

Effects of Heavy-Duty Vehicle Electrification on Infrastructure: The Case of Switzerland

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Abstract—We present a method to simulate the charging (and battery swapping) energy demand of electrified trucks, and apply it to the example of Switzerland. We describe the daily mobility behavior of the Swiss fleet throughout a year, using governmental data sources. Based on this, we calculate the energy demand of each vehicle using vehicle and powertrain simulation. This then flows into a discrete event simulation, which we use to derive time-resolved charging power and battery swapping profiles. From that, we draw conclusions about the number of required swapping stations (respectively the average waiting time if there are not enough stations) and electrical loads they have to bear. We saw that, with better batteries and a maximum of three battery swaps per day, over 95% of heavy-duty vehicles can be electrified. This does not mean that every vehicle swaps its battery three times per day, and therefore the amount of extra batteries needed is not large. Nevertheless, to minimize the time loss for swapping, an adequate number and vehicle throughput of swapping stations should be guaranteed. For instance, to keep the waiting time under half an hour a day (duration of lunch break), a minimum of two swapping stations per large motorway fuel station and a throughput of at least eighteen vehicles per hour (per station) would be needed in Switzerland.

I. INTRODUCTION

At the Paris climate conference (COP21), 195 countries agreed on a legally binding global climate deal, which sets a goal of keeping the global temperature increase to well below 2°C above pre-industrial levels [1]. In harmony with this agreement, many countries develop their own strategies to help the world to achieve this goal. Switzerland has the Swiss Energy Strategy 2050 [2] that aims to reduce the final energy demand and CO_2 emissions by mid-century. In Switzerland, transportation causes more than 40% of CO_2 emissions and is the only sector with growing CO_2 emissions since 1990 [3]. Heavy-duty vehicles cause 11% of the transportation CO_2 emissions in Switzerland. This share may be small compared to passenger cars, but the demand for freight transport continues growing almost twice as fast as that of passenger transport [4]. Today, a lot of effort goes into the electrification of passenger cars, but eventually, heavy-duty vehicles will also have to be electrified to achieve CO_2 mitigation goals in the future. The high energy demand of

these vehicles caused by long distances they travel and heavy weights they carry, makes their electrification more challenging than passenger car electrification. Nevertheless, battery technologies have shown continuous improvement and cost reduction in the past — a trend that is generally expected to continue [5]. Thus, one day the large-scale electrification of heavy-duty vehicles will become possible. Since their energy demand is much larger than that of passenger cars, trucks may have very different energy infrastructure requirements. Nowadays, all-electric drives are prevalent for trolley buses having line-operation. Pure electric freight vehicles are not commonplace yet, but the first examples such as Swiss E-Force One [6] or EMOSS full electric trucks [7] are already in operation.

This study explores the effects of heavy-duty electrification on infrastructure. We define electrification as a technical process, meaning that if a vehicle can satisfy its energy needs every day in a year with a battery-electric powertrain, this vehicle can be electrified in our model. The market and substitution dynamics of the fleet are not considered. Switzerland has the advantage of being one of the three countries – the others being New Zealand and Belgium – around the world, which tracks the heavy-duty vehicles on all of its roads every day and therefore has complete coverage of the driven distances. This conference paper is organized as follows: Section II explains the details of our methodology. Section III shows the cases we consider and then illustrates our findings based on these cases. Section IV discusses the conclusions and possible work that can be done to investigate the subject in more detail.

II. METHODOLOGY

Our model to determine the electrification potential of the fleet and the effects of electrification on infrastructure consists of five parts:

- 1) **Generating Vehicle Usage Profiles:** We use governmental datasets to determine the mobility profile (including distance and payload) for every vehicle in Swiss heavy-duty fleet and every day of the year.

Here we use two datasets, namely LSVA and GTE. LSVA is the Swiss performance-related heavy vehicle charge. Since any heavy-duty freight vehicle¹ travelling in Switzerland is subject to this tax, LSVA gives a complete account of the distance the vehicles drove each day of the year. GTE is a representative survey done annually in Switzerland with a subset of heavy-duty vehicles and contains information about payloads carried by these vehicles. Both datasets also contain information about vehicle weights and types. Combining these two datasets, we determine profiles (containing a distance and payload) for every heavy-duty vehicle in Switzerland for 365 days.

- 2) **Calculating Useful Energy Demand:** We translate the mobility profile determined in step 1 into mechanical (useful) energy. The basis for the energy demand calculation is the longitudinal force equation of a wheeled vehicle on solid ground:

$$F_{prop}(v(t)) = \frac{1}{2} \cdot \rho_{air} \cdot c_D \cdot A_f \cdot v^2(t) + m \cdot g \cdot c_r + m \cdot \frac{dv(t)}{dt} \quad (1)$$

where:

- g is the standard acceleration due to gravity
- ρ_{air} is the ambient air density
- c_D is the vehicle's aerodynamic drag coefficient
- A_f is the vehicle's frontal area
- c_r is the tire rolling resistance coefficient
- m is the total mass of the vehicle, defined as the combined mass of the towing vehicle (curb weight), the trailer (curb weight or 0 if there is no trailer attached) and the payload

Assuming purely dissipative braking, the useful mechanical energy required to move the vehicle along a speed signal $v(t)$ — in our case we use the world-harmonized vehicle cycle (WHVC) — is the positive propulsion work plus any non-propulsive demands:

$$e_{total} = \frac{\int_{WHVC} P_{total}(t) dt}{\int_{WHVC} v(t) dt} \quad (2)$$

e_{total} is a distance-specific value, which depends on the type of vehicle, weight of the vehicle and payload carried by the vehicle. When it is multiplied with the distance driven, it gives the total energy demand for that day.

- 3) **Calculating End Energy Demand (Diesel and electric):** In this part, firstly the demand for the Diesel vehicles is calculated using a constant efficiency of 40%. The calculated end energy demand for Diesel vehicles is multiplied with the CO_2 intensity of Diesel (73.3 t CO_2/TJ) [9] and this is compared with the official CO_2 emission value of the Swiss heavy-duty fleet and used as the validation of our model. Then, each vehicle is redesigned as an battery electric vehicle. For the design of these vehicles, following procedure is followed:

- Internal combustion engine (ICE) and gear-box are removed.
- An electric motor having the same nominal power output as the original Diesel engine is added (see table I for specific mass assumptions).
- Power electronics are added assuming that they have the same nominal power as the electric motor.
- Fuel tanks are removed and batteries are added instead. For batteries, two constraints are set. Firstly, they cannot have a larger volume than the largest available fuel tank volume in their market segment. Secondly, vehicles can use only part of their available space for batteries aiming at not exceeding their original weights by more than 5% of their conventional counterparts's maximum permissible weight. The EU directive 2015/719² mentions that more weight can be allowed for vehicles with alternative powertrains, but does not specify any limit to the extra weight. Since a much heavier vehicle would cause much more damage to the road surfaces, we limit the increase to 5% of the maximum permissible weight of the original vehicle.

Quantity	Component	Value
Specific Mass [kg/kW]	ICE + gear-box	2.17 [10]
	Electric motor	0.80 [10]
	Power electronics	0.10 [10]

TABLE I: Specific masses of the components (or assemblies) used in powertrain design and energy demand computations

After the substitution of the old powertrain with its battery-electric counterpart is done, electricity demand is calculated for the battery-electric vehicles assuming constant efficiencies (see table II).

Quantity	Component	Value
Efficiency [-]	ICE + gear-box	0.40
	Battery charger	0.85 [11]
	Motor + power electronics	0.86 [12]

TABLE II: Efficiencies of the components (or assemblies) used in powertrain design and energy demand computations

- 4) **Checking the Electrifiability:** Here, we check whether the new powertrain is able to provide the energy required by the vehicle 365 days in a year. Each vehicle is charged in the night for 12 hours³. If, on a given day of the year, a vehicle requires more electricity than the initial charge of its battery (if battery swapping is not allowed), then this vehicle cannot be electrified. If battery swapping is allowed, the model compares the electricity required by the

²Paragraph 6 of the EU directive 2015/719 mandates that "[the use of alternative powertrains] for heavy duty vehicles or buses may generate extra weight, but reduces pollution. That extra weight should not be counted as part of the effective load of the vehicle, since this would penalise the road transport sector in economic terms. However, the extra weight should not result in the load capacity of the vehicle being increased either"

³According to the LSVA, 95% of the heavy-duty vehicles in Switzerland are mobile for at most eleven hours per day and we add one hour to this because of breaks a truck driver has to take

¹Swiss legal definition: Any automobile road-vehicle (a) dedicated to the transport of goods for commercial purposes and (b) whose maximum permissible weight exceeds 3.5 metric tonnes [8]

vehicle on that day with the initial charge of the battery plus the energy coming from swapped batteries.

5) **Evaluation of the Effects on Infrastructure:** Here we show the electrification potential and the effect of the electrification on infrastructure for different cases. These cases are defined by the energy density of batteries, available charging power and number of daily battery swaps allowed. Effects on infrastructure are evaluated using the following indicators:

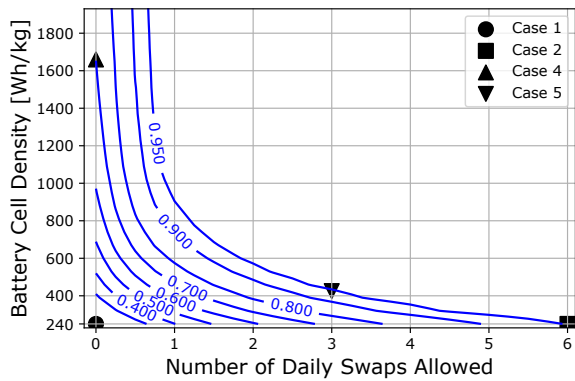
- Annual electricity demand
- Power demand throughout the year (best case and worst case): Worst case happens if all vehicles start their charging process approximately at the same time, while best case happens, if the charging processes of vehicles are perfectly distributed into 12 *h*. In both cases, the power demand coming from swapping stations (if battery swapping is allowed), is added on top as perfectly distributed into 24 *h*, since we give empty batteries in swapping stations 24 *h* to get fully charged in our model.
- Extra batteries needed for swaps (if battery swapping is allowed)
- Congestion in battery swapping stations (if battery swapping is allowed)

Here we should also mention the model about the battery swapping stations. We model the stations using a multi-agent, discrete event simulation, which goes through each vehicle's day and simulates the interaction with swapping stations. In the simulation, each vehicle covers a pre-defined distance (taken from step 1) at a constant average speed. They continue driving until they reach their destination for that day or their battery is empty. Each swapping station can serve one vehicle at a time and works on a first-come, first-served basis. Therefore some vehicles await their turn, while another vehicle gets its battery swapped in t_{swap} seconds. In our simulations, we vary t_{swap} and n_{slots} (number of swapping slots in Switzerland) to reflect different infrastructure development stages. We analyze the time each vehicle spends at the swapping station (time spent both in the queue and in the swapping slot), then we use the maximum time spent daily over all vehicles as indicator. In this model, the spatial component is disregarded, meaning that stations are evenly distributed according to the demand, so that vehicles can access a station on their route without a significant time loss. In our analysis we limit the time lost in swapping stations in a day to 30 minutes and show the infrastructural requirements to stay within this limit.

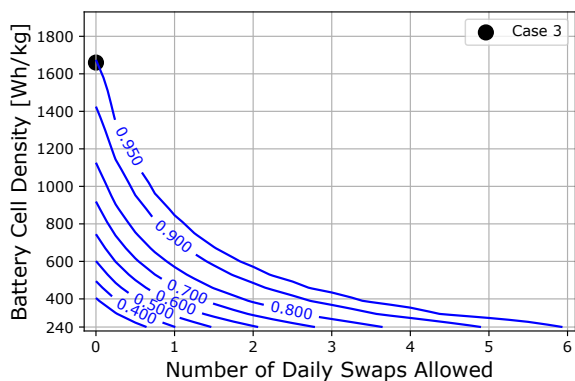
III. RESULTS

In our previous paper [13], we showed that the electrifiability of the heavy-duty vehicles in the future will depend mainly on three parameters; namely battery energy densities, available charging power and if battery swapping is possible. The electrification potential of the Swiss heavy-duty fleet depending on these variables is shown in figure 1⁴.

⁴That these curves are also shown for non-integer values of swaps means that we also consider opportunity charging during the day, e.g. 2.2 swaps show the case in which the battery of the vehicle is swapped twice on that day and it did also opportunity charging for 20% of its battery



(a) Share of electrified vehicles — Charging power: 50 *kW*



(b) Share of electrified vehicles — Charging power: 200 *kW*

Fig. 1: Share of electrified vehicles for different battery cell densities and number of daily battery swaps allowed

In this conference paper, we chose five cases considering these properties and show what the electrified fleet demands from infrastructure. The cases analyzed are as follows (also listed in table III and shown in figure 1):

- The first case assumes today's battery technology and a charging power of 50 *kW*. Battery swapping is not allowed since this technology is not yet available for heavy-duty vehicles in Switzerland. Under these conditions, only 12% of the vehicles in Switzerland can be electrified.
- The second case assumes that the battery technology stays as it is today and battery swapping technology develops. As it can be seen in figure 1, widespread electrification (95% of the fleet) can be achieved with a maximum of six daily swaps allowed for every vehicle.
- The third case assumes that battery swapping technology will not be available and widespread electrification can only be achieved using better batteries. In our previous study [13], we showed that for batteries with a higher energy density than 600 *Wh/kg*, the charging power becomes a limiting factor since with a lower power, vehicles start their next day with a half-charged battery. When charging power is set so high, that all vehicles can be fully charged in a night, the needed density to electrify 95% of the fleet is 1'650 *Wh/kg* (see figure 1b). Assuming a high charging power helps

us to see the sole effect of battery energy density on the electrification potential. The power threshold allowing all batteries with this energy density to get charged fully every day is around 200 kW and thus, this value is chosen as the charging power for this case.

- The fourth case assumes the same battery technology as in case 3. Also here, battery swapping is not allowed. The only difference is that the charging power is assumed to be 50 kW. This case shows the effect of charging power on the electrification potential.
- The last case is, in our opinion, the most realistic scenario since the technology developments for battery energy densities and battery swapping will probably occur concurrently in reality. Here, widespread electrification (95%) is achieved with a battery energy density of 415 Wh/kg and a maximum of three daily swaps allowed as it can be seen in figure 1a.

Case	Bat. Energy Density [Wh/kg]	Charging Power [kW]	Daily Swaps Allowed
1) Electrifying the heavy-duty fleet today	240	50	0
2) Achieving electrification using battery swaps	240	50	6
3) Achieving electrification using better batteries (high charging power)	1'650	200	0
4) Achieving electrification using better batteries (standard fast power)	1'650	50	0
5) Achieving electrification using better batteries and battery swaps	415	50	3

TABLE III: Cases chosen for the analysis of effects of electrification on infrastructure

The table IV shows the electrification rates, while table V demonstrates the electricity/power demands caused by the electrification of the fleet in these five cases.

Case Number	Share of Electrified Vehicles	Share of Electrified Performance (tkm)	Share of Electrified Distance (km)
1	12%	1.4%	2.2%
2	95%	90%	91%
3	95%	89%	90%
4	70%	31%	46%
5	95%	89%	90%

TABLE IV: Electrification rates in different cases

Case Number	Annual Electricity Demand [GWh]	Peak Power (Best Case) [MW]	Peak Power (Worst Case) [MW]
1	64	25	201
2	2'773	715	2'405
3	2'740	1'018	8'391
4	1'210	453	1'503
5	2'783	827	2'296

TABLE V: Electricity demand of and peak power caused by the electrified fleets in different cases

A. Case 1: Electrifying the heavy-duty fleet today

In this case, it is assumed that the batteries in the electric vehicles have the gravimetric and volumetric cell densities

of 240 Wh/kg and 727 Wh/l respectively. These values are the expected density values of the battery cells used in Tesla Model 3 (Panasonic 2170). In addition, we assume a packing density of 70% to estimate the battery pack densities. This value comes from the Tesla S battery pack, which weighs 544 kg and has an energy content of 85 kWh [14] meaning that the battery pack density is 156.3 Wh/kg. Comparing with the cell density of Panasonic 18650 batteries, the packing density equals 70%.

The charging power assumed is 50 kW, the typical power available in a fast-charging station for cars [15] and battery swapping is not allowed since this technology is not yet available for electric trucks in Switzerland.

Figure 2 shows the fluctuations of the power demand caused by the electrified vehicles during the year. In the worst case, the peak power reaches 200 MW, although only 2% of the travelled distance is electrified (see table IV). If the energy demand of vehicles is perfectly distributed into 12 h in the night (best case), the peak power becomes 25 MW. This shows the big impact of smart charging.

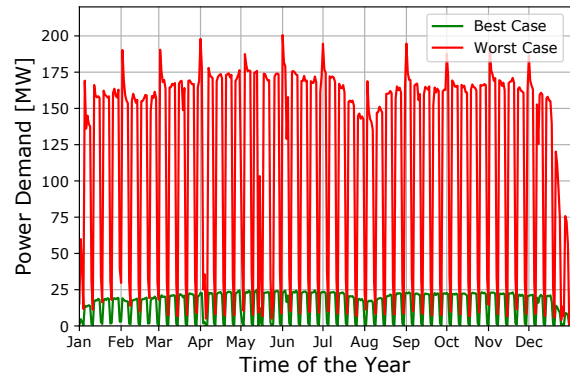


Fig. 2: Daily peak charging power demand from electric trucks assuming current-day battery technology and no battery swapping. Charging power is assumed to be 50 kW (Case 1).

B. Case 2: Achieving electrification using battery swaps

The second case achieves widespread electrification using battery swapping technology (battery energy density is again 240 Wh/kg). To electrify 95% of the Swiss fleet, heavy-duty vehicles should be allowed to swap a maximum of six times per day. This does not mean that all electrified trucks swap their batteries six times a day, but they may do it if they need it to complete their duties that day. Figure 3 shows that the power demand in worst case reaches 2'400 MW sometimes, which is more than one third of the average power demand of whole Switzerland. This means that without smart charging, it is not possible to electrify these vehicles using today's infrastructure.

Another important point to mention is the need of extra batteries for swaps. When six swaps are allowed (see figure 4a), in some days, more than 25'000 batteries are needed in swapping stations so that these vehicles can fulfil their missions that day.

Figure 4b shows the need for battery swapping stations (or slots) assuming that no vehicle should wait more than

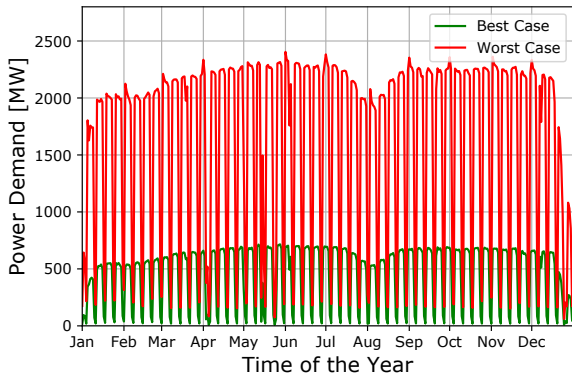
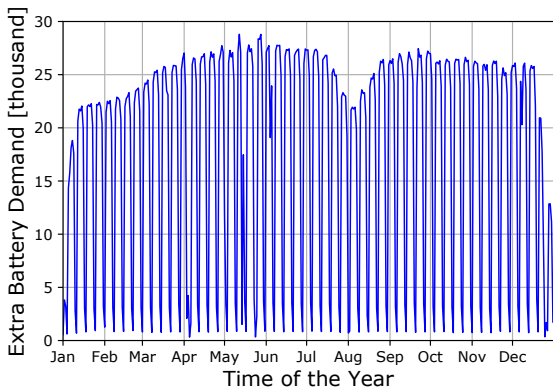
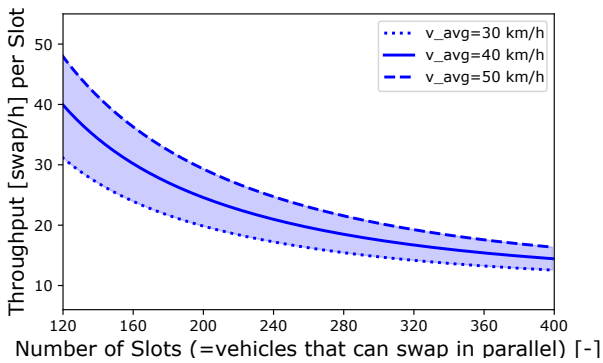


Fig. 3: Daily peak charging power demand from electric trucks assuming current-day battery technology and a maximum of six battery swaps per day. Charging power is assumed to be 50 kW (Case 2).



(a) Daily extra battery demand on every day of the year



(b) Number of slots and throughput needed for three different average velocity assumptions — waiting for a max. of 30 minutes per day

Fig. 4: Infrastructural needs in swapping stations — Figure 4b uses three different average velocity assumptions (Case 2)

30 minutes per day for getting its battery swapped. We know from the LSVa database when each vehicle starts its day. So assuming an average velocity, we model arrival and waiting times in swapping stations. We use 40 km/h since it is similar to the average velocity of the driving cycle we use (WHVC). In this figure, also the sensitivity to different

average velocity assumptions is shown. We see that in the base case (average speed: 40 km/h) if the throughput (how many swaps a station (or slot) can perform in one hour) is 40 swaps/h — which is an optimistic value for today — at least 120 swapping slots is needed to satisfy the 30 minutes target. On the other hand, if only a throughput of 20 swaps/h is achieved, the number of needed slots more than triples.

C. Case 3: Achieving electrification using better batteries (high charging power)

The third case assumes that battery swapping technology will not be available for heavy-duty vehicles, so electrification can only be achieved using better batteries. But when batteries become more energy-dense, a charging power of 50 kW starts to be limiting for the electrification of the heavy-duty vehicles. In this case, we chose a high charging power (200 kW is the threshold which allows the batteries in our model to be fully charged in the night) so that we can see purely the effect of battery energy density on electrification. The battery density needed to electrify 95% of the heavy-duty vehicles in Switzerland is $1'650\text{ Wh/kg}$. In this case, it is seen that the peak power in worst case reaches 8 GW , which is more than the average power demand in Switzerland. Even in the best case, this case give a higher power demand than that of the second case, since in our model swapped batteries have 24 h for a recharge, while the batteries in vehicles only have 12 h .

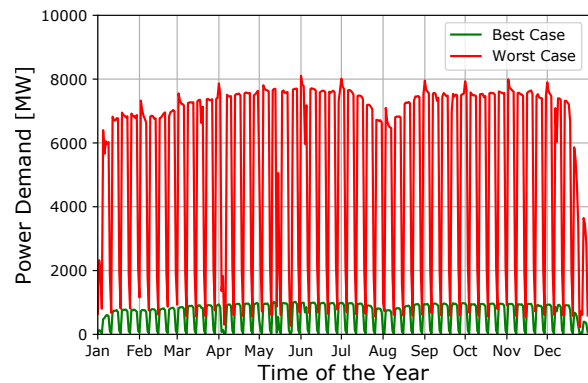


Fig. 5: Daily peak charging power demand from electric trucks assuming a much better battery technology ($1'650\text{ Wh/kg}$ at cell level) and no battery swapping. Charging power is assumed to be 200 kW (Case 3).

D. Case 4: Achieving electrification using better batteries (standard fast charging)

The fourth case has the same conditions as the third case except the charging power, which is 50 kW here instead of 200 kW . This case shows that only 70% of the vehicles can be electrified, although the energy density is already at an unrealistic level ($1'650\text{ Wh/kg}$), because 50 kW can only charge a small part of the "energy-dense" and large batteries in heavy-duty vehicles and therefore the charging power becomes the limiting factor.

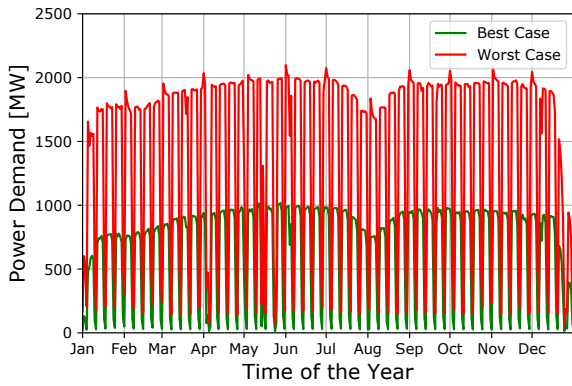


Fig. 6: Daily peak charging power demand from electric trucks assuming a much better battery technology ($1'650 \text{ Wh/kg}$ at cell level) and no battery swapping. Charging power is assumed to be 50 kW (Case 4).

E. Case 5: Achieving electrification using better batteries and battery swaps

The fifth case is, in our opinion, a realistic scenario for the future. Here, both better batteries are developed (a battery energy density of 415 Wh/kg) and battery swapping technology is available for battery-electric trucks (a maximum of three swaps per day). The power demand curves are similar to those in case two (the best-case curve is a bit higher in this case, since less swapping occurs and swapped batteries have 24 h to get charged, while the batteries staying in trucks during the night have only 12 h).

The major difference occurs in extra battery demand for swaps (see figure 8a). This case achieves same level of electrification (95%) using less than half of the batteries used in the second case, since the better energy densities also help here the electrification.

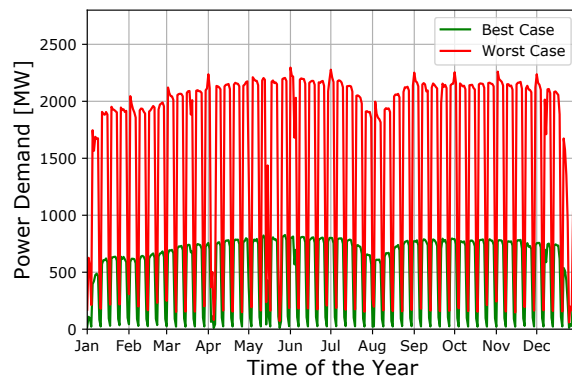
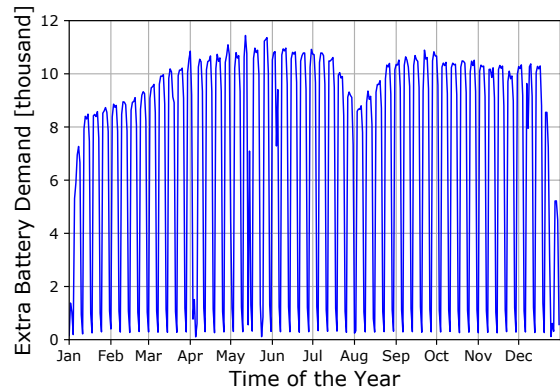


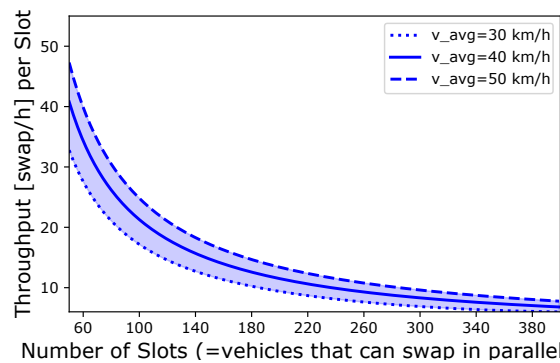
Fig. 7: Daily peak charging power demand from electric trucks assuming a better battery technology (415 Wh/kg at cell level) and a maximum of three battery swaps per day. Charging power is assumed to be 50 kW (Case 5).

Figure 8b demonstrates the need for battery swapping slots assuming again that no vehicle should wait more than 30 minutes per day in swapping stations. We see that in the base case (average speed: 40 km/h), if the throughput is 40 swaps/h, around 60 swapping slots is needed to satisfy the 30

minutes target, this is close to the number of large motorway fuel stations in Switzerland (there are 65 of them [16]). When we assume that each of these stations is converted to a battery swapping station and has two slots, a throughput around 18 swaps/h is required to reach the 30 minutes target.



(a) Daily extra battery demand on every day of the year



(b) Number of slots and throughput needed for three different average velocity assumptions — waiting for a max. of 30 minutes per day

Fig. 8: Infrastructural needs in swapping stations — Figure 8b uses three different average velocity assumptions (Case 5)

IV. CONCLUSIONS AND OUTLOOK

This study examined the effects of heavy-duty electrification on infrastructure for the case of Switzerland. It showed that there are two technology options — using battery swapping technology and developing better batteries (higher energy densities) — which can allow electrification in the future and these options result in different pressures on infrastructure. When battery energy densities improve, the new batteries — containing more energy in the same volume or mass — make electrification easier, while the vehicles having these "energy-dense" batteries require a charging power up to 200 kW to be able to fully charge their batteries in the night. Providing such a high charging power to heavy-duty vehicles results in a huge power demand on the national level. On the other hand, when the battery energy densities stay at the current level and electrification is achieved using battery swapping technology, the peak power throughout the year becomes much smaller, while this development requires tens of thousands of batteries being available in swapping

stations around Switzerland. Besides, the time spent in swapping stations should be kept to a minimum so that the battery electric vehicles can compete with their conventional counterparts. To limit this time to 30 minutes per day, more than 120 swapping slots are needed in Switzerland assuming a throughput of 40 swaps/h per swapping slot. The optimum option is a balanced development of battery energy densities and swapping technology. This results in a peak power similar to the case achieving electrification using battery swapping technology (and current energy densities), while it also keeps the required number of batteries and swapping stations at a much lower level.

As a next step, the spatial component can be added into the model. This would give spatially resolved demand profiles for the grid and battery swapping stations. Besides, the model used in this study can also be applied for other alternative fuel vehicles such as fuel cell electric and plug-in hybrid vehicles, which will be discussed in a subsequent paper.

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