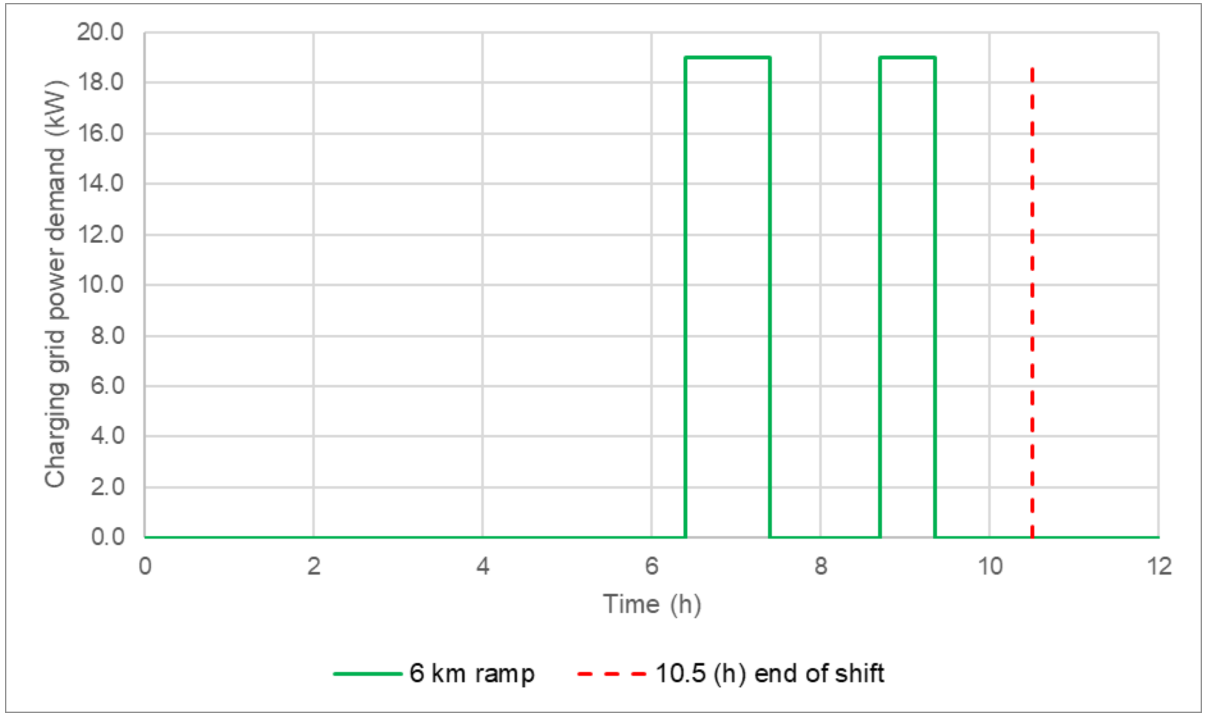




Results – BEV Personnel carrier – Relay

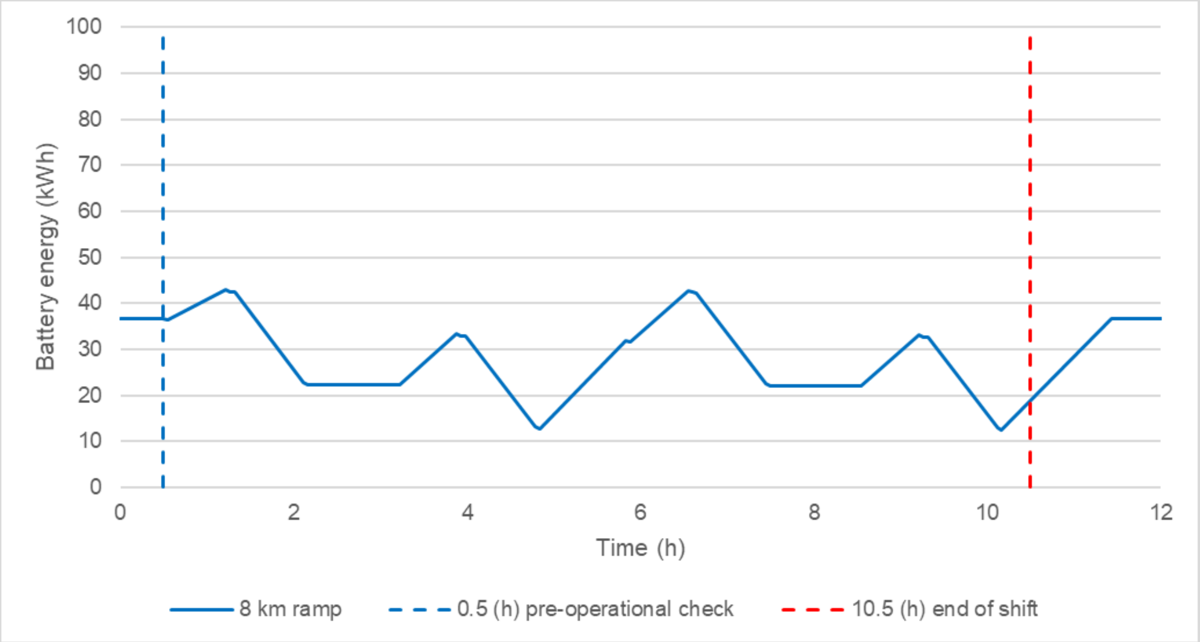
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 6 km ramp)

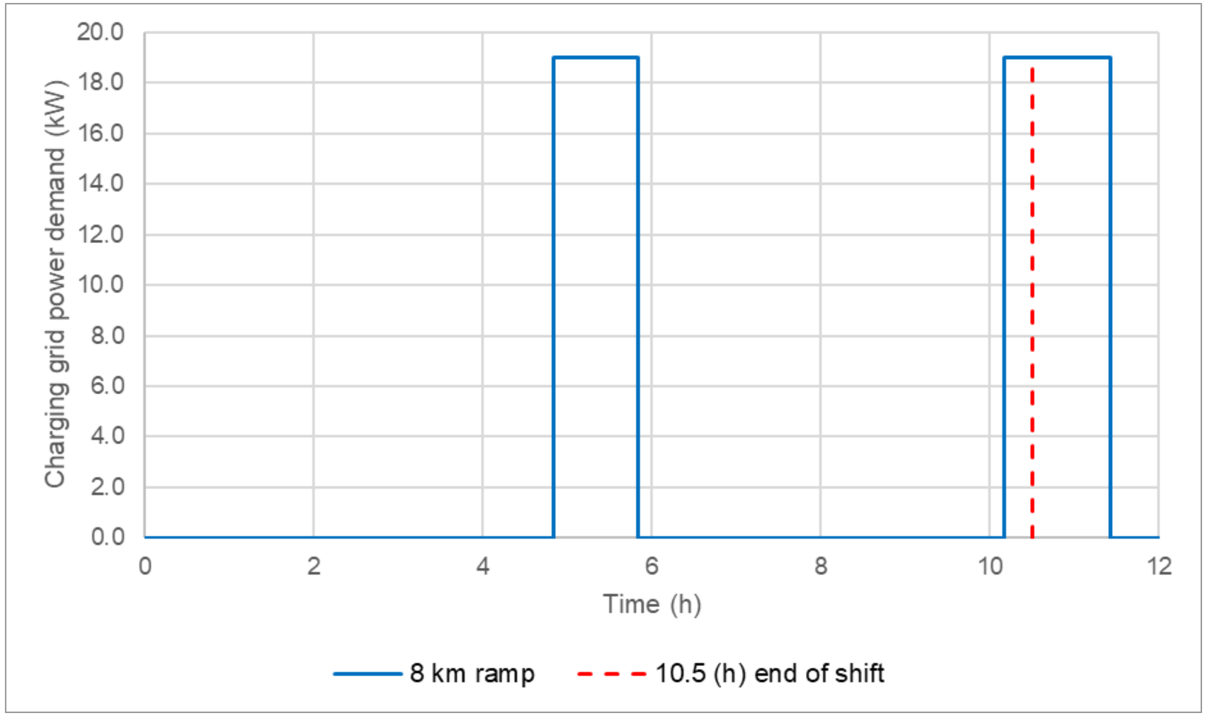




Results – BEV Personnel carrier – Relay

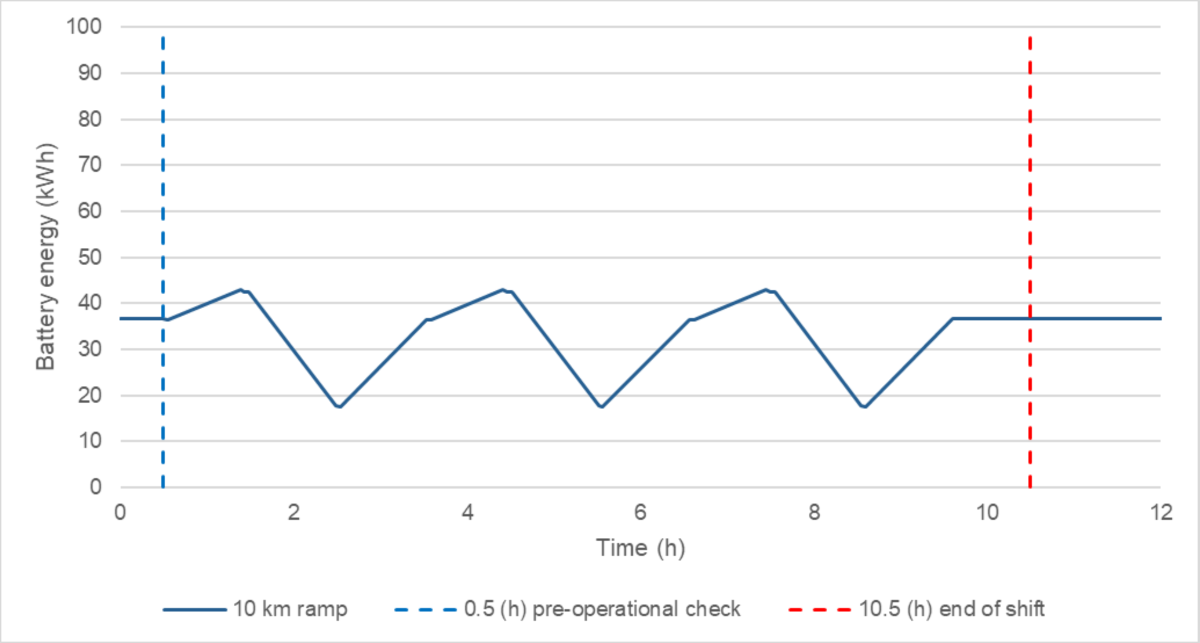
- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 8 km ramp)

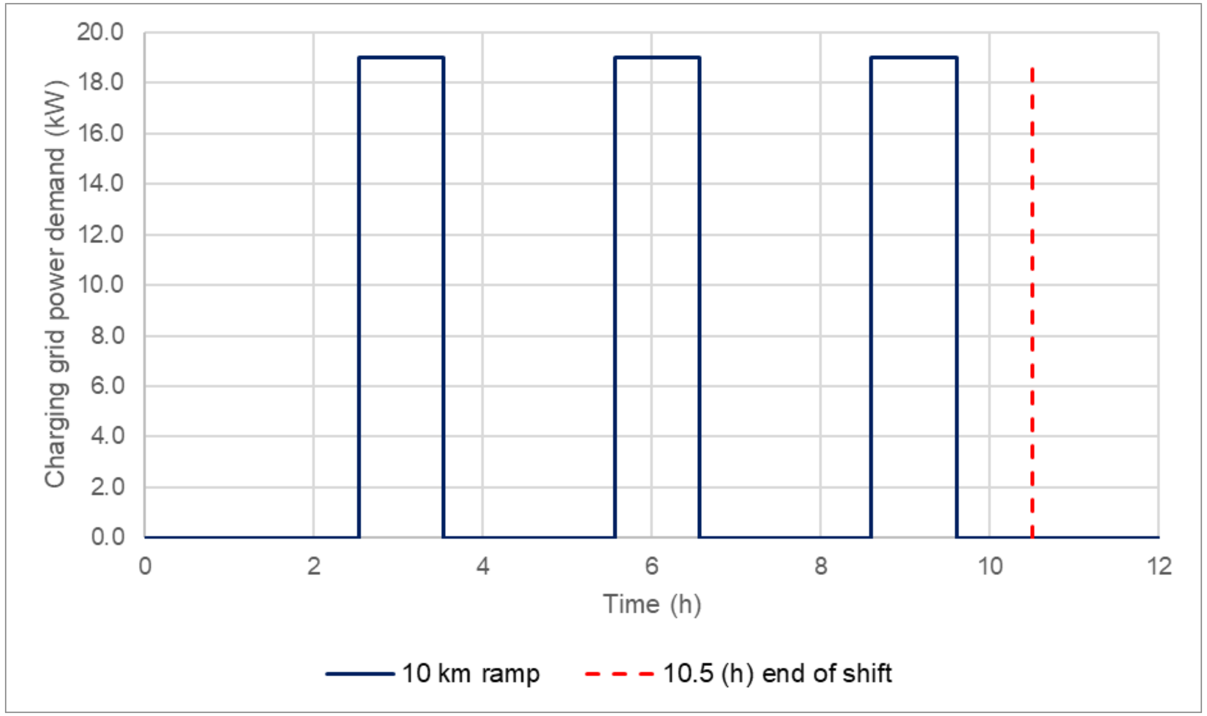




Results – BEV Personnel carrier – Relay

- Energy consumed and charged for 12-hour shift (shift supervisor duty cycle, 10 km ramp)





Results – BEV Personnel carrier – Relay

- 12-hour shift (shift supervisor duty cycle) summary
- With the proposed duty cycle, distances between 36 and 66 km can be achieved during the shift
- Energy charged varies from 19 to 57 kWh

Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)
2 km ramp	6	6	36	19
4 km ramp	10	5	50	26
6 km ramp	14	4	56	32
8 km ramp	18	4	72	43
10 km ramp	22	3	66	57

Maximum distance up 15% ramp loaded is 8.8 km (with 48 kWh battery and energy used from 85% to 20% SoC)

Results – BEV Personnel carrier – Summary

- Several inputs are required for each simulation such as: speed, grade, load, distances, schedule, battery power and energy, charger power and location, charging strategy/logic, among others
- This allows for an exponential number of 'what if' scenarios that can be generated considering different mine designs and expected duties (duty cycles)
- These inputs can affect when the charge will be required/available and as a result the grid power demand over time
- However, the grid power demand is estimated based on the number of chargers that can simultaneously be charging at any time, and as a result, any 'what if' scenario will be included in such envelope
- Queue process for travelling in the ramp or for charging was not considered in this analysis and could result in less available time to perform work and an associated reduced grid power demand

Results – BEV Personnel carrier – Summary

- The two personnel carriers simulated were able to perform the different suggested duty cycles
- The battery sizes considered (48 kWh versus 100 kWh) were not a factor that limited the performance of the vehicles during the shift for the suggested duty cycles
- The two batteries had enough capacity to store more than the required energy for the suggested duty cycle, and enough time and charging power to replenish what energy was needed during the working breaks during the shift

Vehicle class – BEV Load Haul and Dump (LHD)

- Part of the mine “prime movers”, battery electric LHDs

ST14 SG

TORO LH518iB

R1700 XE

ST18 SG

Vehicle class – BEV LHD

- Vehicle specifications

Description	Epiroc ST14	Epiroc ST18	Sandvik LH518iB	CAT 1700XE
Payload – Tonnes	14	17.5	18	14.8
Operating weight – Tonnes	42	54.5	54.8	48
Gross weight – Tonnes	56	72	72.8	62.8
Motor power (auxiliary power) – kW	200 (+150)	260 (+150)	540 (+80 x 2)	220 (+226)
Battery power continuous – kW	N/A	N/A	482	840

Note: N/A means not available in equipment specifications. Motor power is continuous.

Vehicle class – BEV LHD

- Charging specifications

Description	Epiroc ST14	Epiroc ST18	Sandvik LH518B	CAT 1700XE
Charger type	Off board	Off board	Off board	Off board
Charger power – kW	160	160	180 x 2	500 / 1000
Charge range SoC%*	20% to 85%	20% to 85%	20% to 85%	20% to 85%
Time to charge (h:mm)	1:50	3:00	2:00	0:30 / 0:15
Battery energy nominal/usable – kWh	N/A / 300	N/A / 450	482 / N/A	213 / N/A

*Charge range SoC% associated to time to charge (hh:mm). Battery can be charged to 100% if needed. In downhill applications less than 100% charge will be needed to accommodate charge via regenerative braking.

ECM – BEV LHD

- Energy consumption model (ECM) – calibration parameters (specifications)

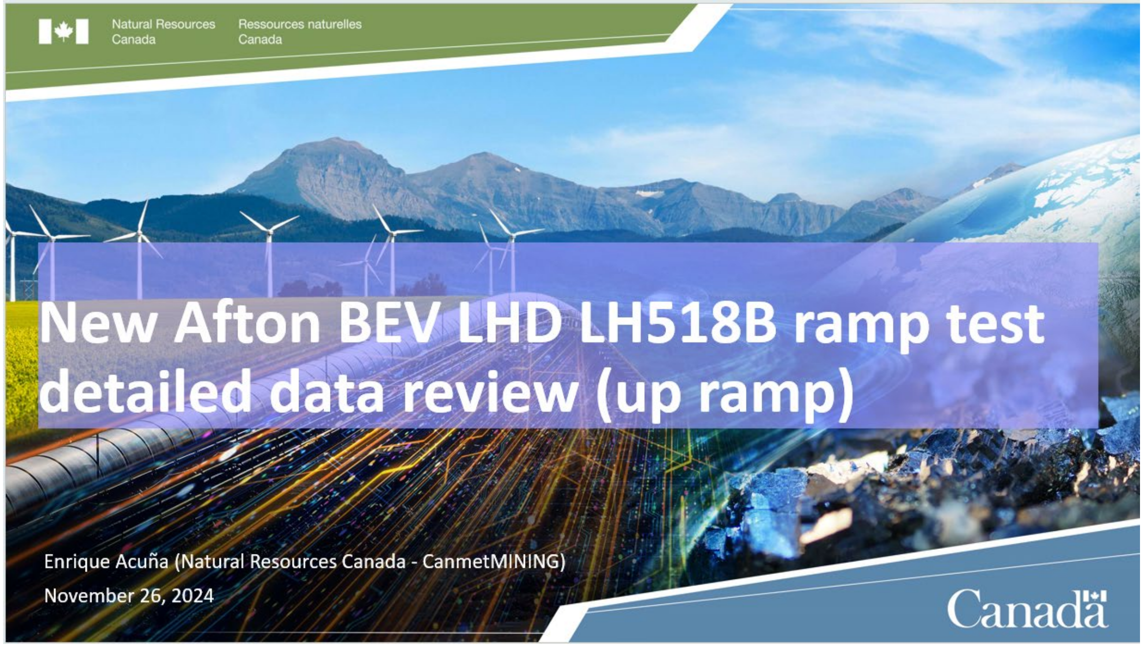
Description	Epiroc ST14	Epiroc ST18	Sandvik LH518B	CAT 1700XE
Rolling resistance (%)	3	3	3	2
Vehicle efficiency (%)	95	97.5	91.7	80
Auxiliary power (kW)	0	0	0	0

- Performance data (table with maximum speed per grade, load and gear) from specifications used to calibrate ECM
- Vehicle efficiencies are not consistent between OEMs
- Results only apply to the hauling portion
- Load and dump power needs are not included in specifications for ECM

ECM – BEV LHD

- ECM – calibration parameters (field test)

Description	LH518B
Rolling resistance (%)	3
Vehicle efficiency (%)	85
Auxiliary power (kW)	6.3



- Load energy 0.9 (kWh) per cycle
- Dump energy 1.3 (kWh) per cycle

Note: ECM calibration parameters from New Afton BEV LHD LH518B ramp test detailed data review (up ramp). Parameters could change as the data set is explored in more detail: down ramp and near flat production tests. Only LH518B was simulated as example due to having calibrated ECM.

Duty cycles and charging strategy – BEV LHD

- General duty cycles considered include:
  - Stope or development face, for development on level or at ramp, to truck or to ore pass
  - Charger strategy is offboard and either opportunistic regular charging or swapping

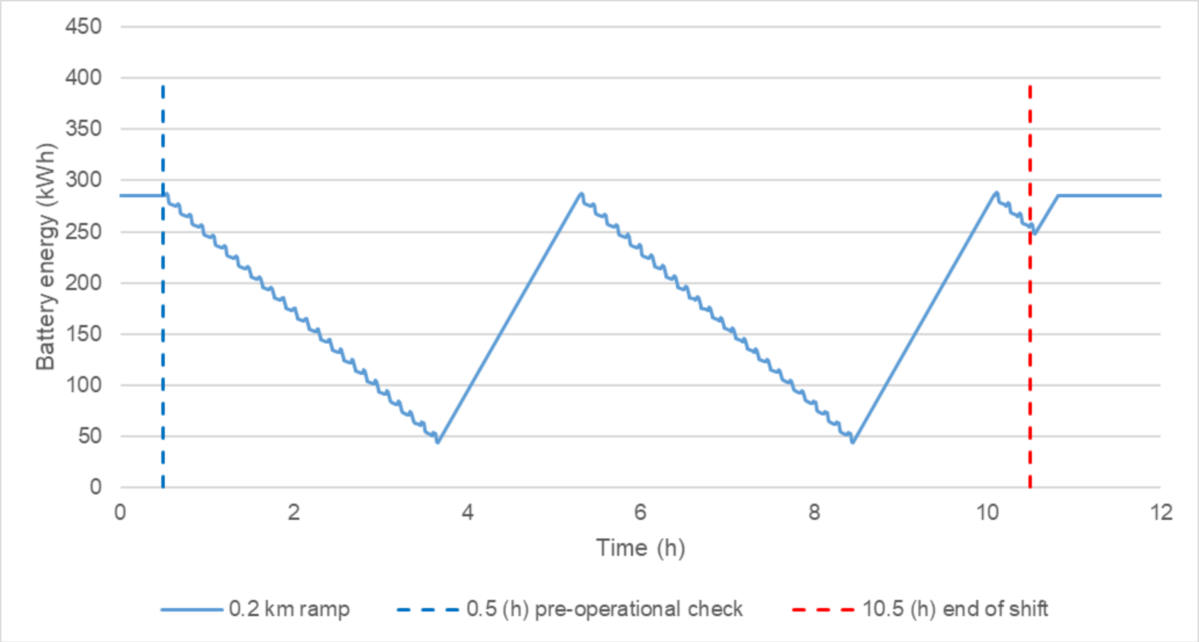
ID	Class	Duty (schedule)	Duty description	Charger	Charging strategy
9	Prime mover	Development face	to truck or to ore/waste pass	Offboard	end of shift + opportunistic
10	Prime mover	Development ramp face	to truck	Offboard	end of shift + opportunistic
11	Prime mover	Development face	to truck or to ore/waste pass	Offboard	swapping
12	Prime mover	Development ramp face	to truck	Offboard	swapping
13	Prime mover	Production stope	to truck or to ore pass	Offboard	swapping

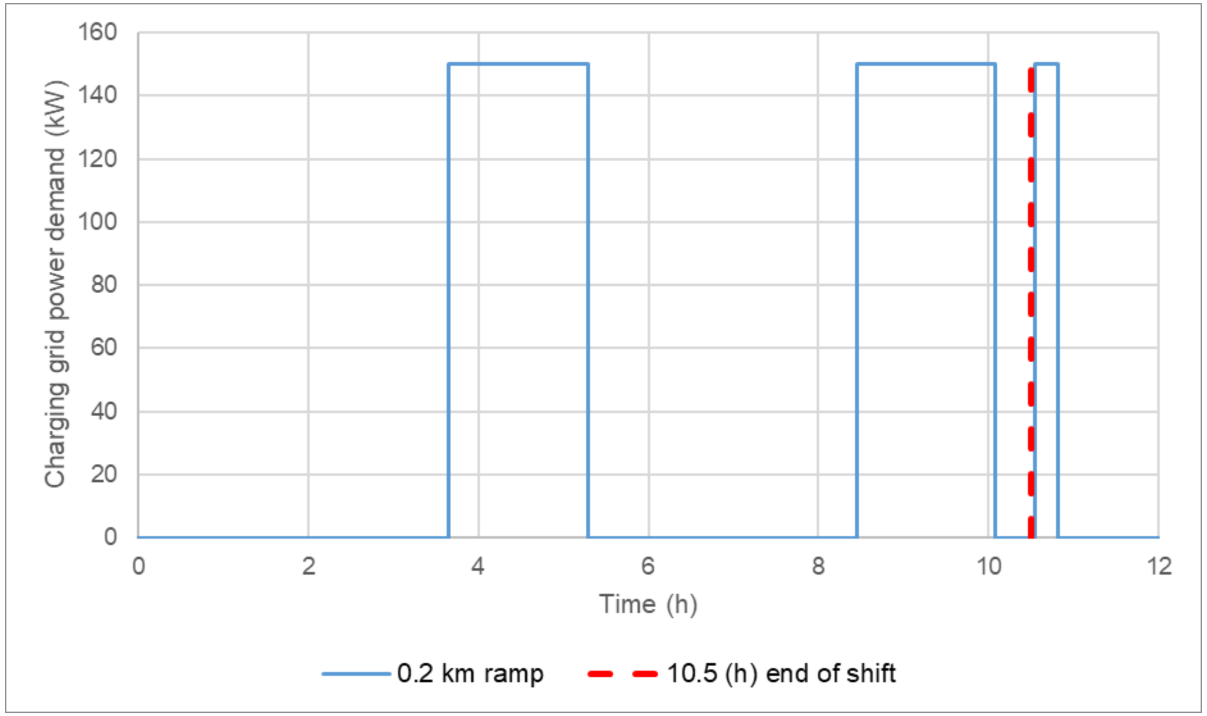
Duty cycles and schedule – BEV LHD

- Proposed duty cycle (ramp development face based on New Afton test)
  - Start at level ramp access (empty) and move at 10.8 km/h
  - Route:
    - 0.1 km from level to ramp access (and 0.1 km back)
    - Variable 15% ramp distances 0.2, 0.3, 0.4 and 0.6 km at 10.8 km/h empty (and full returning)
    - 0.1 km from ramp to load area (and back)
    - Load bucket (time and power for process)
    - Dump to truck (time and power for process)
  - Repeat until battery reaches arbitrary minimum SoC% (15%) and keep cycle/bucket count
  - Go to charge (charge or swap)
  - Perform all complete cycles possible for 12-hour shift
  - Work schedule is the same as presented for man carrier class
  - Lunch breaks for LHD drivers were excluded, as they would be covered by the charging pause.

Results – LHD LH518B

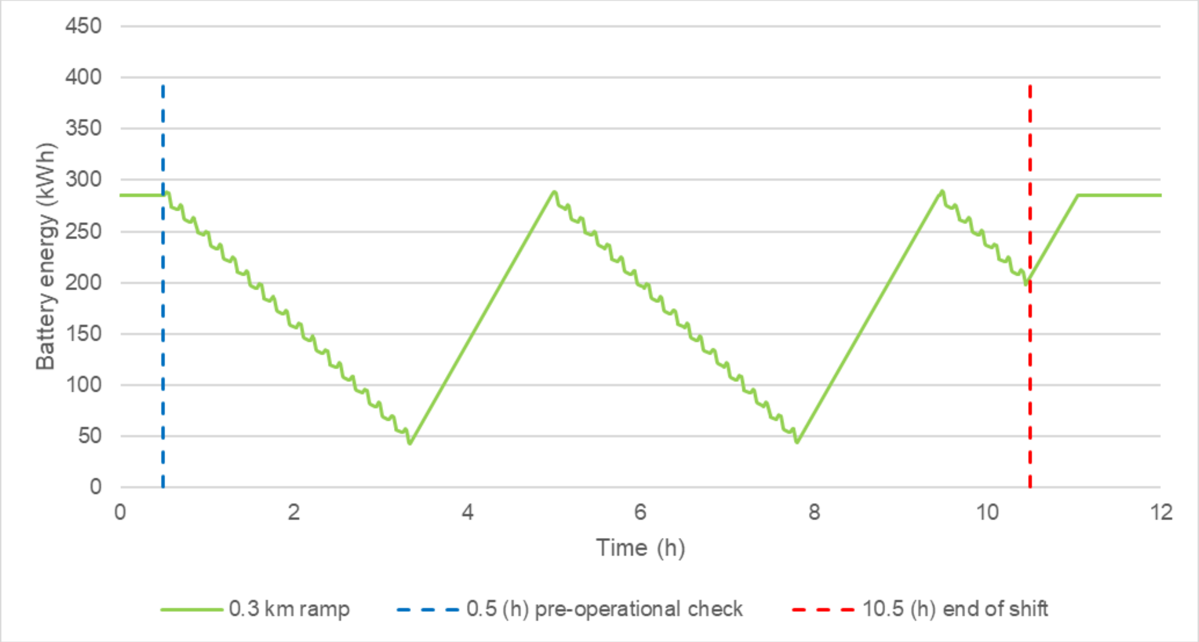
- Energy consumed and charged for 12-hour shift (regular charging strategy, 0.2 km ramp)

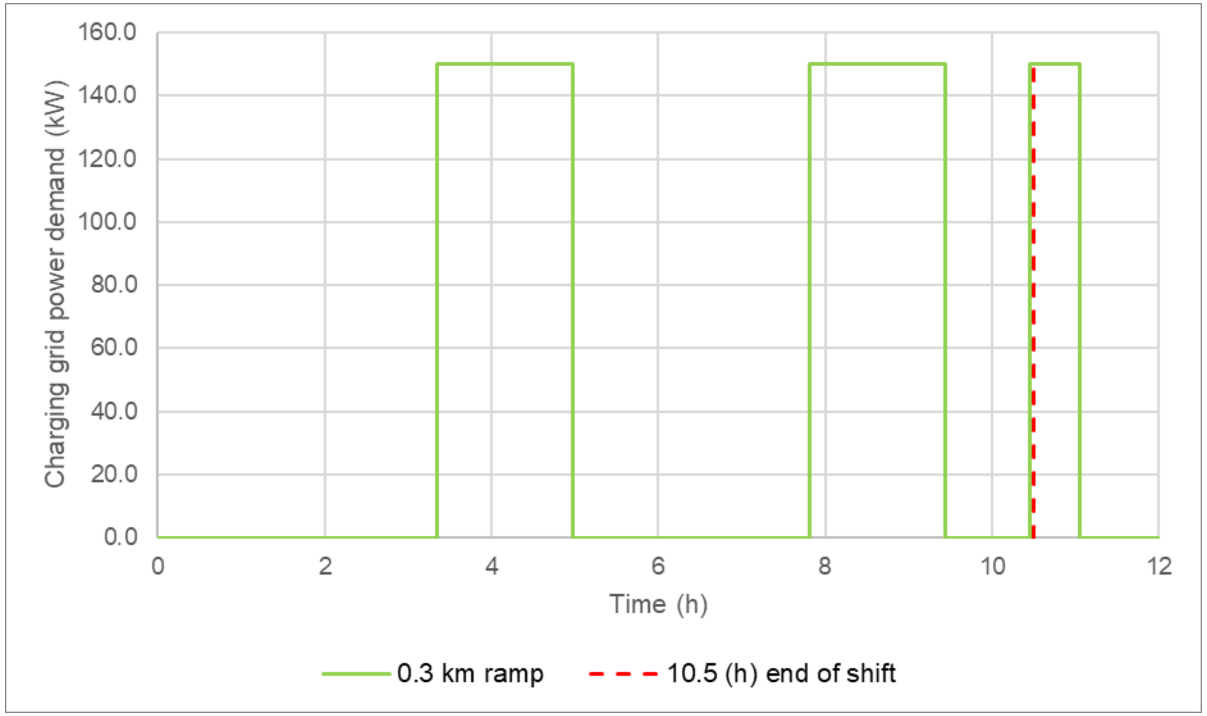




Results – LHD LH518B

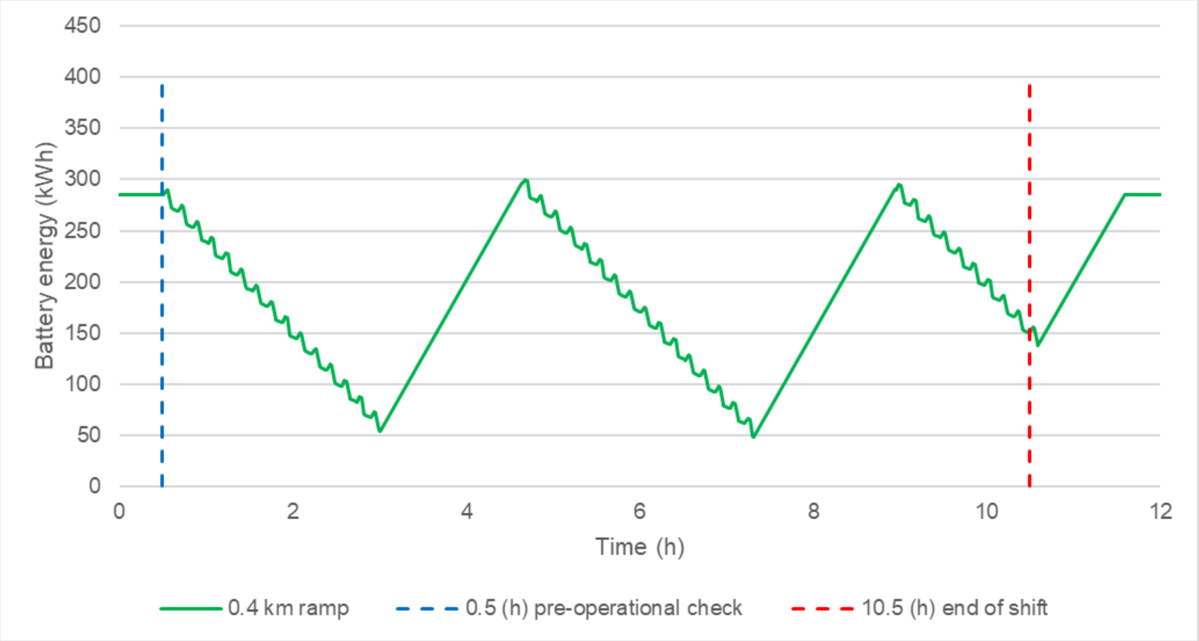
- Energy consumed and charged for 12-hour shift (regular charging strategy, 0.3 km ramp)

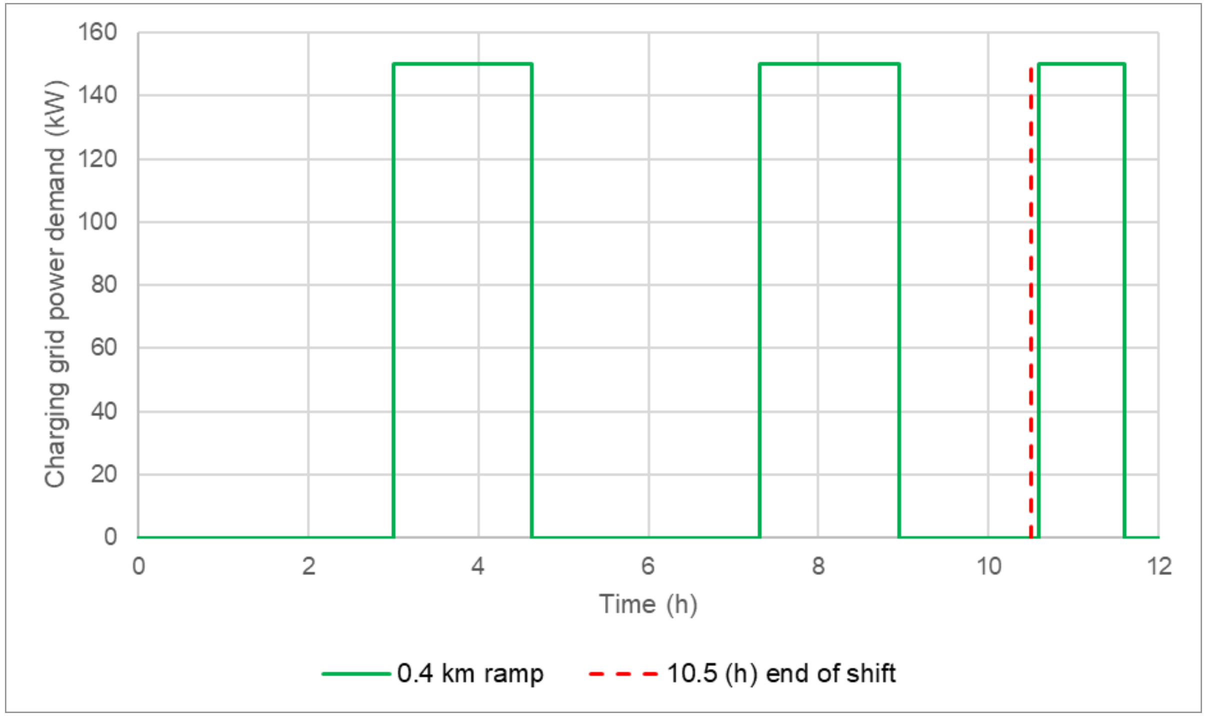




Results – LHD LH518B

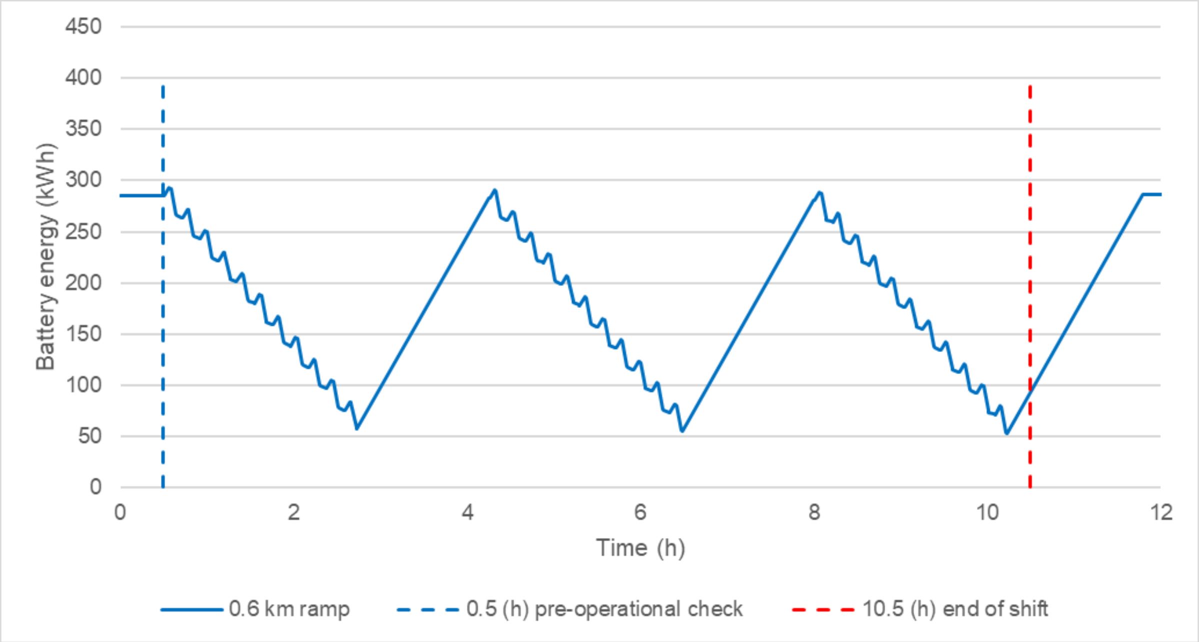
- Energy consumed and charged for 12-hour shift (regular charging strategy, 0.4 km ramp)

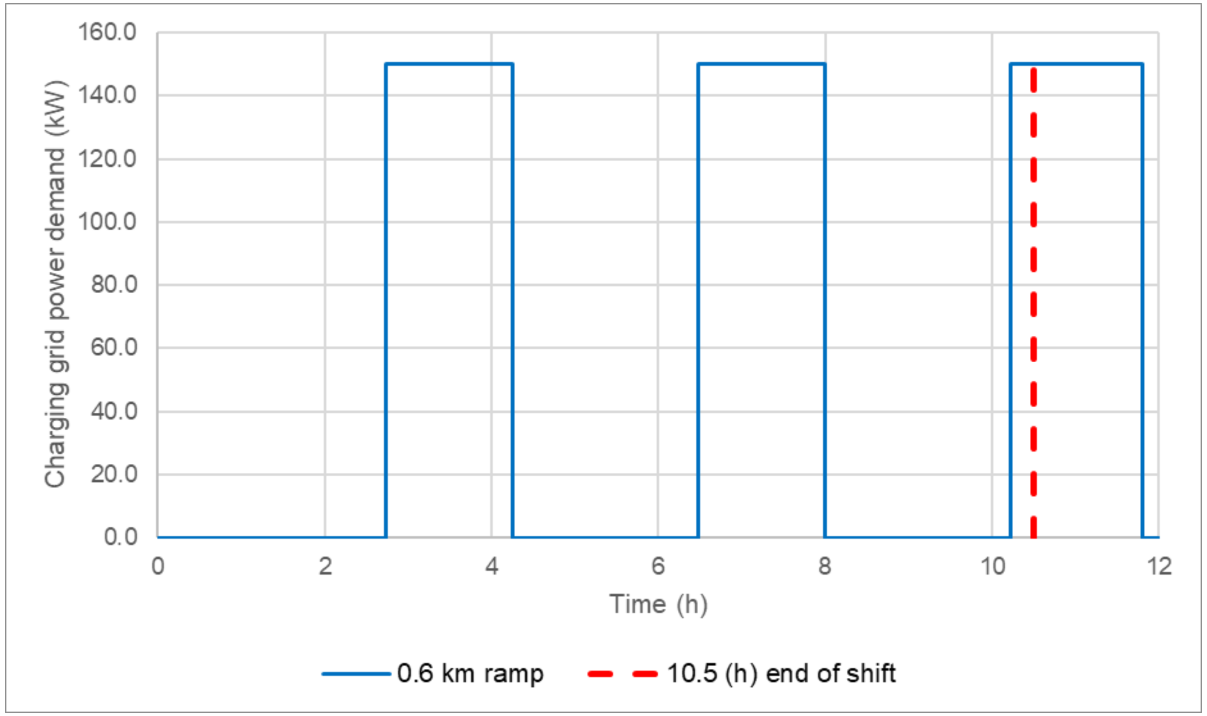




Results – LHD LH518B

- Energy consumed and charged for 12-hour shift (regular charging strategy, 0.6 km ramp)





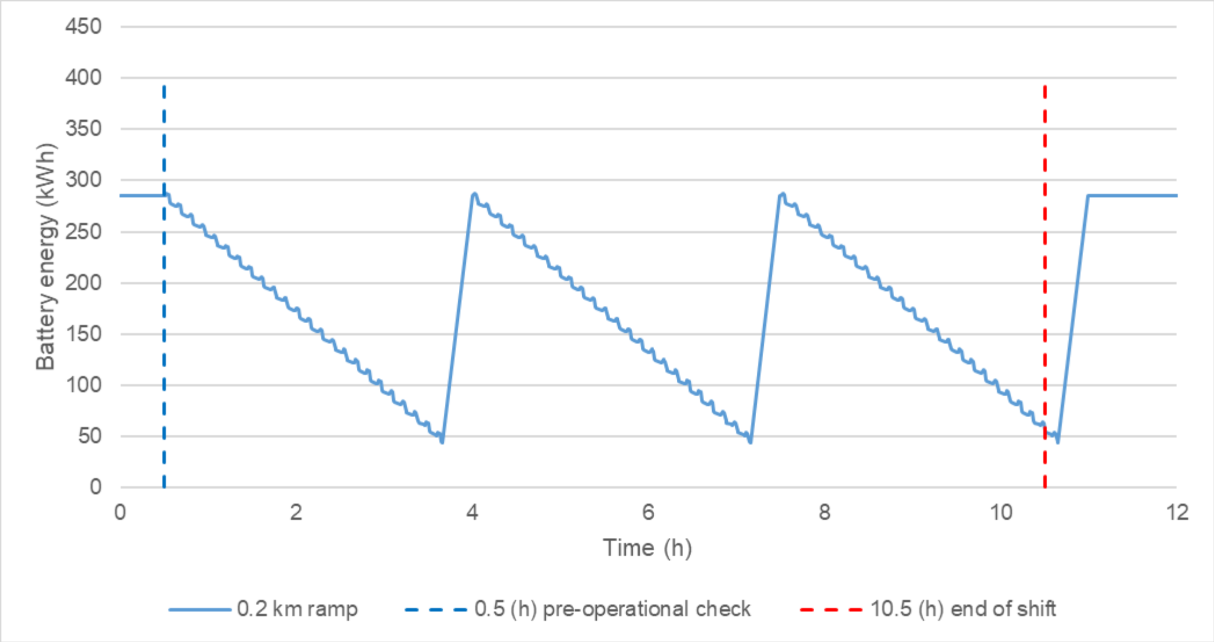
Results – LHD LH518B

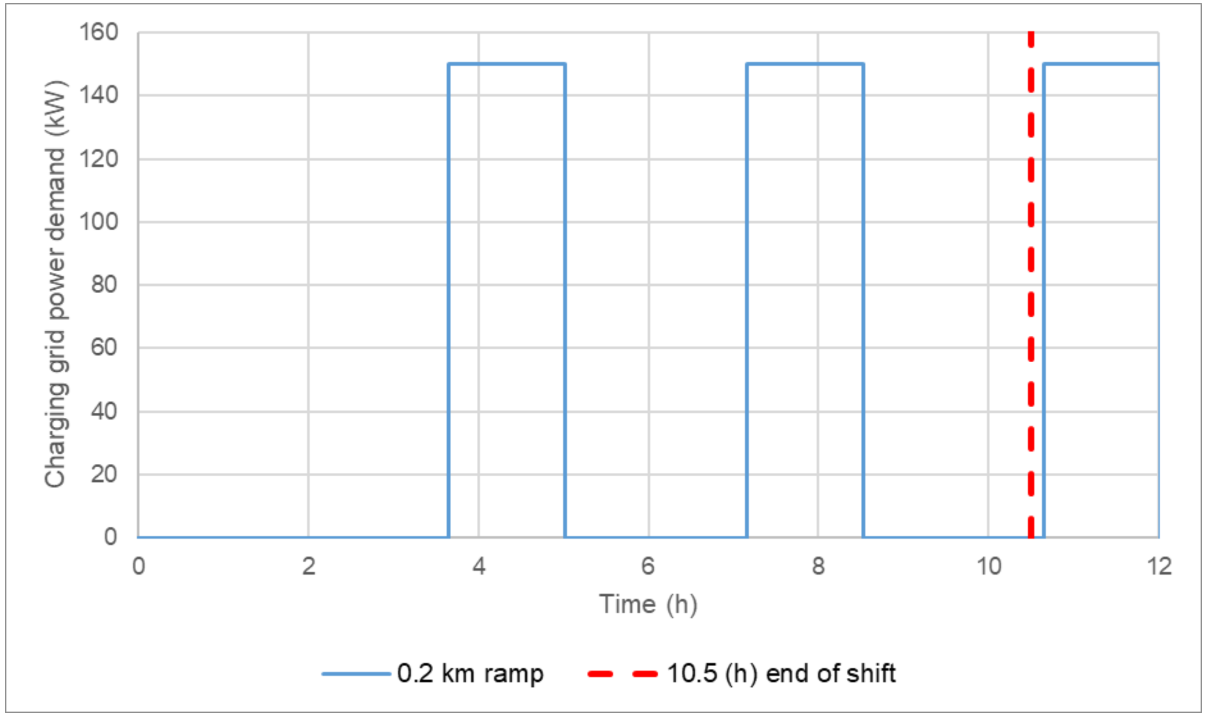
- Charging strategy: charging
- Total distance achieved during shift ranges from 41 to 52 (km)
- Battery is depleted sooner on longer ramps (less stop time) and results in lower number of buckets or cycles carried per shift
- Energy charged increases with longer ramp
- 1 LHD cycle is equivalent to 1 bucket moved
- Bucket count per freshly blasted heading can be over 30, which can be achieved in all simulated ramp lengths

Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)
0.2 km ramp	0.8	52	41.6	530
0.3 km ramp	1.0	45	45.0	579
0.4 km ramp	1.2	41	49.2	639
0.6 km ramp	1.6	33	52.8	692

Results – LHD LH518B

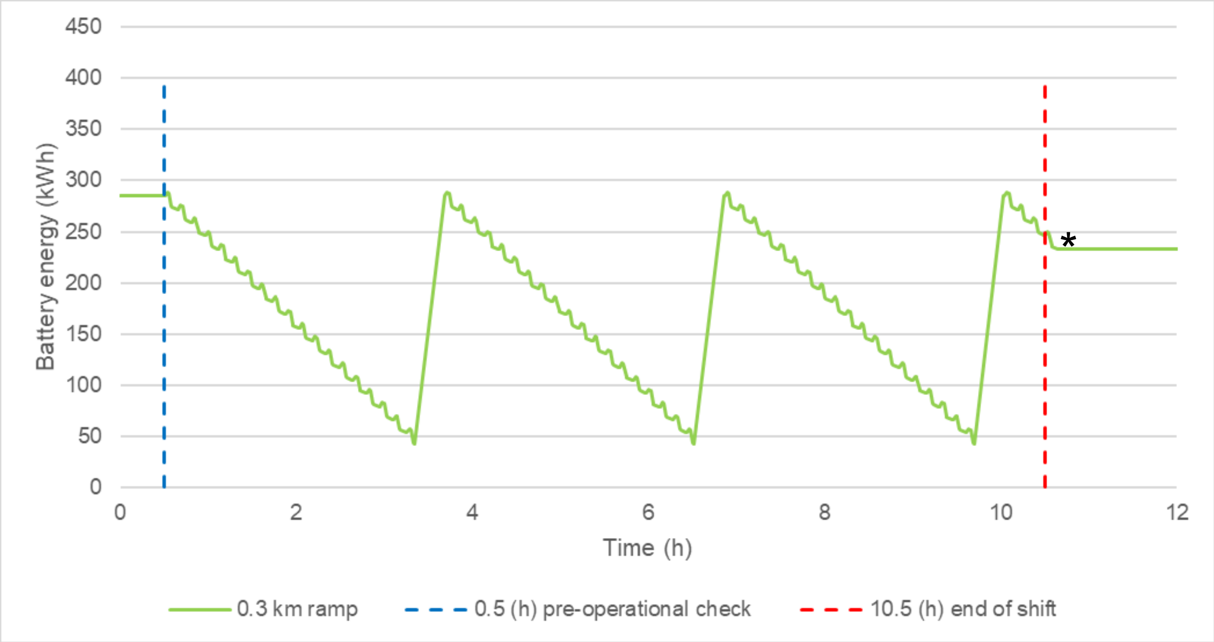
- Energy consumed and charged for 12-hour shift (swapping charging strategy, 0.2 km ramp)

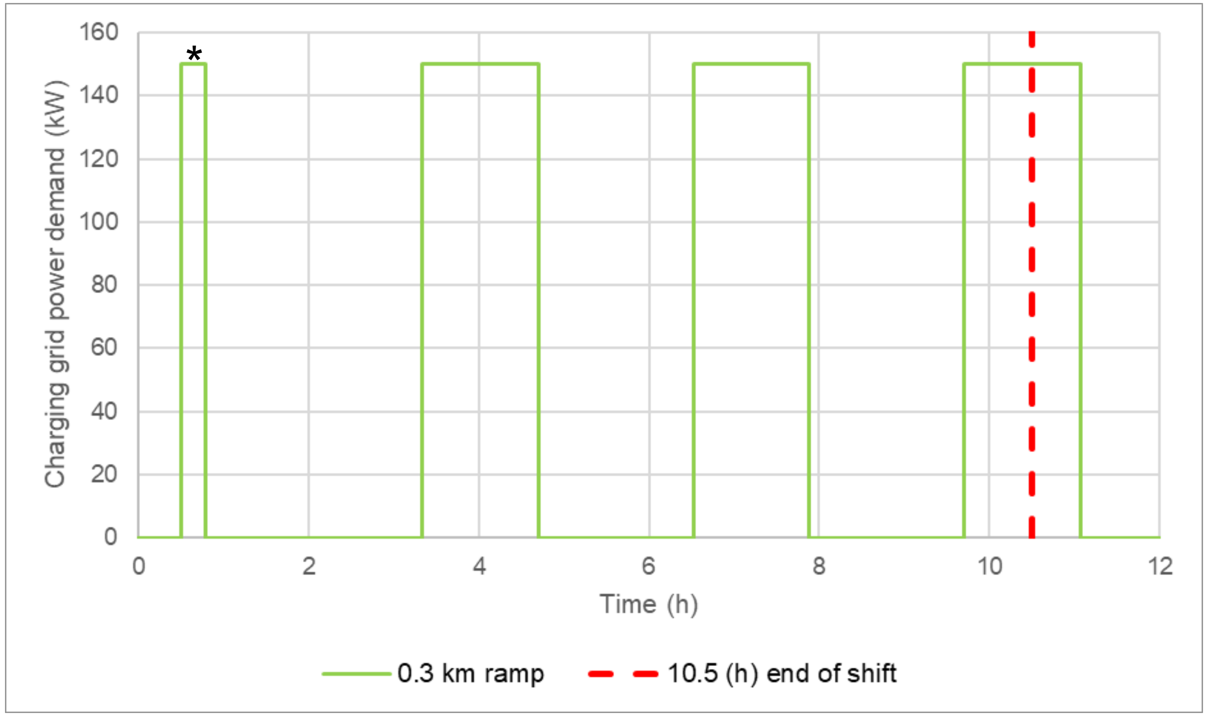




Results – LHD LH518B

- Energy consumed and charged for 12-hour shift (swapping charging strategy, 0.3 km ramp)

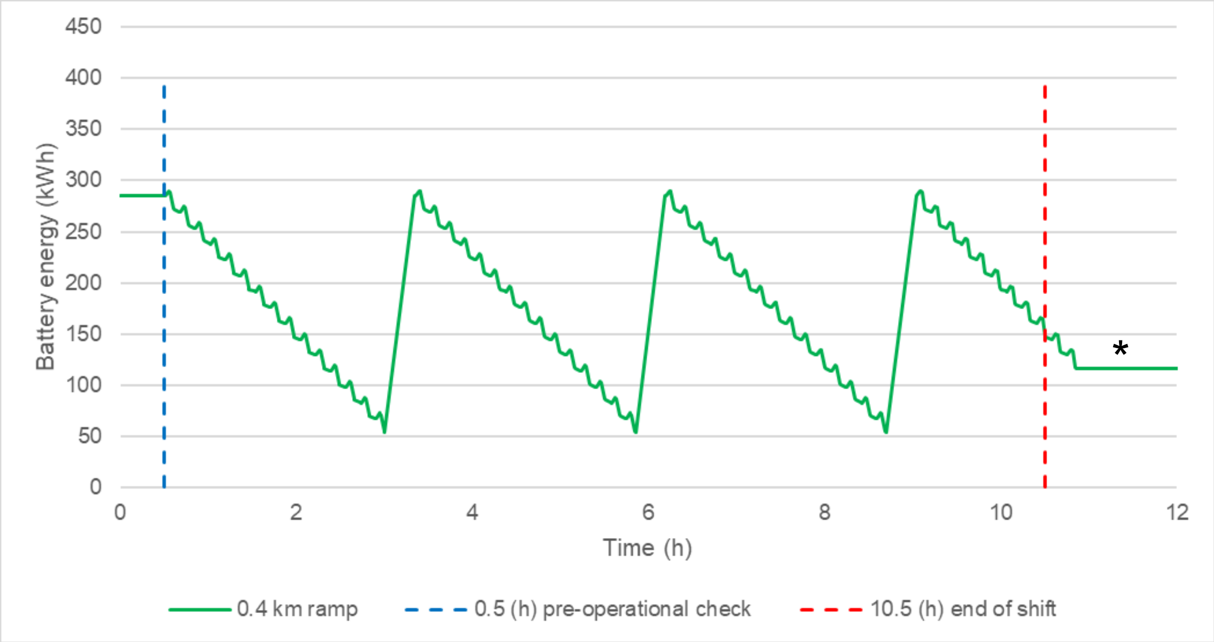


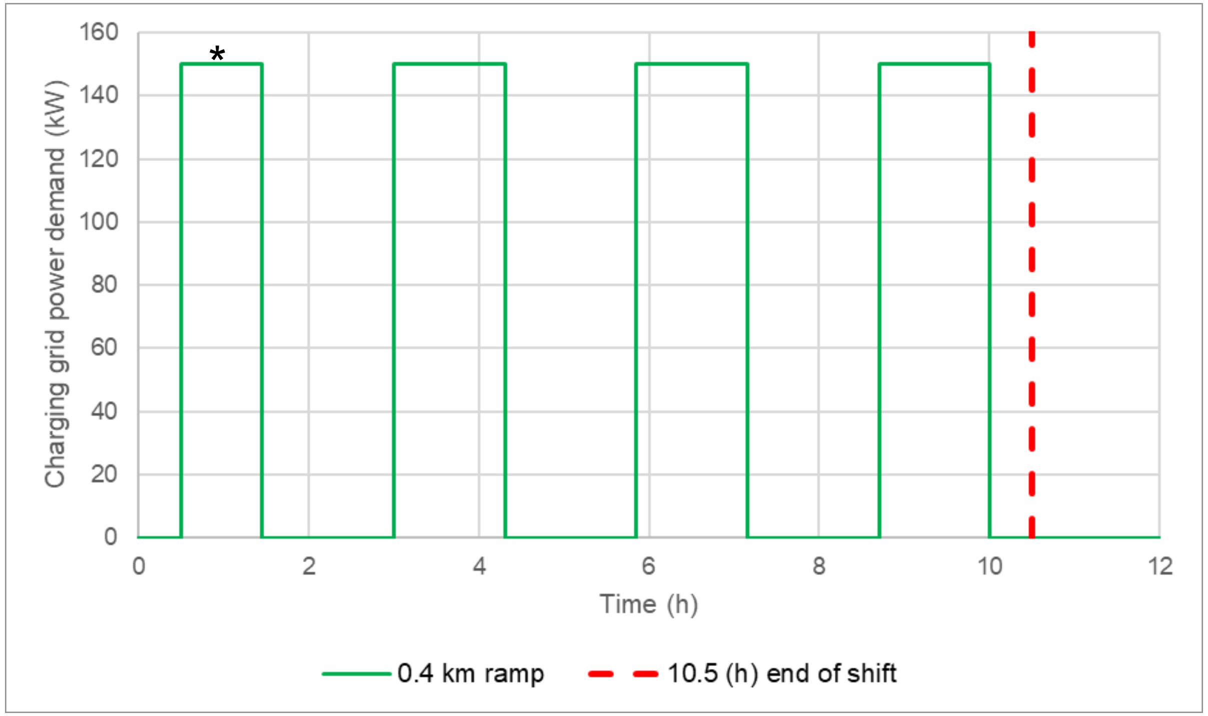


*Battery below initial SoC% is charged at beginning of next shift after pre-operational check

Results – LHD LH518B

- Energy consumed and charged for 12-hour shift (swapping charging strategy, 0.4 km ramp)

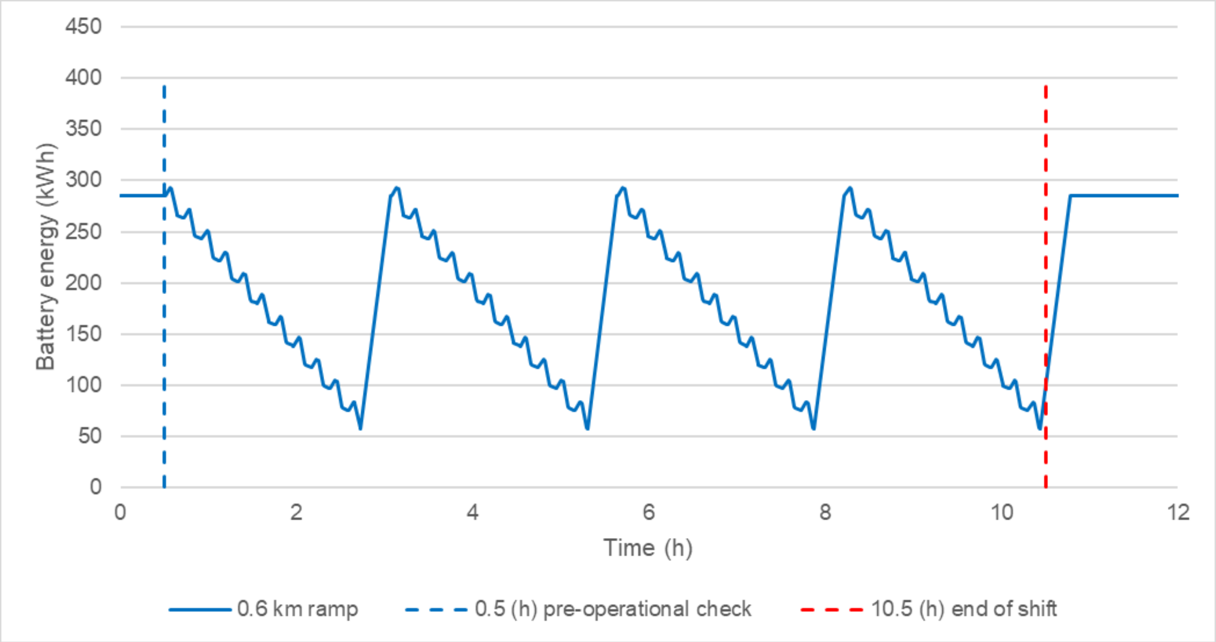


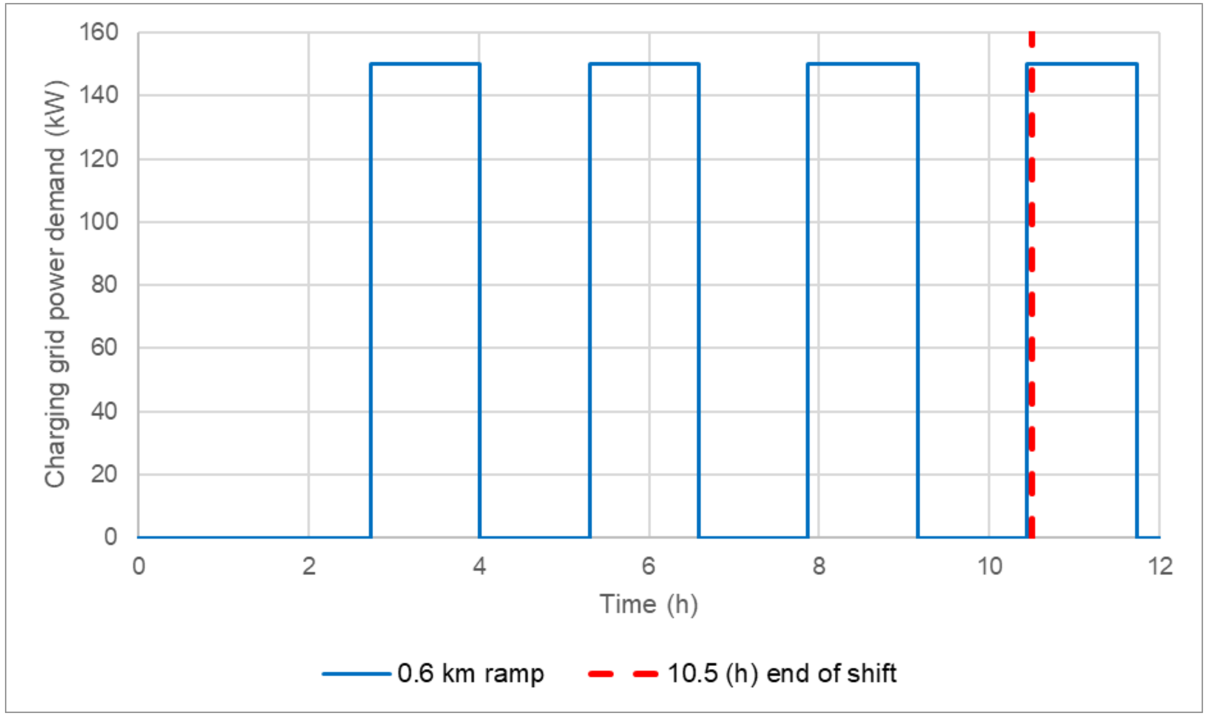


*Battery below initial SoC% is charged at beginning of next shift after pre-operational check

Results – LHD LH518B

- Energy consumed and charged for 12-hour shift (swapping charging strategy, 0.6 km ramp)





Results – LHD LH518B

- Charging strategy: swapping
- Total distance achieved during shift ranges from 57 to 70 (km)
- Longer ramps increase energy used and charge, and increase active time (less pauses observed as less cycles completed)
- Bucket count per freshly blasted heading can be over 30, which is achieved in all ramp lengths

Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)
0.2 km ramp	0.8	72	57.6	732
0.3 km ramp	1.0	61	61	784
0.4 km ramp	1.2	56	67.2	868
0.6 km ramp	1.6	44	70.4	921

Results – LHD – Summary

- Swapping allows for more operational time than charging, although it will depend on the application and the effective LHD work demand:
  - Charging can be a valid option for attending freshly blasted development headings, as the BEV LHD could be able to charge in between two headings work in the same shift (less power/energy demand)
  - Swapping would be the preferrable option for a stope that could require a complete shift to empty, as it will allow to maximize production (buckets moved or cycles) during the shift (more power/energy demand)

		Charging			Swapping		
Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)	Number of cycles	Total distance (km)	Energy charged (kWh)
0.2 km ramp	0.8	52	41.6	530	72	57.6	732
0.3 km ramp	1.0	45	45.0	579	61	61	784
0.4 km ramp	1.2	41	49.2	639	56	67.2	868
0.6 km ramp	1.6	33	52.8	692	44	70.4	921

Results – LHD – Summary

- The battery swapping charging strategy simulated could be performed using 2 batteries per LHD as the energy was consumed at a slower rate than the battery was charged
- As the distance between the working area and the charger increases, the effective time to work will be reduced
- This simulation assumed that the scoop had an available re-muck, or ore/waste pass or truck to load when needed. The reality of a mine could be different which would reduce the effective operational time expected from the LHD. In such case battery charging could be needed less often

Vehicle class – BE haul truck

- Part of the mine “prime movers”, battery electric haul trucks

MT42B

TH550B

TH665B

Artisan Z40 and Z50 haul trucks are still operating in certain Canadian mines (Macassa, New Afton, Brucejack).
In September 2021, Sandvik launched the TH550B as a combination of Sandvik and Artisan technologies.

Vehicle class – BE haul truck

- Vehicle specifications

Description	Epiroc MT42B	Artisan Z50	Sandvik TH550B	Sandvik TH665B
Payload – Tonnes	42	50	50	65
Operating weight – Tonnes	37.7	48	49.6	56.4
Gross weight – Tonnes	79.7	98	99.6	121.4
Motor power – kW	200 x 2 (+160)	980 (+125)	720 (180 x 4)	630
Battery power continuous – kW	N/A	480	540	N/A

Note: N/A means not available in equipment specifications. Motor power is continuous.

Vehicle class – BE haul truck

- Charging specifications

Description	Epiroc MT42B	Artisan Z50	Sandvik TH550B	Sandvik TH665B
Charger type (options)	Off board	Off board	Off board	Off board
Charger power – kW	160	N/A	N/A	N/A
Charge range SoC%	15% to 85%	15% to 85%	15% to 85%	15% to 85%
Time to charge (hh:mm)	3:00	N/A	N/A	N/A
Battery energy nominal/usable – kWh	N/A / 375	354 / N/A	354 / N/A	354 / N/A

Note: N/A means not available in equipment specifications.

ECM – Haul truck

- Energy consumption model (ECM) – calibration parameters

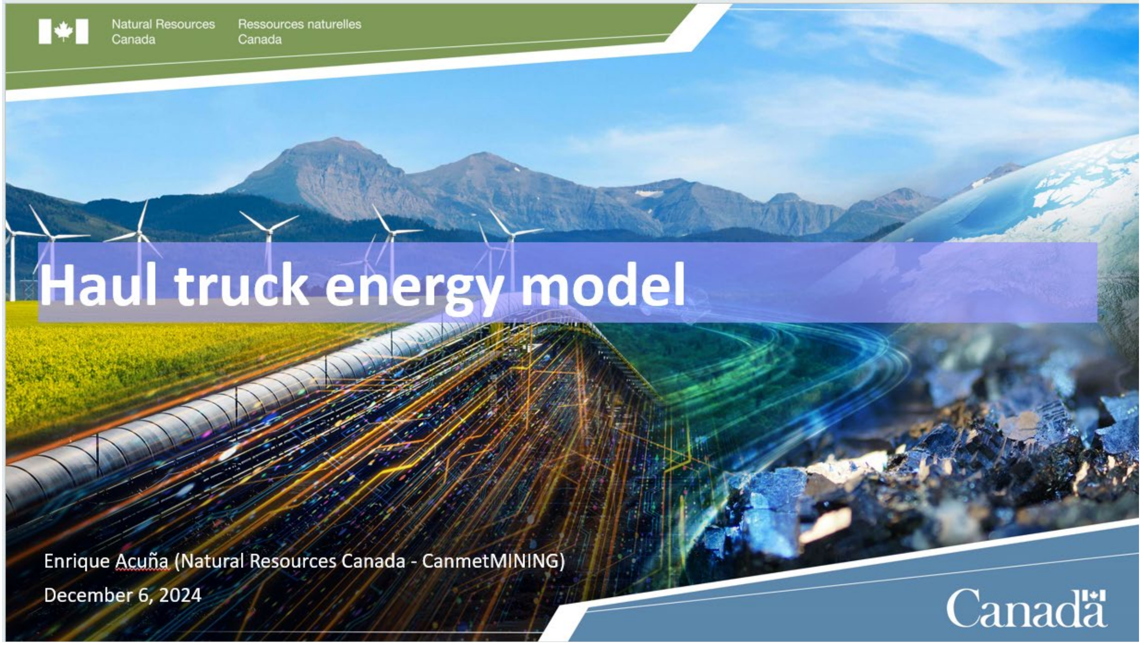
Description	Epiroc MT42B	Artisan Z50	Sandvik TH550B	Sandvik TH665B
Rolling resistance (%)	3	3	3	3
Vehicle efficiency (%)	89.5	86.3	87.0	86.3
Auxiliary power (kW)	0	0	0	0

- Performance data (table with maximum speed per grade, load and gear) from specifications used to calibrate ECM
- Vehicle efficiencies are in a limited range (86.3 to 89.5%)
- Results only apply to the hauling portion; dumping needs to be added to ECM

ECM – Haul truck

- ECM – calibration parameters (specifications and literature)

Description	Theoretical haul truck
Rolling resistance (%)	3
Vehicle efficiency (%)	85
Auxiliary power (kW)	4.6*



- Dump energy is negligeable
- Could be added if needed

* New Afton field test results for the LHD show that the average auxiliary power did not vary with the load (empty or loaded). The auxiliary power was normalized by the empty weight and prorated to build an estimate for the haul truck. This will be revised later with the haul truck test results.

ECM – Haul truck

- Using 3% rolling resistance, 85% vehicle efficiency, 15% ramp grade, loaded 1km up ramp and empty 1 km down ramp (2 km lap):
  - Haul truck Epiroc MT42B with 4.6 kW auxiliary power results in 36 kWh (2.5% auxiliary energy of total)
  - Haul truck Artisan Z50 with 5.9 kW auxiliary power results in 44 kWh (2.7% auxiliary energy of total)
  - Haul truck Sandvik TH550B with 6.1 kW auxiliary power results in 44.2 kWh (2.2% auxiliary energy of total)
  - Haul truck Sandvik TH655B with 6.1 kW auxiliary power results in 55 kWh (2.1% auxiliary energy of total)
- Auxiliary power consumed can be considered negligible as compared to total (less than 3%)

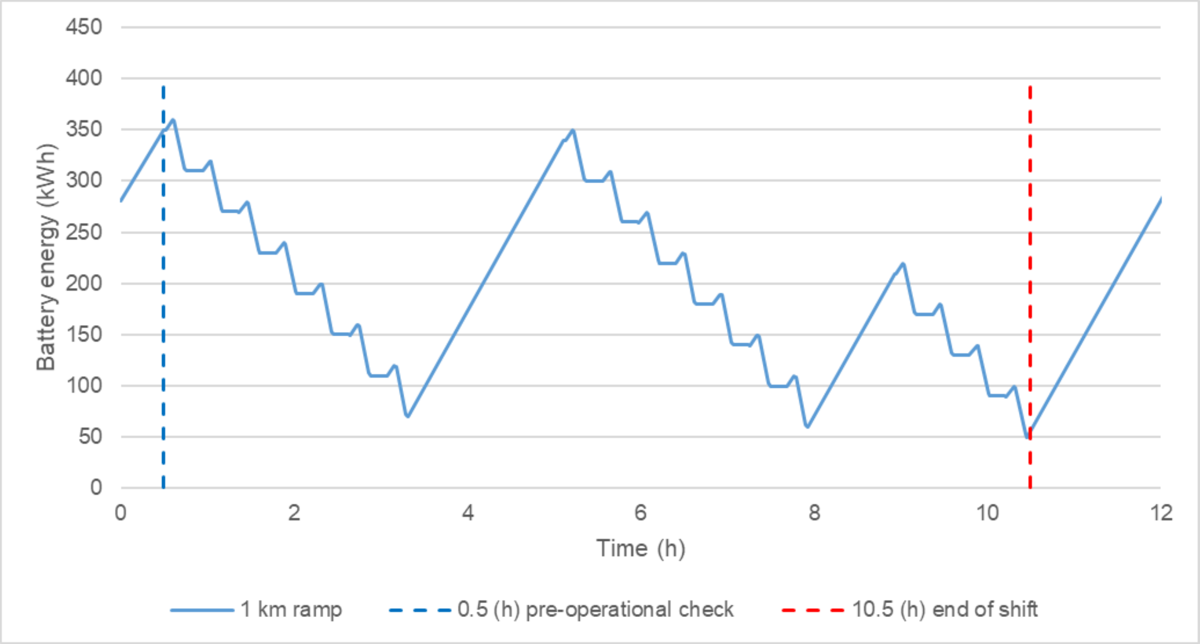
Duty cycles and schedule – Haul truck

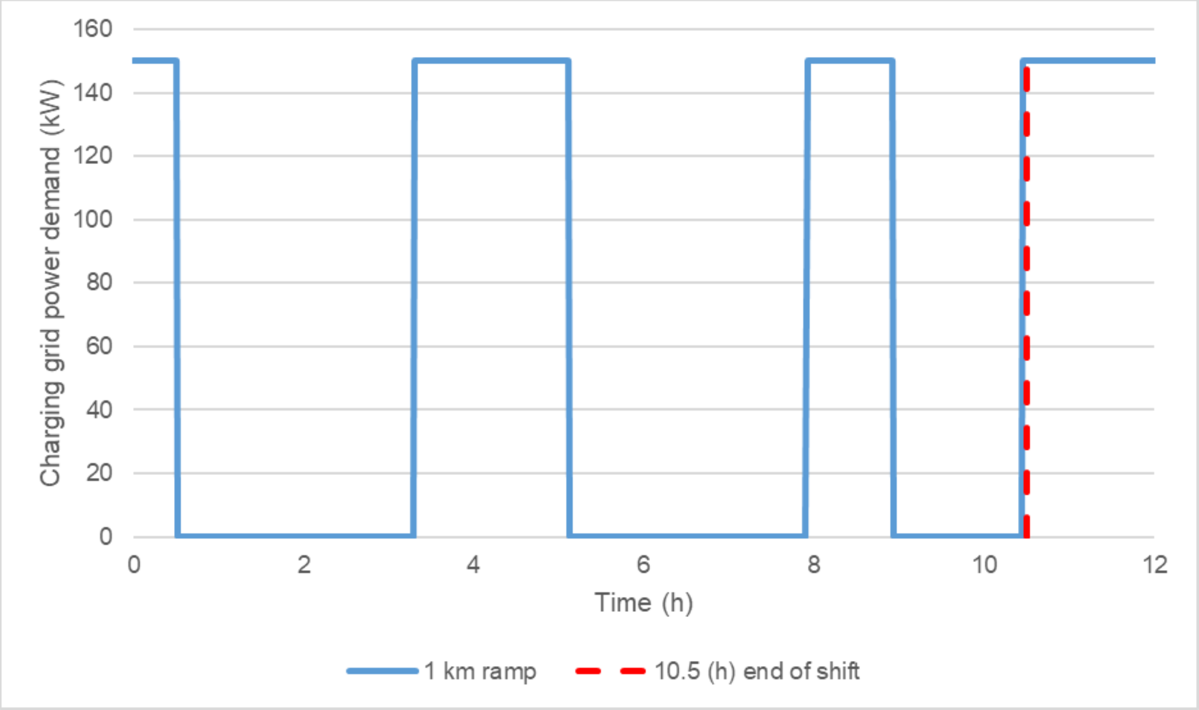
- Proposed duty cycle
  - Travel down empty at 12 km/h and travel up loaded at 8.8 km/h*
  - Route:
    - 0.2 km from level to ramp
    - Variable ramp distances 1, 2, 4, 6 km
    - 0.1 km from ramp level access to be loaded by scoop
    - Ramp grade 15%
    - Surface and level access 2%
  - Each cycle considers time to load and unload
  - Perform as many complete cycles as possible for 12-hour shift (10 effective hours)
  - Repeat until battery reaches minimum SoC% (15%) and keep cycle count
  - Work schedule is the same as presented for personnel carrier class
  - Lunch time for haul truck drivers was considered within charging periods

*Empty speed from field observation and literature, loaded speed from ECM and nominal traction motor power

Results – Haul truck MT42B

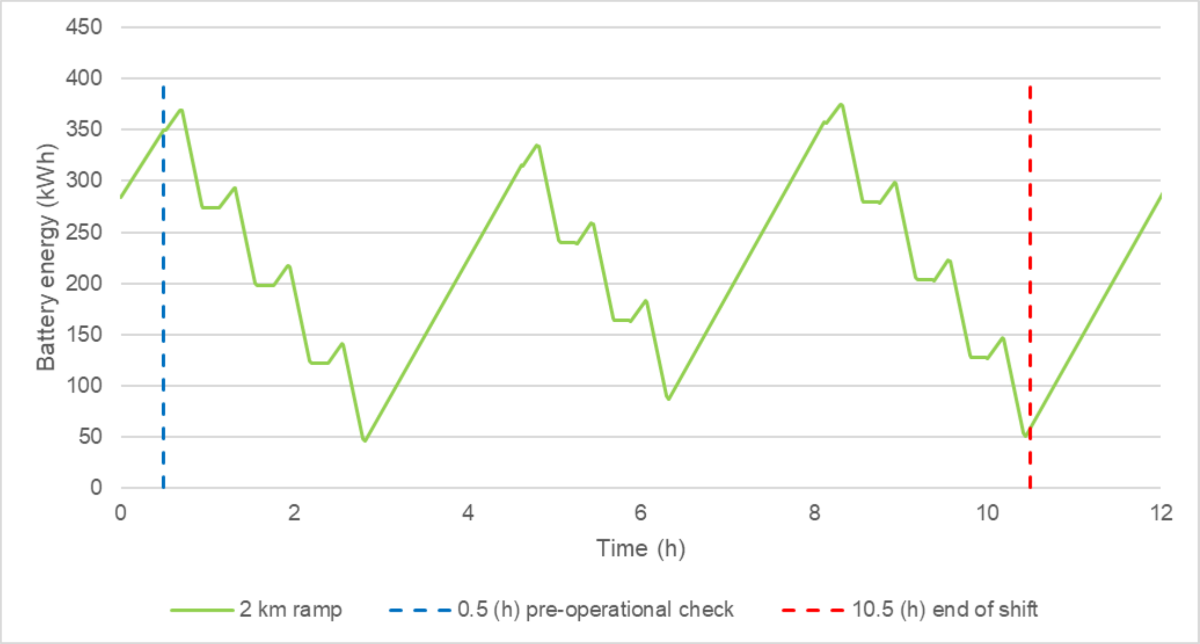
- Energy consumed and charged for 12-hour shift (regular charging strategy, 1 km ramp)

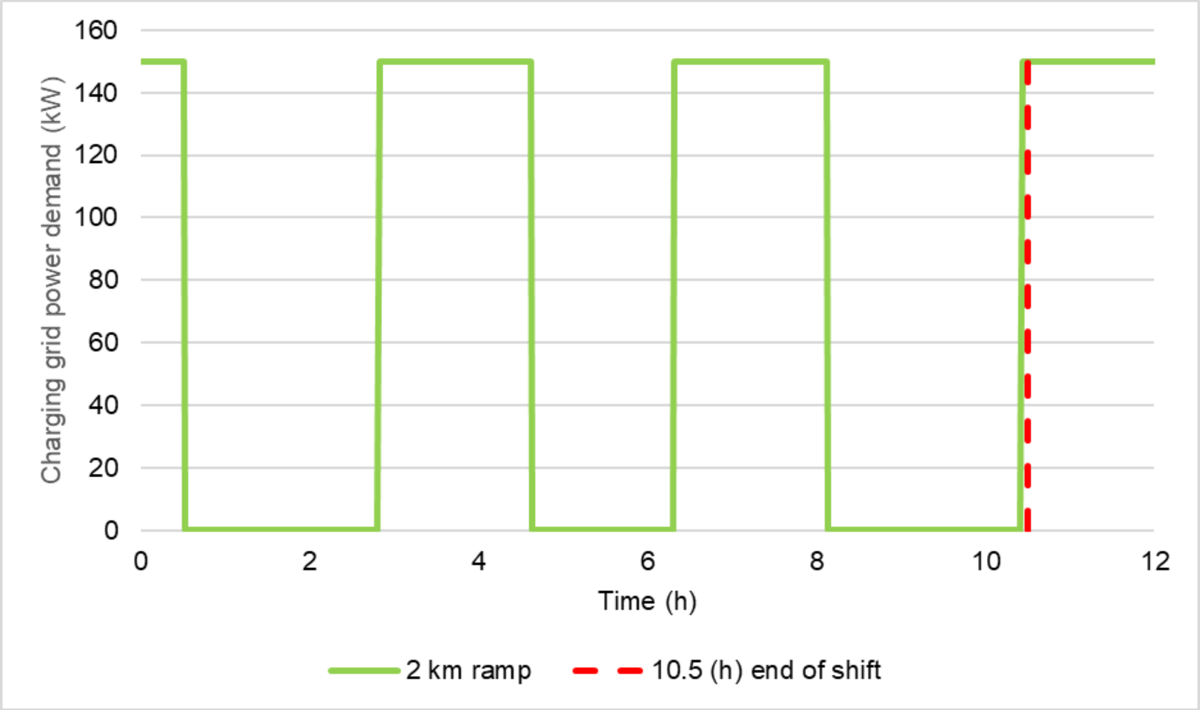




Results – Haul truck MT42B

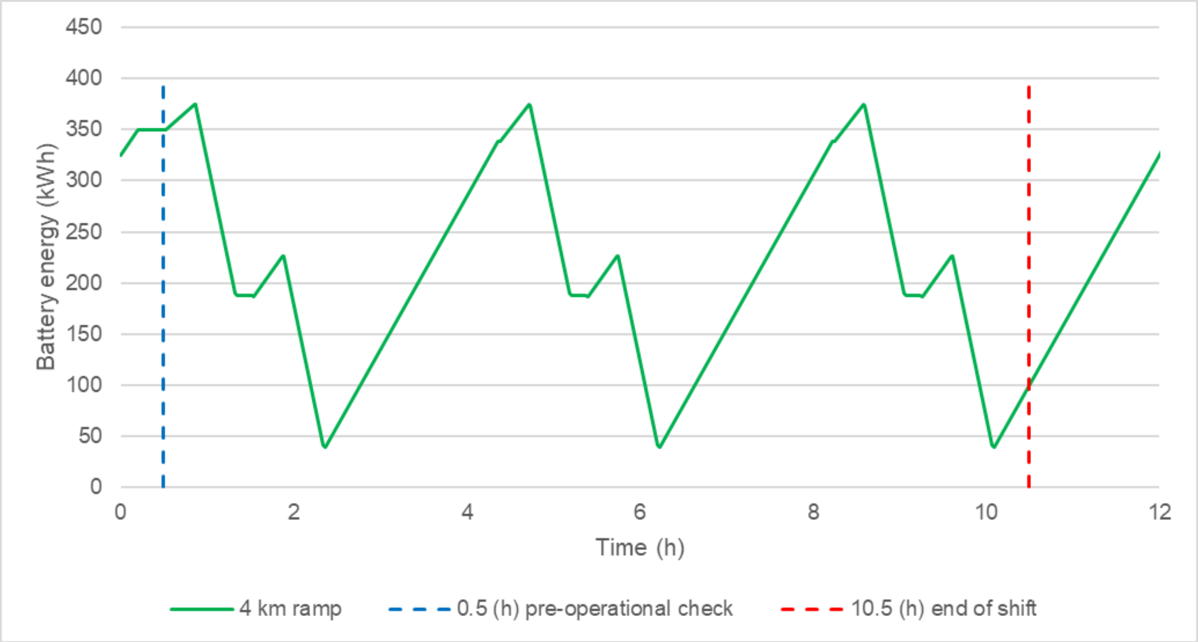
- Energy consumed and charged for 12-hour shift (regular charging strategy, 2 km ramp)

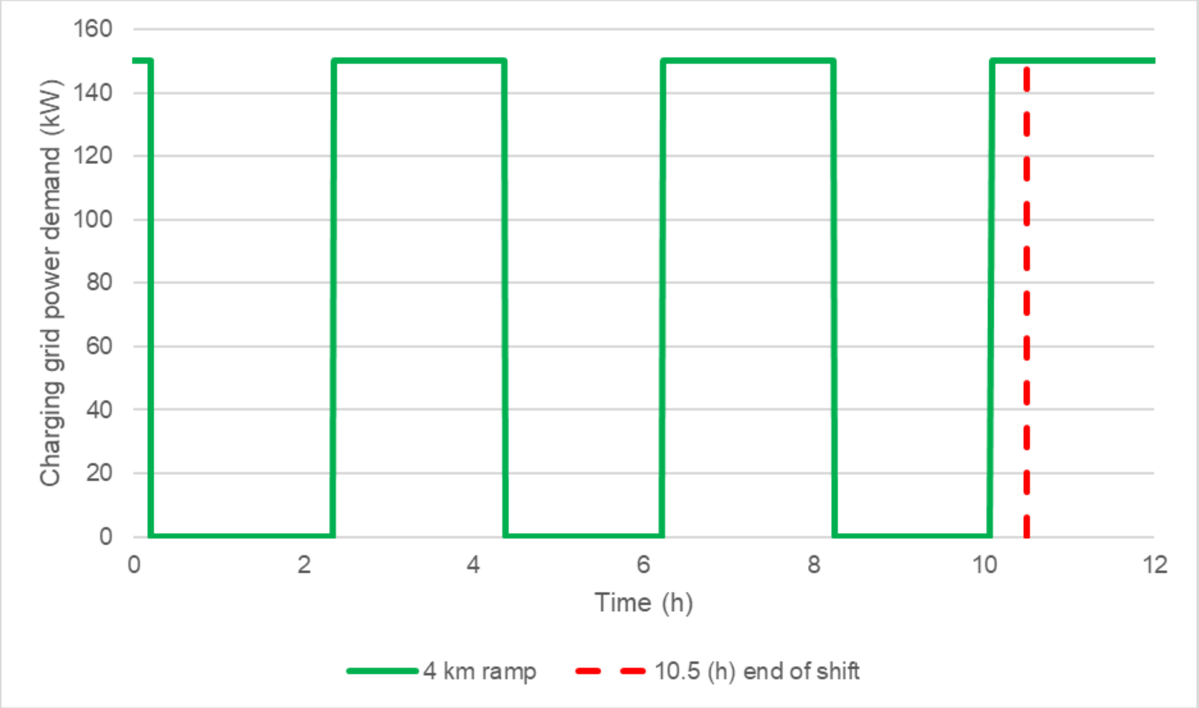




Results – Haul truck MT42B

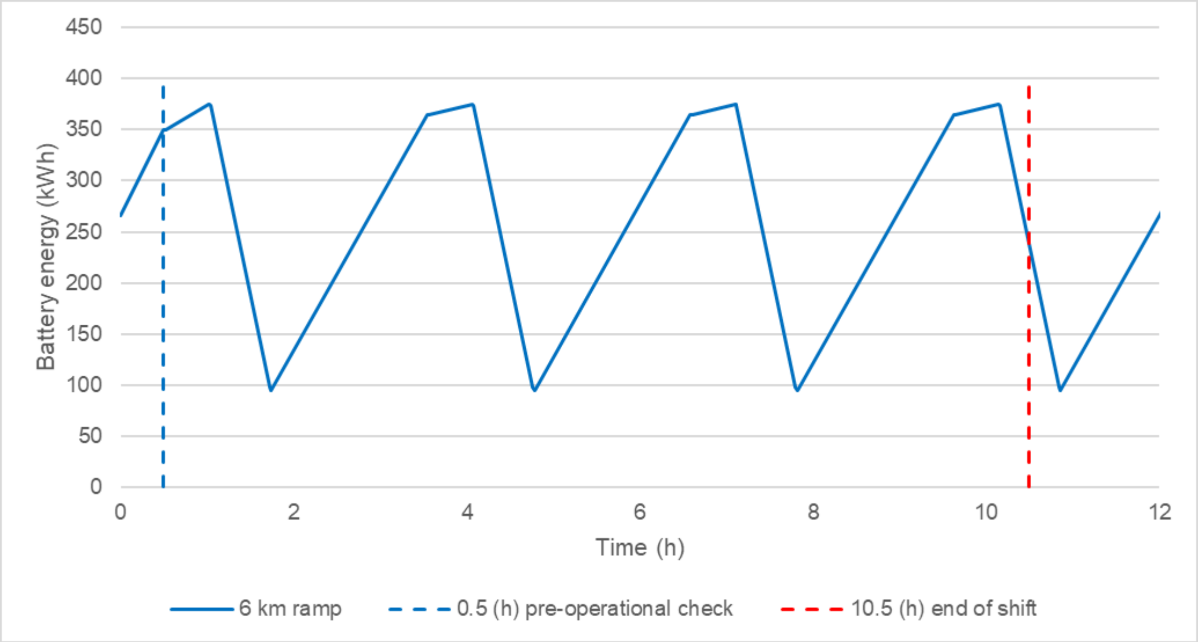
- Energy consumed and charged for 12-hour shift (regular charging strategy, 4 km ramp)

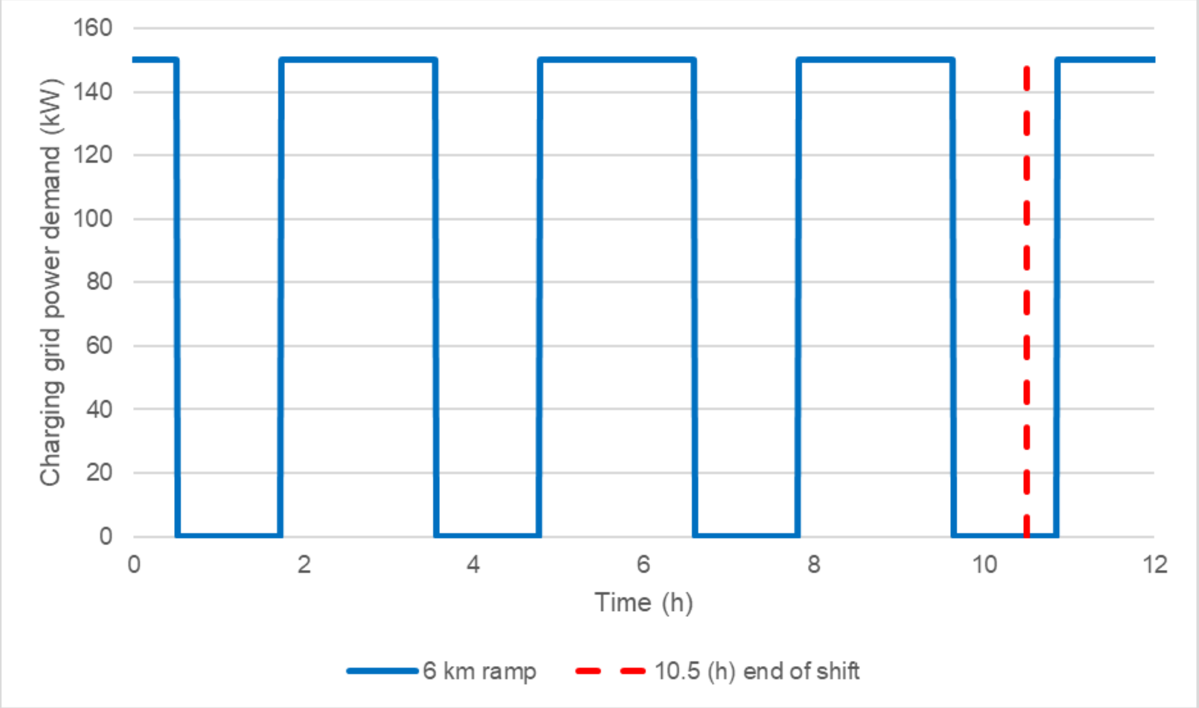




Results – Haul truck MT42B

- Energy consumed and charged for 12-hour shift (regular charging strategy, 6 km ramp)





Results – Haul truck MT42B charging

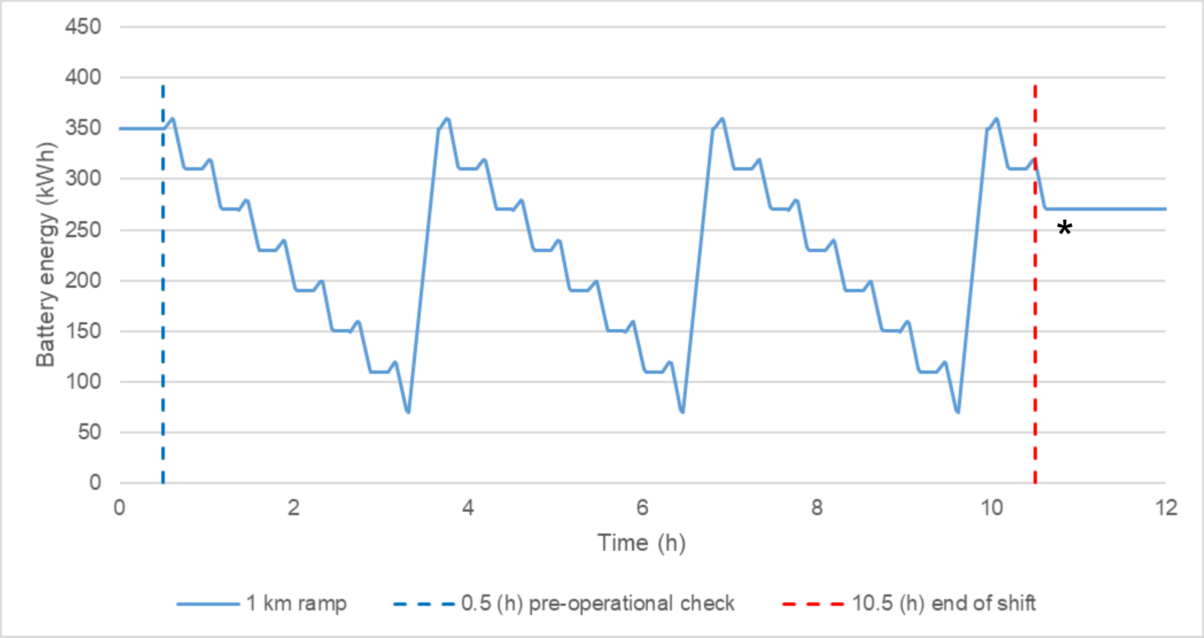
- Considering ramp and level accesses, when ramp length reaches over 6 km, a battery charge is needed per cycle
- Longer ramp consumes energy faster (less time to pause between cycles) and needs more time to charge
- Total distance achieved during shift is between 47 and 52 km

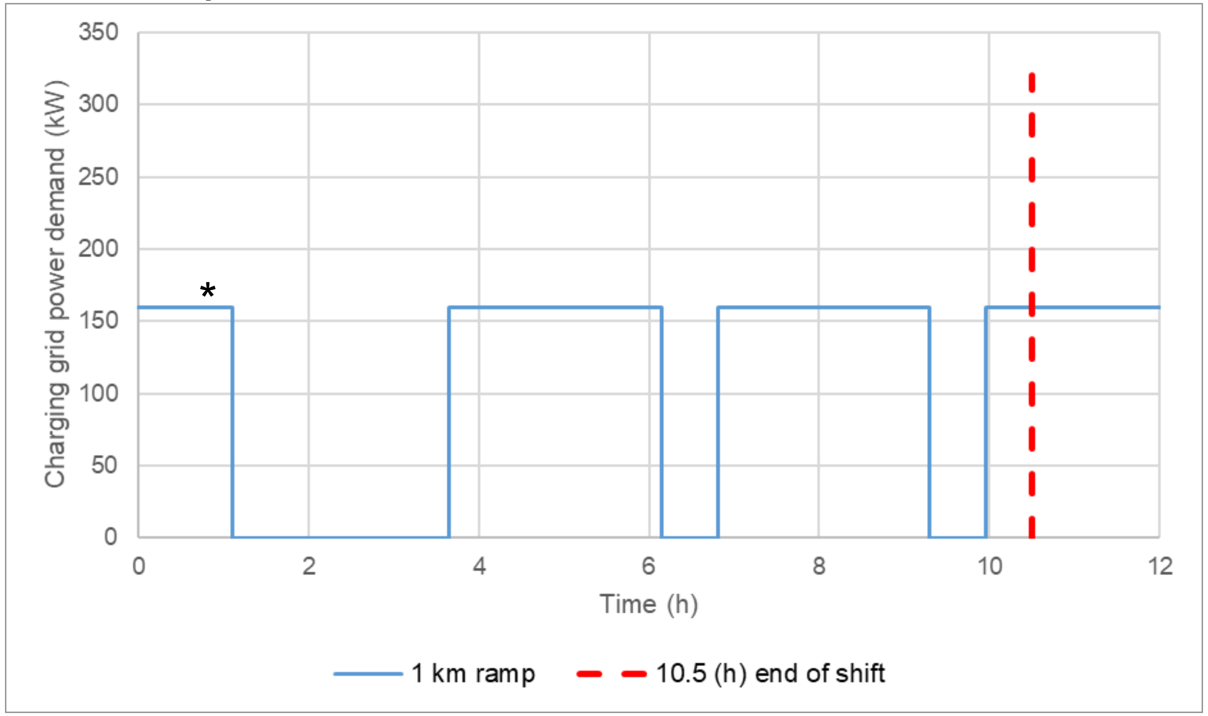
Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)
1 km ramp	2.6	18	46.8	726
2 km ramp	4.6	11	50.6	839
4 km ramp	8.6	6	51.6	915
6 km ramp	12.6	4	50.4	1055

8 km ramp cycles could not be completed with 375 kWh battery and energy used from 85% to 15% SoC

Results – Haul truck MT42B

- Energy consumed and charged for 12-hour shift (swapping charging strategy requires 2 batteries, 1 km ramp)

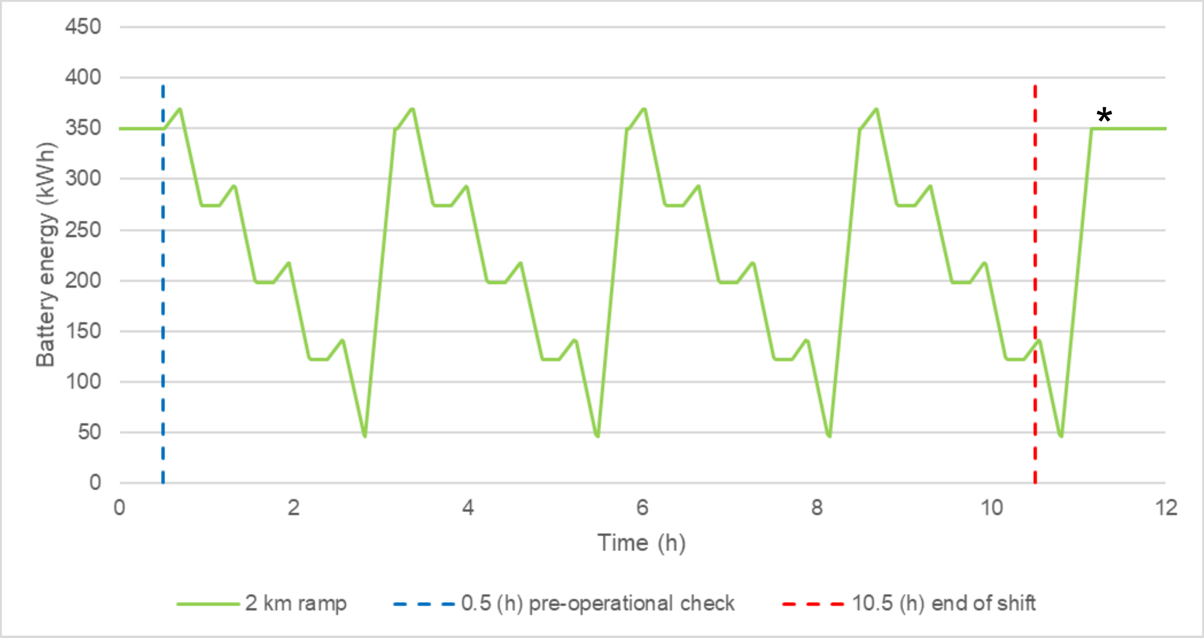


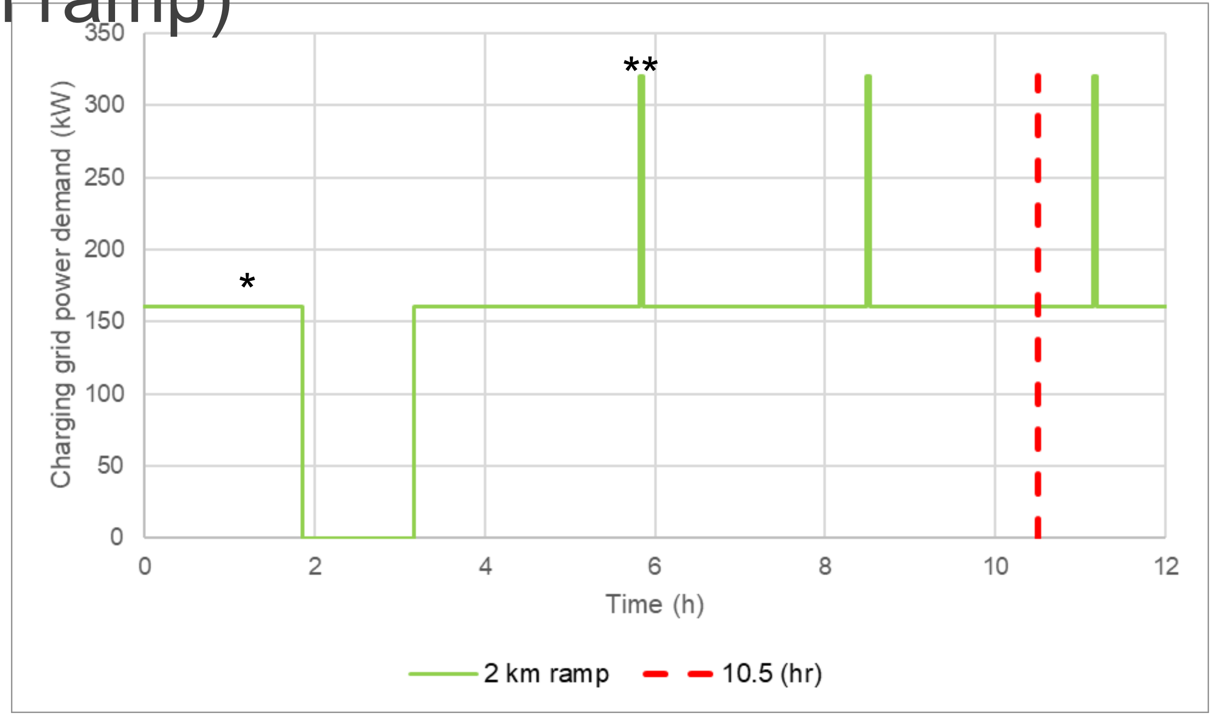


*Battery below initial SoC% is charged at beginning of next shift after pre-operational check

Results – Haul truck MT42B

- Energy consumed and charged for 12-hour shift (swapping charging strategy requires 3 batteries, 2 km ramp)



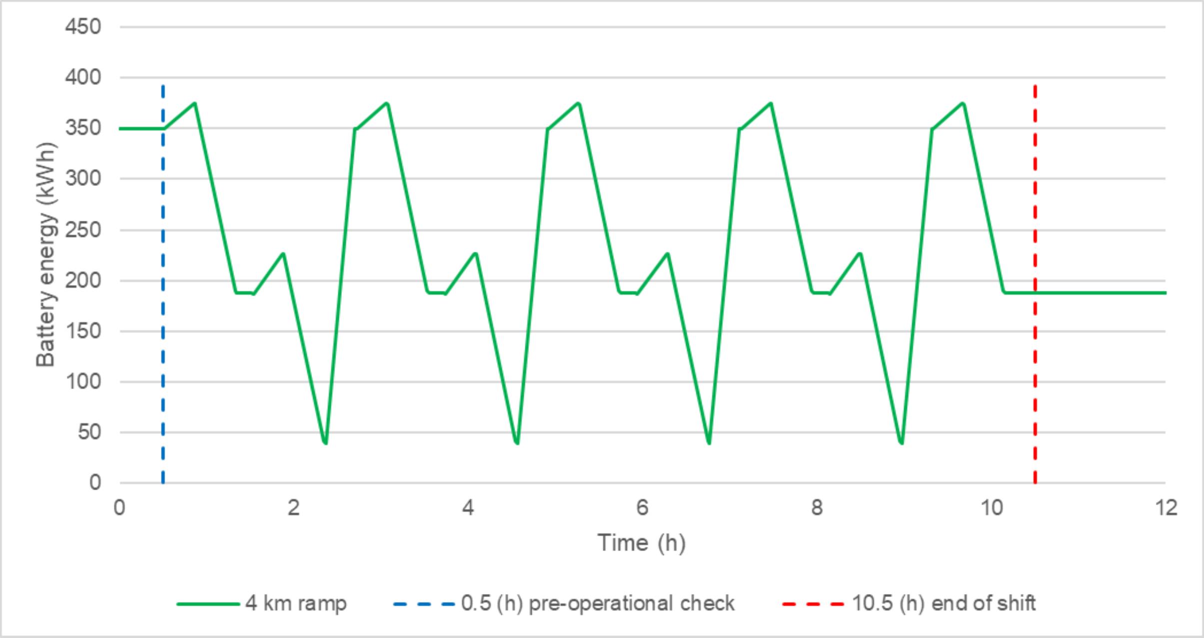


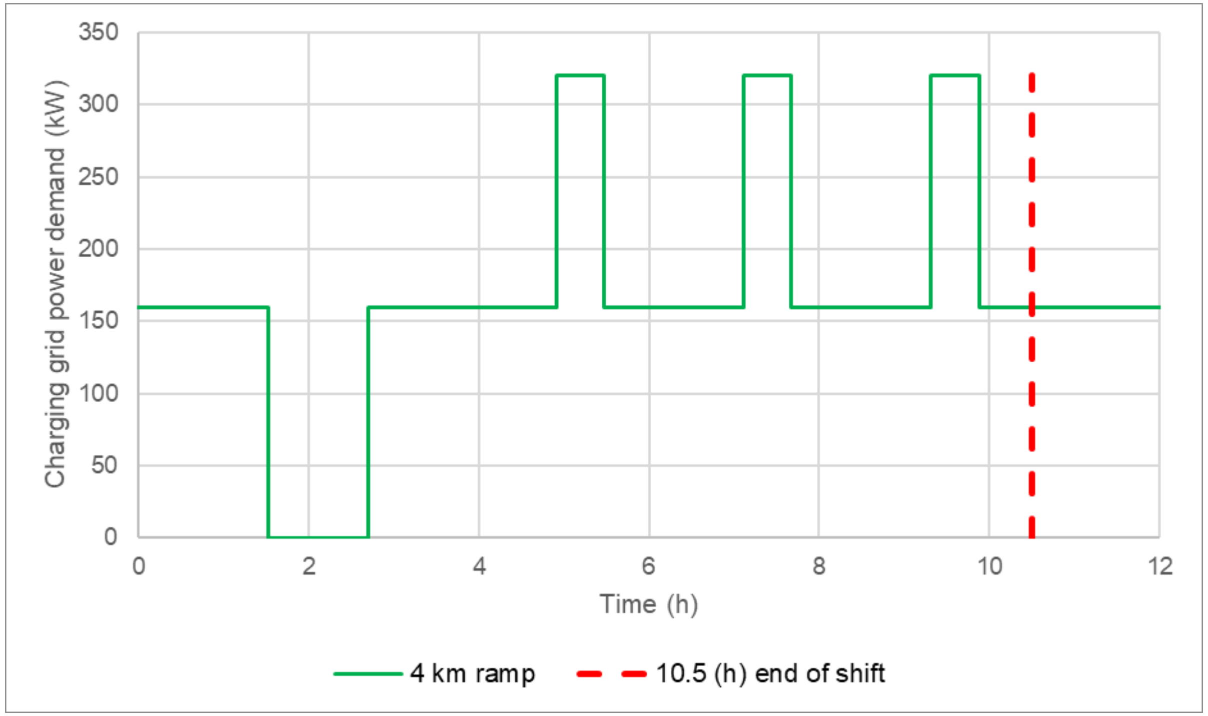
*Battery swapping is shown at the end of the shift but charging happens at beginning of next shift

**A third battery is required as part of the battery swapping charging strategy to keep the haul truck going, as the haul truck consumes energy faster than the charger can charge the battery for this duty cycle.

Results – Haul truck MT42B

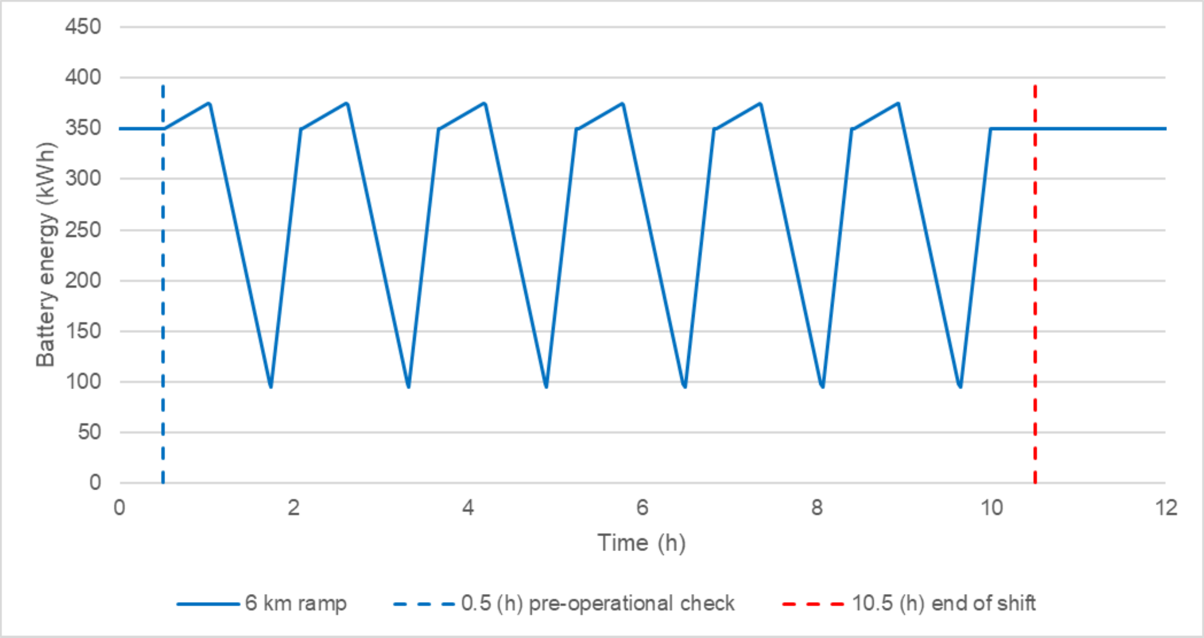
- Energy consumed and charged for 12-hour shift (swapping charging strategy requires 3 batteries, 4 km ramp)

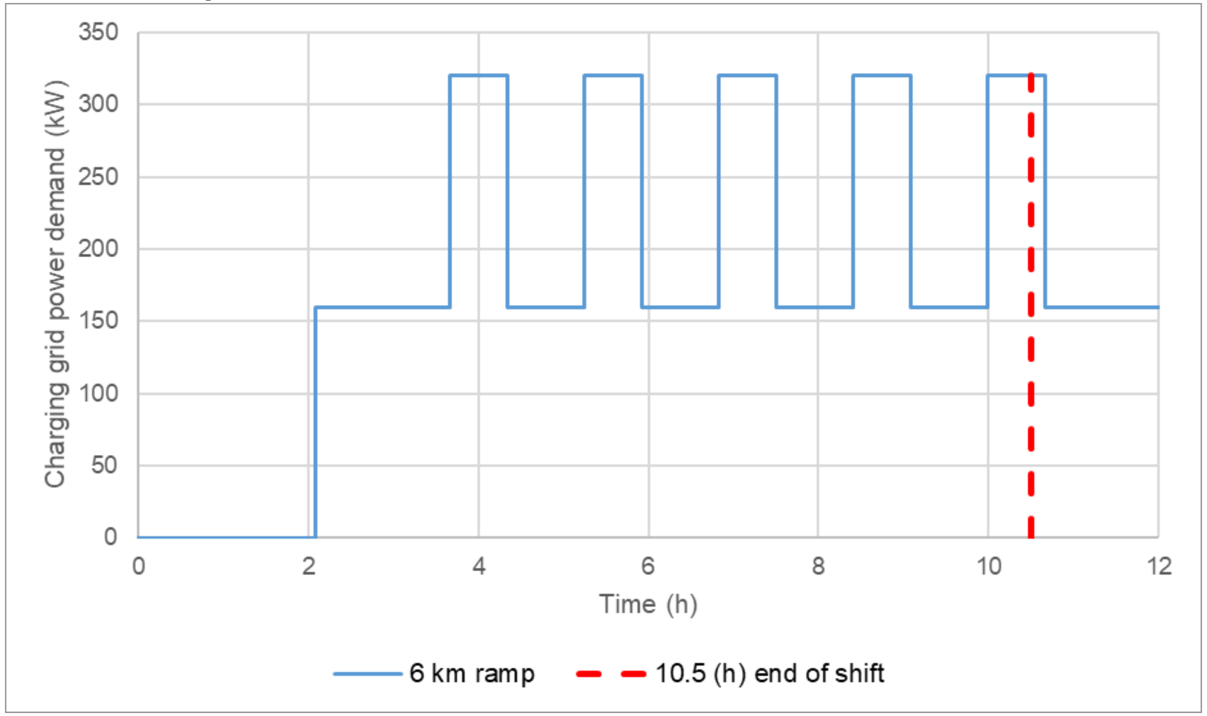




Results – Haul truck MT42B

- Energy consumed and charged for 12-hour shift (swapping charging strategy requires 3 batteries, 6 km ramp)





Results – Haul truck MT42B swapping

- Total distance achieved during shift varies between 60 to 77 km
- Longer ramp consumes energy faster (less time to pause between cycles)
- Cycles achieved in the shift vary between 23 and 6 depending in the ramp length considered from 1 to 6 km.

Scenario	Cycle distance (km)	Number of cycles	Total distance (km)	Energy charged (kWh)
1 km ramp	2.6	23	59.8	1130
2 km ramp	4.6	16	73.6	1400
4 km ramp	8.6	9	77.4	1563
6 km ramp	12.6	6	75.6	2100

Results – Haul truck – Summary

- To maximize haul truck availability swapping should be considered when haul trucks are the bottleneck of material movement
- The battery size currently limits the application range of the haul trucks to 6 km ramps unless swaps are considered as part of the ramp traverse
- With a 1 km ramp, swapping can be achieved with 2 batteries
- For the 2 to 6 km ramps, a third battery is needed to complete the swapping process as energy is consumed faster than it is charged
- The need for a third battery could be mitigated if:
  - longer waiting times are expected for dumping and/or swapping
  - traffic interaction that was not considered for this analysis (queues for ramp access, dumping and charging, only an arbitrary delay was considered), is considered
  - a payload less than the 42 tonnes maximum load is expected
  - a more powerful grid-charger-battery combination is available

Results – BEV fleet

- BEV fleet distribution (45 units in 3 classes)
- For each class of equipment, the quantity of vehicles was arbitrarily distributed as an example according to the different duty cycles previously simulated
- For example, 12 haul trucks in 15% ramp (in blue):
  - 0 haul trucks doing 1 km ramp duty cycle
  - 4 haul trucks doing 2 km ramp duty cycle
  - 4 haul trucks doing 4 km ramp duty cycle
  - 4 haul trucks doing 6 km ramp duty cycle

	1 km ramp	2 km ramp	4 km ramp	6 km ramp
Haul truck ramp	0	4	4	4

Results – BEV fleet

- BEV fleet distribution (45 units in 3 classes)
- For each class of equipment, the quantity of vehicles was distributed according to the different duty cycles previously simulated

	1 km ramp	2 km ramp	4 km ramp	6 km ramp
Haul truck ramp	0	4	4	4

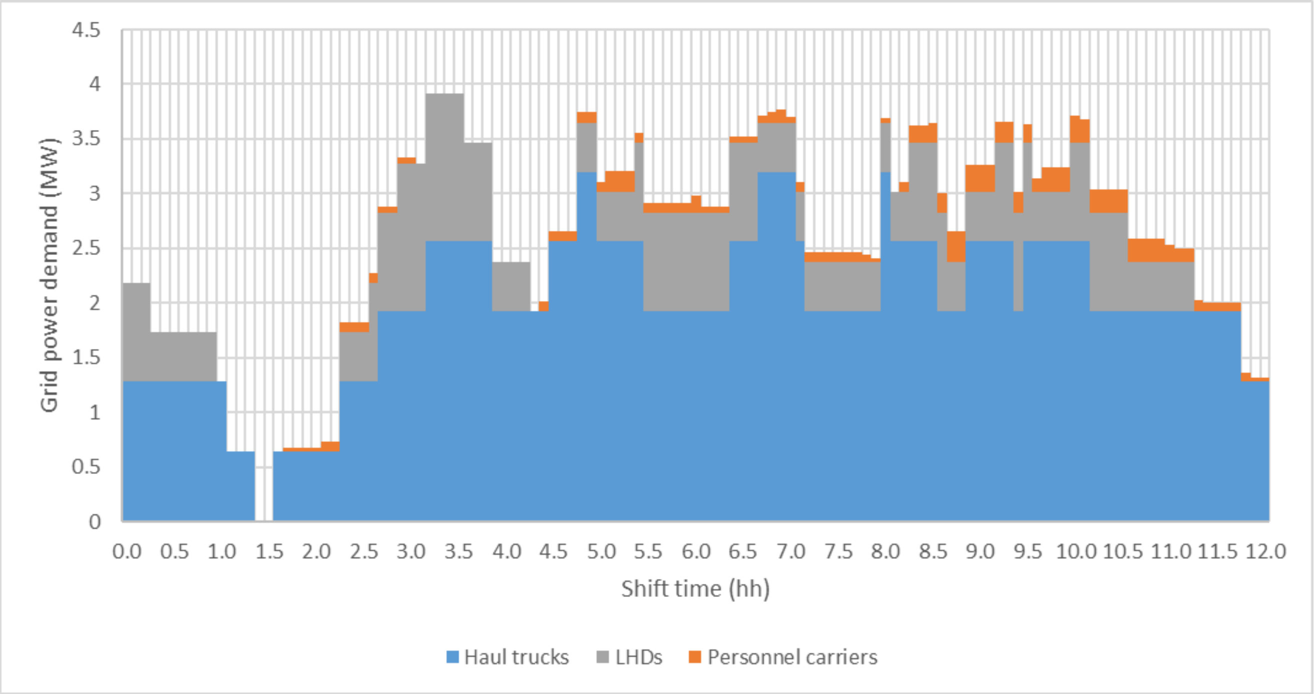
	0.2 km ramp	0.3 km ramp	0.4 km ramp	0.6 km ramp
LHD charging ramp	0	0	0	0
LHD swapping ramp	0	3	3	3

	2 km ramp	4 km ramp	6 km ramp	8 km ramp	10 km ramp
Personnel carrier Rokion ramp	2	2	2	3	3
Personnel carrier Relay ramp	2	2	2	3	3

Results – BEV fleet

- Grid charging power demand over a 12-hour shift
- Scenario from “example” mine study
- Peak power at 3.9 MW during 3rd hour of the shift
- End of the shift demand (after hour 10) is close to peak power and starts decreasing towards hour 12 (start of new shift operations)
- Peaks and valleys in power demand suggest that additional studies could potentially help reduce the peak demand

Scenario	Number of operational vehicles
Haul trucks	12
LHDs	9
Personnel carriers	24

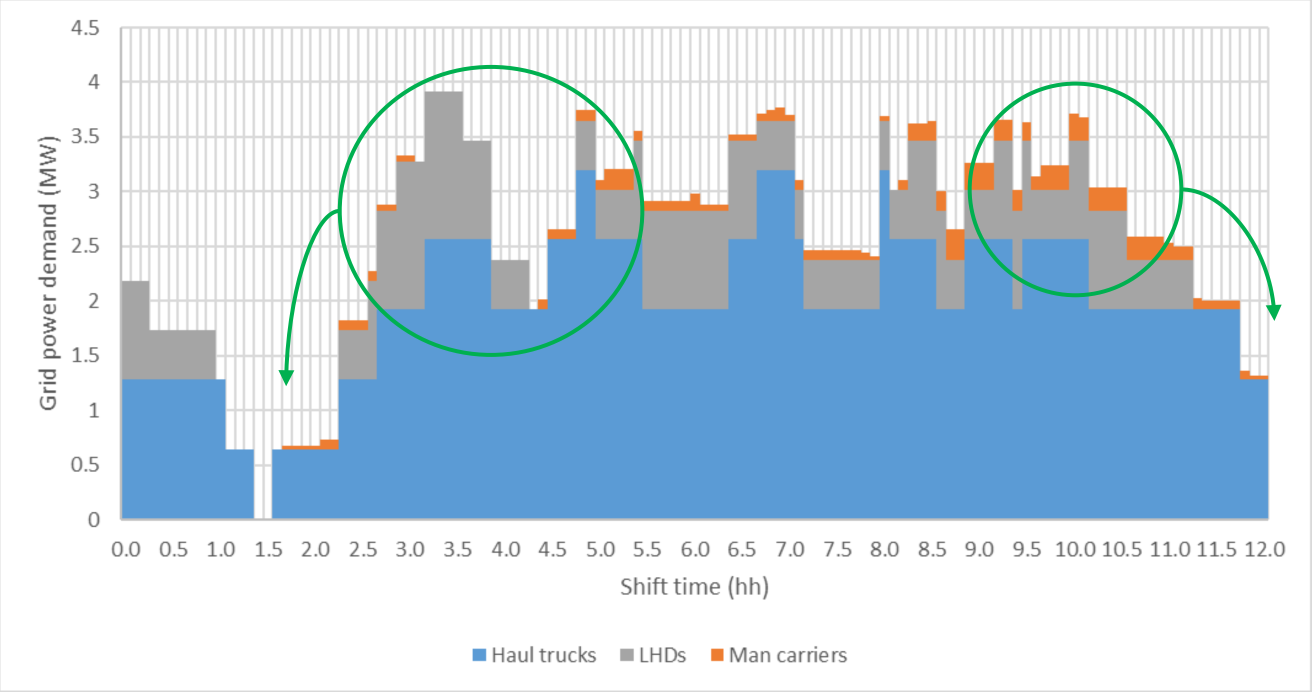


Potential next steps – Faster charging rates

- Faster charging rates can apply to all categories of mobile equipment and can speed up charging process, but could increase the peak power requirement
- For the case of haul trucks, it also has the potential to avoid the 3rd battery needed for swapping
- Limitations: only has a significant impact for vehicle classes that are the bottleneck of a process and only one manufacturer (CAT) has introduced the half to megawatt charging option to market to date for an LHD for which we do not have field test data
- As a result, the analysis can be developed using the specification sheet data from the OEM CAT

Potential next steps – Power grid flexibility

- In this case it refers to the ability to reduce the charging peak power during the shift by changing the schedule of the charge when and if possible
- The opportunity can be found before and after the shift change. The rate of charge for the equipment is not considered as a variable for this analysis
- In Ontario this can have the economical benefits of reducing the cost per kW, as the results of targeting the 5 consecutive peaks (5CP) methodology for power pricing
- There are other potential benefits that could be obtained by reducing the peak power demand, such as a more robust electrical system and infrastructure cost



Suggested future field test work

- Field charging measurements are needed to determine:
  - Power demand at the grid, charger and power stored in the battery
  - Power demand profile over time while charging the battery
  - Time required to charge the battery from X to Y% of SoC
- The charging data is required for different combinations of:
  - Grid power availability
  - Charging equipment
  - Battery C rate
  - As any of these three variables has the potential to actively limit the charging rate

Thank you!
Questions?

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