



The potential of electric trucks – An international commodity-level analysis

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HIGHLIGHTS

- Methodology for international comparison of truck electrification potential developed.
- Electric trucks may cover 71% of tonne-kilometers in Switzerland, but 38% in Finland.
- Electrification potential varies considerably between commodities.
- Electric trucks increase annual electricity consumption by only 1–3%.
- Electric trucks have large impact on local grids near charging stations.

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ABSTRACT

Development of battery technology is making battery electric heavy duty trucks technically and commercially viable and several manufacturers have introduced battery electric trucks recently. However, the national and sectoral differences in freight transport operations affect the viability of electric trucks. The aim of this paper is to develop a methodology for estimating the potential of electric trucks and demonstrate the results in Switzerland and Finland. Commodity-level analysis of the continuous road freight survey data were carried out in both countries. As much as 71% of Swiss road freight transport tonne-kilometers may be electrified using battery electric trucks but Finland has very limited potential of 35%, due to the use of long and heavy truck-trailer combinations. Within both countries the electrification potential varies considerably between commodities, although in Finland more so than in Switzerland. Commodities which are constrained by payload volume rather than weight and are to large extent carried using medium duty or < 26t rigid trucks seem to provide high potential for electrification even with the current technology. Electric trucks increase the annual electricity consumption by only 1–3%, but truck charging is likely to have a large impact on local grids near logistics centres and rest stations along major roads. A spatial analysis by routing the trips reported in the datasets used in this study should be carried out. Future research should also include comparison between the alternate ways of electrifying road freight transport, i.e. batteries with charging, batteries with battery swapping and electrified road systems.

1. Introduction

Global CO₂ emissions from transport are 9000 billion tons, 18% of which are man-made emissions, and these are expected to grow by 60% until 2050 [1]. Freight transport currently accounts for slightly less than half of emissions from transport, but the share is expected to grow significantly as emissions from road freight transport are expected to grow by 56%–70% [1,2] and emissions from international sea and air freight are expected to almost triple between 2015 and 2050 [1]. Emissions are expected to grow despite large improvements in energy efficiency [2] because of expected strong growth in demand [1]. Hence,

there is a growing need for electrification of transport, including heavy-duty road freight transport.

Battery electric trucks have not been a viable option to replace heavy duty trucks because of the high energy requirements and low energy density of batteries [3]. However, recent developments in battery technology [4] are making electric heavy duty trucks technically and commercially viable as mild and full hybrid [5] and battery electric [6]. As battery prices are expected to decrease significantly, the life cycle costs of heavy duty electric trucks are expected to become lower than those of heavy duty diesel trucks, making electrification of heavy duty trucks an interesting research area [4,6].

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Table 1
Specifications of some electric trucks.

Manufacturer	Commercial name	Type	Maximum weight	Battery capacity (kWh)	Range (km)	Energy consumption (kWh/km)	Charging power (AC/DC kW)	Source
Mitsubishi	eCanter	medium duty	7.5t	82.8	120	0.69		[7]
BYD	T7	medium duty	11t	175	200	0.88	100/150	[8]
Freightliner	eM2 106	medium duty	12t	325	370	0.88	260	[9]
Volvo	FL Electric	rigid	16t	100–300	100–300	1.00	22/150	[10]
Renault	D Z.E.	rigid	16t	200–300	300	1.00	22/150	[11]
eMoss	EMS18	rigid	18t	120–240	100–250	1.00	22/44	[12]
Mercedes-Benz		rigid	26t	212	200	1.06		[13]
Renault	D WIDE Z.E.	rigid	26t	200	200	1.00	22/150	[11]
Tesla	Semi	semitrailer	36t		480–800	< 1.25		[14]
BYD	T9	semitrailer	36t	350	200	1.75	100/150	[8]
Freightliner	eCascadia	semitrailer	40t	550	400	1.38	260	[9]

Sen et al. [5] perform a life cycle analysis with different Class 8 (approx. 36t) trucks in the United States and conclude that battery electric trucks outperform other alternative fuels in terms of costs and emissions, despite their incremental costs and electricity generation related emissions. Mareev et al. [4] also calculate life cycle costs of 40t semi-trailer trucks in Germany and show that battery electric trucks can perform at the same cost level as diesel trucks, even when batteries are dimensioned up to 825 kWh and recharging stations up to 880 kW charging power in order to enable 4.5 h trip durations and full recharge during 45 min mandatory rest periods of drivers. Several, both traditional and new, truck manufacturers have introduced battery electric trucks recently. Table 1 summarizes some of the key aspects of these trucks.

Table 1 shows that many manufacturers aim to provide a range of at least 300 km, which can be considered as a minimum requirement, because trucks can cover around 350 km during the 4.5 h driving period before the compulsory rest period according to EU regulation 561/2006 [15]. However, the battery capacities of the electric semitrailers do not meet the 800 kWh threshold set by Mareev et al. [4].

An alternative to high battery capacity are electric road systems (ERS) that can be implemented either by inductive or conductive power transfer by in-road and in-vehicle coils or with overhead catenary lines or in-road power lines and retractable pantograph or connecting arm [16]. Connolly [17] estimates that ERS on main roads in Denmark, combined with low capacity batteries in vehicles, would be a cheaper solution for electrifying transport than high capacity batteries in vehicles without ERS or a continued dependence on oil. Jelica et al. [18] analysed the effect of ERS on electricity demand and conclude that electrifying all major roads would enable almost half of the vehicle mileage in Sweden to be electrified, while increasing the peak electricity load by 10% in Sweden. Taljegard et al. [19] presented similar analysis in Norway and estimated the peak load to increase by 7% in Norway, with approximately two thirds of the additional load coming from heavy vehicles, i.e. buses and trucks. Zhao et al. [20] compare catenary system, dynamic inductive charging and hydrogen fuel cell technologies for long-haul freight trucks and conclude that all these have high infrastructure investment costs and benefit from large scale applications. Hence, policies promoting infrastructure investments and vehicle uptake would be needed to enable electrified road systems or hydrogen fuel cell trucks. Battery electric trucks, on the other hand, do not require as high investments in infrastructure as electrified road systems or hydrogen trucks because battery electric vehicles and charging infrastructure can be gradually scaled up from medium duty trucks to heavy duty rigid trucks and finally to semitrailer trucks from short-haul to long-haul applications as battery technology improves.

The purpose of this study is to analyze the potential of battery electric trucks in various scenarios of gradually improved batteries and charging infrastructure. Similar analysis has been carried out by Cabukoglu et al. [21] for Switzerland, but this study is the first to present a methodology and results of an international comparison of the

potential of battery electric trucks. This study is also the first to present a commodity-level analysis of the potential of battery electric trucks. The results give policy makers guidance on the carbon dioxide emission mitigation potential of trucks, fleet managers an overview on the potential of electric trucks for various commodities to enable informed investment decision and electric grid managers an overview on the electricity consumption and charging power requirements of electric trucks.

2. Literature

The competitiveness of medium duty delivery electric trucks (Class 4–6, 6–12t gross vehicle weight) against diesel and alternative fuel trucks has been a focus area of some research during 2010s. Davis & Figliozzi [22] developed a methodology to evaluate the competitiveness of electric trucks and Feng & Figliozzi [23] showed that electric trucks are economically competitive in high utilization scenarios. Lee et al. [24] found that the total cost of ownership (TCO) of electric delivery trucks is 22% less than that of diesel trucks in the New York City Cycle, while Lee & Thomas [25] reported robust benefits in urban driving in many areas of the United States. Zhou et al. [26] challenge these findings in Toronto, Canada, by showing that medium-duty battery electric trucks have lower life cycle greenhouse gas (GHG) emissions but higher TCO than diesel trucks. Zhao et al. [27] challenge also the environmental benefits as they have slightly higher GHG emissions than other trucks as the regional electricity mix has a strong effect on life cycle GHG emissions. These studies conclude that even with an electric truck purchasing price three times that of a diesel truck, electric trucks are competitive if annual mileage is high enough and battery lifetime matches the vehicle lifetime. Furthermore, the benefits of electric trucks depend on the drive cycle (low payload weight, low speeds and frequent start/stop favor electric) and charging infrastructure costs. Battery electric trucks certainly reduce public health costs due to lack of tailpipe emission and mostly reduce GHG emission costs, although on some occasions GHG emissions may increase due to carbon intensive electricity production.

If medium duty electric trucks are already competitive in terms of life cycle costs and even heavy duty electric trucks are becoming competitive in the future, what kind of role can electric trucks have in decarbonizing road freight transport? Mulholland et al. [2] estimate that electric trucks (medium duty trucks partly battery electric and partly catenary electric, heavy duty trucks catenary electric) will influence road freight emissions from 2035 onwards and account for one third of the emission reductions in 2050. Talebian et al. [28] analyzed the role of electric trucks in achieving the GHG emission reduction targets in British Columbia, Canada, and conclude that, even with stringent regulations on fuel efficiency of diesel trucks, > 65% of truck fleet need to be fully electric by 2040, which would require all new trucks to be electric from 2025 onwards. T&E [6] argue that there are low hanging fruit in improving conventional trucks, but electric trucks

should achieve 20% share of new truck sales by 2025 and 60% share by 2035.

The most comprehensive analysis yet on the potential of battery electric trucks on a national scale was presented by Cabukoglu et al. [21] for Switzerland. Their analysis showed that 12% of vehicles were electrifiable and only 2.1% of CO₂ emissions would be avoided using current battery technology. Achieving higher levels of electric vehicles (up to 95%) and CO₂ reductions (up to 90%) is possible, but would require exemptions from maximum permissible weight regulations, coordinated smart charging with high capacity (> 50 kW) grid connections at home bases and development of extensive battery swapping infrastructure [21]. Margaritis et al. note that heating or refrigeration requirements for cargo can reduce effective range by increasing electricity use [29]. Mareev et al. [4] also highlighted that the weight of the battery will limit maximum payload if no exemptions are made to maximum permissible weight regulations. Mareev et al. [4] found that 69% of truck trips in Germany were shorter than 350 km. Cabukoglu et al. [21] showed that in Switzerland the daily distance travelled with rigid trucks is rarely > 400 kms and with articulated trucks there is a peak in the frequency of daily distance around 300 kms. While the electric trucks may be becoming a viable alternative in countries like Switzerland where freight transport consists of mostly short distances with semitrailers, the situation is very different in countries such as Finland where truck and trailer vehicle combinations with maximum gross vehicle weight (GVW) of 76t are used to cover long distances.

Cabukoglu et al. [21] used a unique dataset with the precise account of the distances each vehicle has traveled in Switzerland provided by the Swiss heavy vehicle road tax collection system. Unfortunately, such a dataset is not available in other countries, because distance-based road taxes are not implemented or are only in use on motorways. Hence, there is a need for developing other methods for analysis to enable internationally comparable results.

The aim of this paper is to develop a methodology for estimating the potential of electric trucks based on the data from continuous road freight surveys carried out according to EU regulation 70/2012 [30] and demonstrate the results of using the methodology in Switzerland and Finland. Specifically, we study the following research hypotheses:

H1: Useful comparable analysis between countries on the potential of electric trucks is possible using the data from continuous road freight transport surveys.

H2: Electric trucks could perform majority of freight transport in Switzerland, but only a small share in Finland due to the extensive use of truck-trailer combinations with gross vehicle weight (GVW) of up to 76t for long distance transport.

H3: Availability of fast recharging infrastructure and sufficient charging time has a major effect on the potential of electric trucks.

H4: Improvements are needed to the electric grid because of the charging needs of electric trucks.

H5: There are major differences in the potential of electric trucks with different commodities.

H6: Certain electric truck types can be identified to have commercial potential with certain types of freight transport operations based on the commodity-level data (range analysis by commodity, size, weight).

3. Methodology

3.1. Data

We chose Finland and Switzerland as the case countries because they have almost identical annual road freight transport volumes in terms of the weight of goods carried: 274.6 million tons in Finland and 274.1 million tons in Switzerland in 2016 [31]. However, the countries represent very different types of freight transport needs due to geography, types of freight vehicles, types of commodities as illustrated by the large difference in total haulage, with 24.6 billion tkm in Finland

and 9.9 billion tkm in Switzerland in 2016, and shares of haulage by NST2007 commodity groups [31]. Furthermore, there is comparable data available from both countries and there is a previous study available [21] with which the Swiss results acquired using the new methodology can be compared.

The data used in this study consists of the continuous road freight surveys carried out according to the EU regulation 70/2012 [30] in both Finland and Switzerland. Similar datasets are available also in other European countries, enabling similar analysis in other countries. The Swiss data was provided by BFS [32] and Finnish data by Statistics Finland [33] who also publish regular updates on the development of road freight transport based on the same survey. Both surveys are continuously sent to the owners of a representative sample of trucks (GVW > 3.5t). In Finland the sample is 10,000 annually and the trips performed on 3 or 4 days per truck are reported. In Switzerland the sample is 8500 and survey period is one week for each truck. Both domestic and international trips are reported in the surveys, but this study analyses only the domestic trips.

The dataset from both countries consist of a sheet on truck data and a sheet on trip data. Truck data includes various specifications of the truck, but for the purposes of this study just a few are used, most importantly the maximum GVW and vehicle type (rigid or articulated with either semitrailer or trailer). Trip data consist of details on the origin and destination, trip length, payload weight and type of payload. Swiss data from 2016 consists of 84,544 trips and Finnish data of 18,110 trips. Truck data is combined with trip data using the identification number for each truck. Each truck also has its own grossing factor that is used to scale the results to correspond with the whole sampling frame.

3.2. Analysis methods

In order to assess the electrification potential of road freight transport and its benefits, the diesel fuel consumption and electricity consumption for each trip reported in the dataset was calculated using the following procedure:

1. Own weight of the truck and trailer combination used in the trip was calculated in Swiss dataset based on the own weight of the truck available in the dataset and assuming a 7t own weight for a trailer. In Finnish dataset the own weight was calculated based on the maximum GVW and maximum payload weight available in the dataset.
2. Total weight of the vehicle on the trip was calculated by adding the reported payload weight to the own weight calculated in step 1. On distribution trips the payload weight changes during the trip, in these cases the maximum payload weight during the trip was used.
3. Diesel consumption of the trip was then calculated based on the total weight of the vehicle by using the following equation developed by Liimatainen & Pöllänen [34] and used in various analysis since:

$$FC = 5.7767 \times W^{0.6672}$$

where FC is the diesel consumption in l/100 km and W is the total weight of the vehicle in tons.

This equation gives the average diesel consumption on urban roads for an emission class Euro 0 truck. Subsequent Euro classes have smaller diesel consumption due to improvements in vehicle and engine design; hence the average diesel consumption is multiplied by the factor of 0.931, 0.924, 0.948, 0.899 and 0.909 for Euro1, Euro2, Euro3, Euro4 and Euro5/6 truck, respectively. Average diesel consumption is then multiplied by the trip length to determine the total diesel consumption of the trip. Total diesel consumption is then multiplied by 2.66 kg/l to determine the CO₂ emissions of the trip.

4. The electricity consumption is then calculated by dividing the diesel

Table 2
Specifications of the electrification scenarios.

Scenario	Current technology	Improved vehicles	Improved vehicles and charging	Towards full electrification
Battery capacity (kWh rigid/articulated)	150/400	250/600	250/600	350/800
Gravimetric density of batteries (Wh/kg)	120	240	240	360
Overnight (8 h) charging power (kW)	50	50	150	150
On-road (2 h) recharging power (kW)	50	150	250	400

consumption in liters by 9.794 to have the diesel energy consumption in kWh. Electric energy consumption is calculated then by dividing the diesel energy consumption by 2.5. This factor was found by Mareev et al. [4] to be the average ratio between diesel and electric energy consumption, with variations between 2.4 and 2.7 in average and heavy routes due to the variation in the efficiency of diesel engine. These variations are considered by performing a sensitivity analysis.

5. Cumulative and total daily electricity consumption are then calculated for each truck by adding the electricity consumptions of the trips each day.
6. Sufficiency of battery capacity is then evaluated by comparing the battery capacity to the daily electricity consumption. If the battery consumption is not sufficient, recharging need in kWh is calculated by subtracting battery capacity from daily electricity consumption and the number of recharge visits is calculated based on the assumption that the battery will be charged to full capacity.
7. Electrification potential analyses are carried out by altering the following specifications as shown in Table 2 (current technology scenario in bold):
 - a. Battery capacity: **150–250–350 kWh** for medium (< 12t GVW) and heavy (> 12t GVW) duty rigid trucks, **400–600–800 kWh** for semitrailer and articulated trucks.
 - b. Gravimetric density of the batteries: **120–240–360 Wh/kg**, while also considering the reduction in vehicle weight due to removing diesel engine and related equipment, the weight of which is estimated to be 850 kg for < 18 t rigid trucks and 1700 kg for heavier trucks.
 - c. Charging power and time variations: overnight charge of **8 h** with **22–50–150 kW** and on-road recharging of **2 h** with **50–150–250–400 kW** during the day. The charging times are estimated so that they would allow two 8-hour work shifts with a 45 min recharging break during each shift and a half hour recharging between the shifts.

4. Results

4.1. Electrification potential in the four scenarios

The potential of electric trucks is first analyzed on national level in

the four scenarios, which were presented in Table 2. Fig. 1 presents the results of these scenarios and it can be seen that improving the battery capacity and gravimetric density of batteries together with improving the charging infrastructure will lead to higher increase in electrification potential than merely improving the charging infrastructure.

Fig. 1 highlights the great difference in the potential of electric trucks between the two countries. Electric trucks in the current technology scenario could cover 50% of trips in Finland, which is almost the same as in Switzerland (52%). However, the potential share of electric trucks barely increases compared to the significant growth in Switzerland from current technology to other scenarios. Even in the towards full electrification scenario the electric trucks could only cover 81% of trips, 61% of mileage and reduce 50% of CO₂ emissions in Finland, whereas in Switzerland the shares are 93%, 86% and 82%, respectively.

The difference between the countries is due to the fact that in Finland there is only a limited amount of transport operation available for electrification because long and heavy truck-trailer combination are extensively used. This is illustrated by the fact that electric trucks' potential share of tonne-kilometers (tkm) is only 6–35% in Finland depending on the scenario, whereas in Switzerland the respective share is 18–71%. Analyzing the results by truck type further validates this conclusion (Table 3).

Compared to the overall potential of electric trucks presented in Fig. 1, the differences between countries are significantly smaller when results are shown by truck type as in Table 3. In fact, the electrification potential is in some aspects higher in Finland than in Switzerland for rigid trucks. These findings confirm that the second hypothesis presented in the introduction is true.

With semitrailers and articulated trucks the difference in average trip length is large, as in Finland these are 100 km for semitrailers and 106 km for articulated truck, but in Switzerland 58 km and 21 km, respectively. Hence, trip length and daily mileage are one factor preventing the use of electric trucks in Finland. Another factor preventing the use of electric trucks in Finland is the high average loads of semitrailers and articulated trucks. In Switzerland both semitrailers and articulated trucks have the maximum GVW of 40t, whereas in Finland semitrailers have maximum GVW of 48t (5-axle) or 52t (6-axle) and articulated trucks have the maximum GVW of 44t (5-axle), 53 t (6-axle), 60t (7-axle), 68t (8-axle) or 76t (9-axle). This affects the average payload of semitrailers and articulated trucks, which are significantly

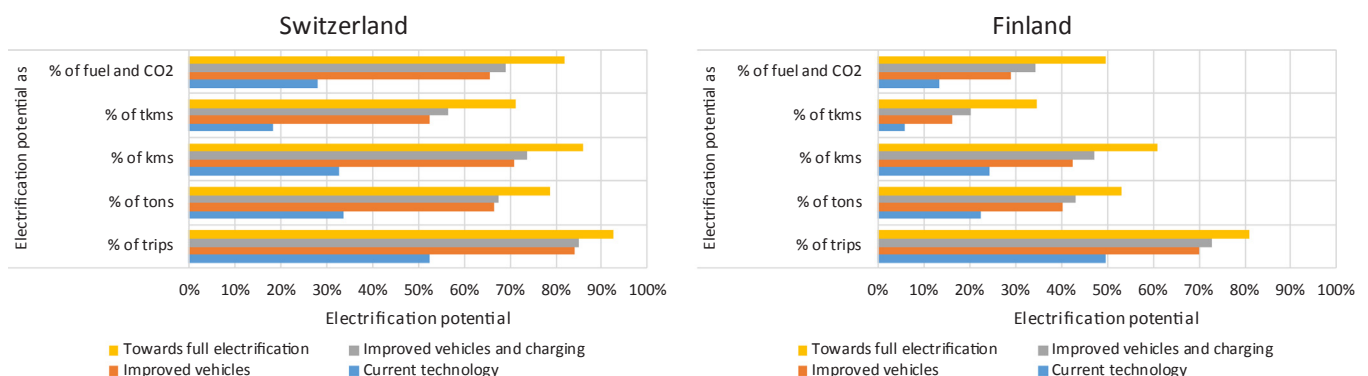


Fig. 1. The potential of electric trucks in various battery capacity and charging power scenarios in Switzerland and Finland.

Table 3
Electrification potential of medium duty and heavy duty rigid trucks by country in current technology and towards full electrification scenarios.

Scenario	Medium duty trucks				Rigid < 26t trucks			
	Switzerland		Finland		Switzerland		Finland	
	Current technology	Towards full electrification	Current technology	Towards full electrification	Current technology	Towards full electrification	Current technology	Towards full electrification
% of trips	88%	95%	85%	93%	58%	95%	63%	89%
% of tonnes	67%	81%	55%	82%	42%	88%	56%	84%
% of km	75%	92%	66%	78%	30%	85%	33%	76%
% of tkm	53%	78%	37%	66%	18%	75%	28%	73%
% of fuel	70%	89%	58%	75%	27%	82%	30%	75%
% of CO2	70%	89%	58%	75%	27%	82%	30%	75%

higher in Finland (12.1t and 20.2t) than in Switzerland (7.8t and 15.6t). Furthermore, because of more axles and longer vehicles, the vehicles' own weight is higher in Finland than in Switzerland. These result in higher electricity consumption per km in Finland (2.1 kWh/km and 2.7 kWh/km) than in Switzerland (1.8 kWh/km and 2.5 kWh/km).

4.2. Sensitivity analysis of various diesel to electric energy ratios

In the analyses presented above, electric energy consumption is calculated by dividing the diesel energy consumption by 2.5 because battery electric trucks have higher drivetrain efficiency. This factor was found by Mareev et al. [4] to be the average ratio between diesel and electric energy consumption, with variations between 2.4 and 2.7 in heavy and average routes, respectively. Variation in the ratio is due to the variation in the efficiency of the diesel engine, which is higher on hilly heavy routes. These variations are taken into account by performing a sensitivity analysis (Fig. 2).

The sensitivity analysis shows that the electric truck potential, in terms of % of tkm, decreases in both countries when diesel to electric energy ratio decreases as it does on hilly highway routes and increases if the ratio increases as it does on flat highway routes and in urban areas with idling which consumes diesel significantly but very little electricity. The decrease in electric truck potential is 1–7% in Switzerland and 4–5% in Finland if diesel to electric energy ratio is low and the increase is 3–15% in Switzerland and 9–13% in Finland if the diesel to electric energy ratio is high. The current technology scenario with low battery capacities have the highest sensitivity in the electric truck potential and towards full electrification scenario with high battery capacities has the lowest sensitivity.

4.3. Sensitivity analysis on the effect of battery weight on electrification potential

Cabukoglu et al. [21] argued that volume and especially weight of batteries are a major constraint to electrification when they restrict the battery capacity. However, it can be argued that electric trucks can be

designed to accommodate, in terms of volume, the necessary battery capacity, as can be seen from the range of battery capacities available for many electric trucks presented in Table 1. Hence, battery volume is not considered as an obstacle. Weight, on the other hand, is an obstacle because battery weight limits the payload due to gross vehicle weight (GVW) restrictions. Fig. 3 presents the electrification potential as % of tkm in the scenarios if a 5% or unlimited GVW increase is allowed. The potential increases significantly in both countries, but in Finland a 5% increase in GVW is enough to almost provide full electrification whereas in Switzerland it would require 10% increase in GVW to gain full electrification potential. This difference is likely to be because of the difference in the maximum GVW of semitrailers between the countries. In Switzerland the limit is 40t but in Finland it is 44t or 53t, depending on the number of axles. Hence, it is more common to load a semitrailer close to maximum weight in Switzerland than in Finland. Furthermore, semitrailers are much more important in Switzerland than in Finland as 42% of tkm are carried by semitrailers in Switzerland but only 14% in Finland.

However, the overall effect of allowing an increase in GVW is higher in Finland than in Switzerland as the amount of tkm that could be electrified would increase by 41–54% in Finland, compared to 24–45% in Switzerland, if unlimited GVW increase would be allowed.

4.4. Electrification potential by truck type and on-road recharging time

The differences between the two countries are further highlighted when analyzing the electrification potential by truck type with various on-road recharging times. As seen from Fig. 4, the electrification potential of medium duty truck reaches 50% of tkm in Switzerland in the current technology scenario while in Finland the electrification potential reaches only 38%. With rigid trucks the electrification potential is similar in both countries in working towards a full electrification scenario, but Finland has higher potential in the current technology scenario. With semitrailers Finland has lower potential in both scenarios. With articulated trucks Switzerland surprisingly has lower potential, but it should be noted that articulated trucks have a very low share of

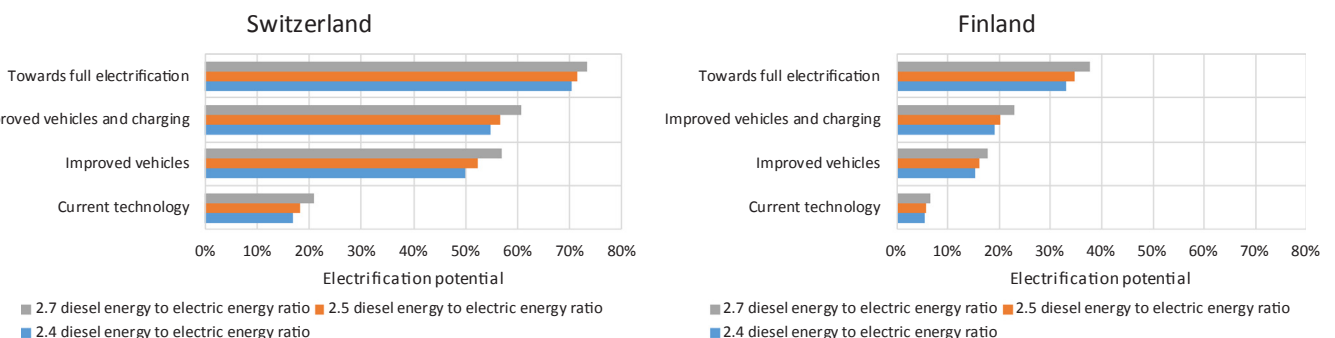


Fig. 2. Sensitivity analysis of electric truck potential as % of tkm using different diesel energy to electric energy ratios.

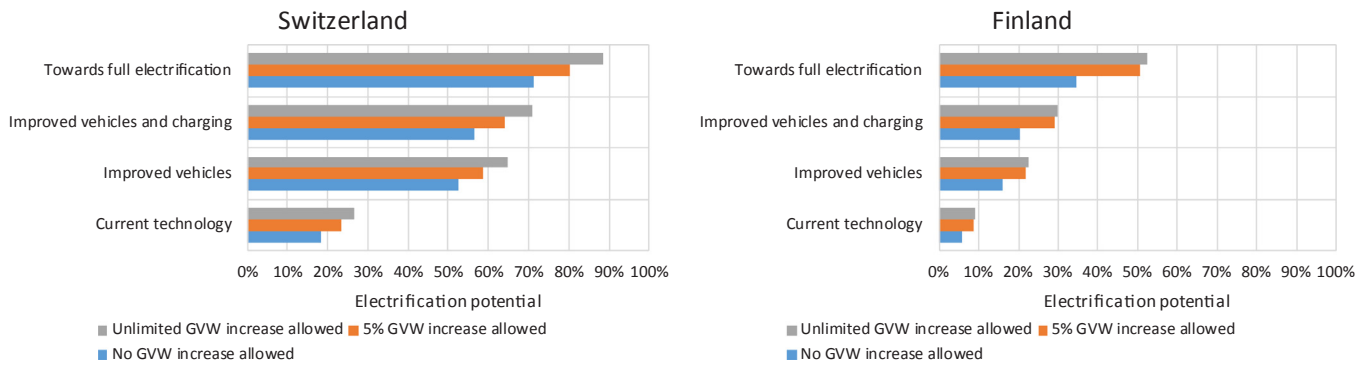


Fig. 3. The potential of electric trucks in terms of % of tkm in the scenarios allowing increase in gross vehicle weight.

total haulage in Switzerland and electrification potential is mostly limited by the GVW issue discussed above. If unlimited increase in GVW would be allowed, haulage with articulated trucks could be entirely electrified in Switzerland in the towards full electrification scenario.

Fig. 4 also highlights the difference between the countries in terms of the dominant vehicles type. In Switzerland the total electrification potential is approximately the average between semitrailers and heavy duty rigid trucks, whereas in Finland total potential follows closely the potential of articulated trucks. Another noticeable issue is the difference between countries in the development of electrification potential of semitrailers in the towards full electrification scenario. Near-full potential is achieved in Switzerland with 1-hour of on-road charging time with 400 kW chargers, but in Finland the potential grows almost linearly until 2-hour charging time. We attribute this to the longer daily distances driven in Finland. Overall, the effect of on-road recharging time is significant, as the electrification potential doubles compared to only overnight recharging for most truck types in both scenarios when charging time reaches 2 or 2.5 h. Hypothesis H3 is therefore found to be true.

If the electrification potential of the scenarios would be entirely used, the total annual electricity consumption in Finland would be from 507 GW h in current technology scenario to 1882GW h in the towards full electrification scenario and in Switzerland from 706GW h to 2066GW h, respectively. Majority of the electricity consumption would

naturally be overnight charging, but on-road charging would also have 16–40% share in Finland and 23–34% share in Switzerland (Fig. 5). Total electricity consumption in Finland was 85150GWh [35] and in Switzerland 62617GWh [36] in 2016, so the truck electricity consumption would add only 1–3% to total electricity consumption.

Electric truck charging does not have significant effect on the electricity grid on a national level, however, there might be implications to the grid on a local level if 400 kW fast chargers would be newly built as in the towards full electrification scenario.

4.5. Electrification potential by commodity

The high level of electrification potential for medium duty trucks in current technology scenario and for all types of rigid trucks in the towards full electrification scenario suggest that there might be some types of commodities in which high level of electrification could be achieved relatively quickly with current technology. The relative importance commodities, in terms of each commodity’s share of total haulage in tkm, is quite similar between the countries, with a few notable exemptions. Agricultural products and forestry as well as wood products have a much higher share of total haulage in Finland than in Switzerland, whereas mining and quarrying as well as food products and waste have higher share in Switzerland (Fig. 6). Grouped goods has a high share in Finland and unidentifiable goods in Switzerland, which

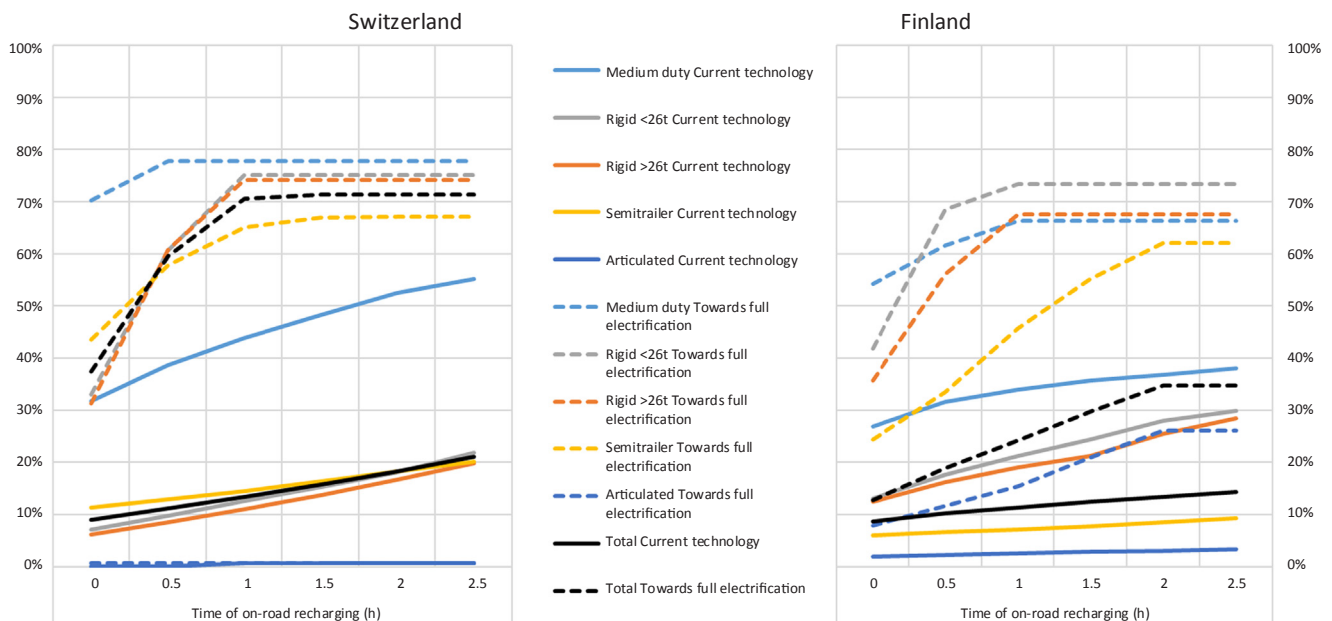


Fig. 4. Electrification potential as % of tkm by truck type and battery capacity by country. Continuous lines show current technology scenarios for different types of trucks, dotted lines show the towards full electrification scenarios.

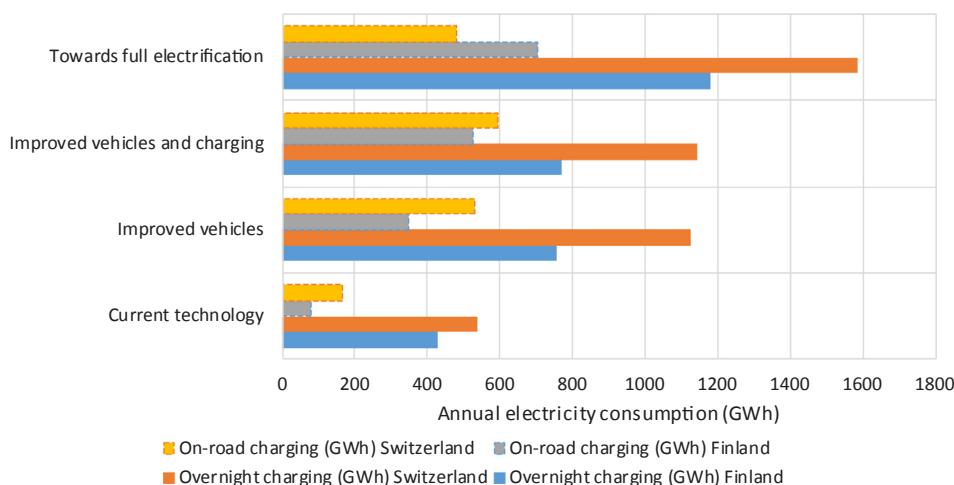


Fig. 5. Annual electricity consumption of electric trucks in the scenarios.

might be due to differences in the wording of these alternatives. They basically have the same meaning, miscellaneous goods transported at the same time.

The electrification potential, presented in Fig. 6 as % of tkm in the current technology scenario, varies significantly between commodities. In Finland the electrification potential is only 3% with agricultural, wood and chemical products whereas it reaches 30% with machinery and equipment. In Switzerland the electrification potential is about 10% with agricultural products, mining, mail and unidentified goods, while approximately 40% electrification potential is available for textiles, removals and other goods. The electrification potential at commodity level should be interpreted with caution, because there is very limited number of trips in the data for some commodities, however, the hypothesis H5 can be said with a high level of confidence to be true in both countries.

The differences between Switzerland and Finland are also clear when assessing the electrification potential by commodity types. In most commodities the electrification potential is significantly higher in Switzerland than in Finland. However, with coal, machinery and

equipment and unidentifiable goods the electrification potential is higher in Finland. The differences in average trip length and payload explain the differences in electrification potential also at commodity level. For example, the average trip length (23 km in Finland, 19 km in Switzerland) and payload (FIN 23t, CH 17t) are quite similar for mining and quarrying, and the electrification potential is therefore similar, but very different for wood products (FIN 151 km, 18t; CH 41 km, 4t).

Analyzing the electrification potential at the commodity level in the scenarios (Fig. 7) shows that there are differences in how the potential increases between scenarios. For some commodities, such as transport equipment and textiles in Switzerland and coal and mining and quarrying and textiles in Finland, the improved vehicles scenario brings the electrification potential close to the potential of towards full electrification scenario. However, for some commodities there is a more gradual increase in electrification potential from one scenario to another.

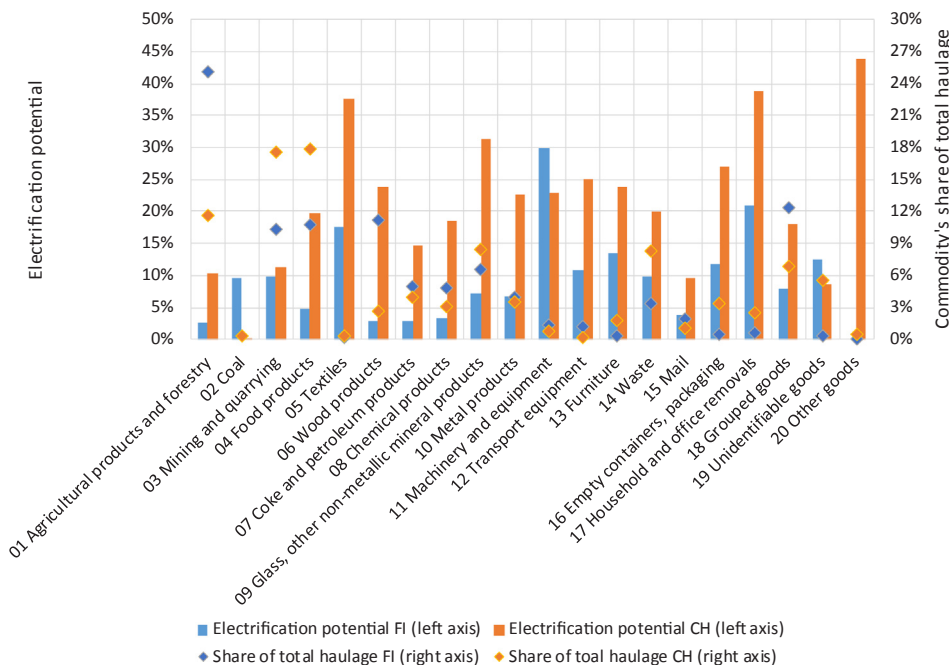


Fig. 6. Share of total haulage and electrification potential in current technology scenario by commodity in Finland and Switzerland.

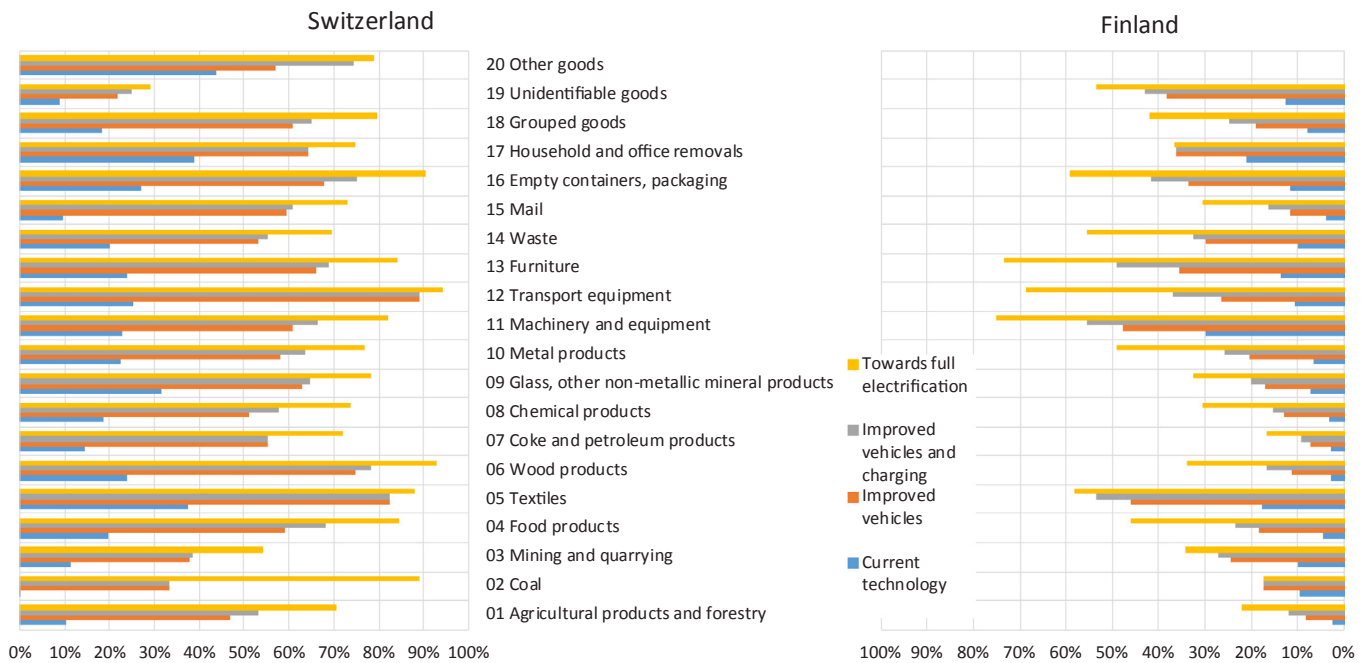


Fig. 7. Electrification potential as % of tkm by commodity in the scenarios.

4.6. Identifying market potential for certain types of electric trucks

Based on the commodity level analysis, there are certain types of commodities in which electric trucks have high potential even with current technology scenario. The commodities, e.g. textiles, glass and other non-metallic products, machinery and equipment, empty containers and packaging, which are constrained by payload volume rather than weight and are to a large extent carried using medium duty trucks seem to provide high potential for electrification (Fig. 8). However, it should be noted that medium duty trucks only represent 1% of total haulage in both countries, while still representing 4 and 5% of CO₂ emissions and 7% and 17% of mileage in Switzerland and Finland, respectively.

There are also a few other specific operations which show above-average levels of electrification potential. E.g., textiles haulage with semitrailers shows fairly high potential in both countries. Also, haulage of chemical product with > 26t rigid trucks has high electrification potential in both countries.

Assuming that each truck type would have the annual mileage calculated as the average daily mileage of each truck type in the data multiplied by 365 days, the electrification potential in the current technology scenario would be around 2000 medium duty trucks and 3200 rigid < 26t trucks in Switzerland and 3700 and 1500 trucks in Finland, respectively (Table 4). The market potential is largest with the medium duty and < 26t rigid trucks, where truck manufacturers have mostly introduced their vehicles. There is also market potential in

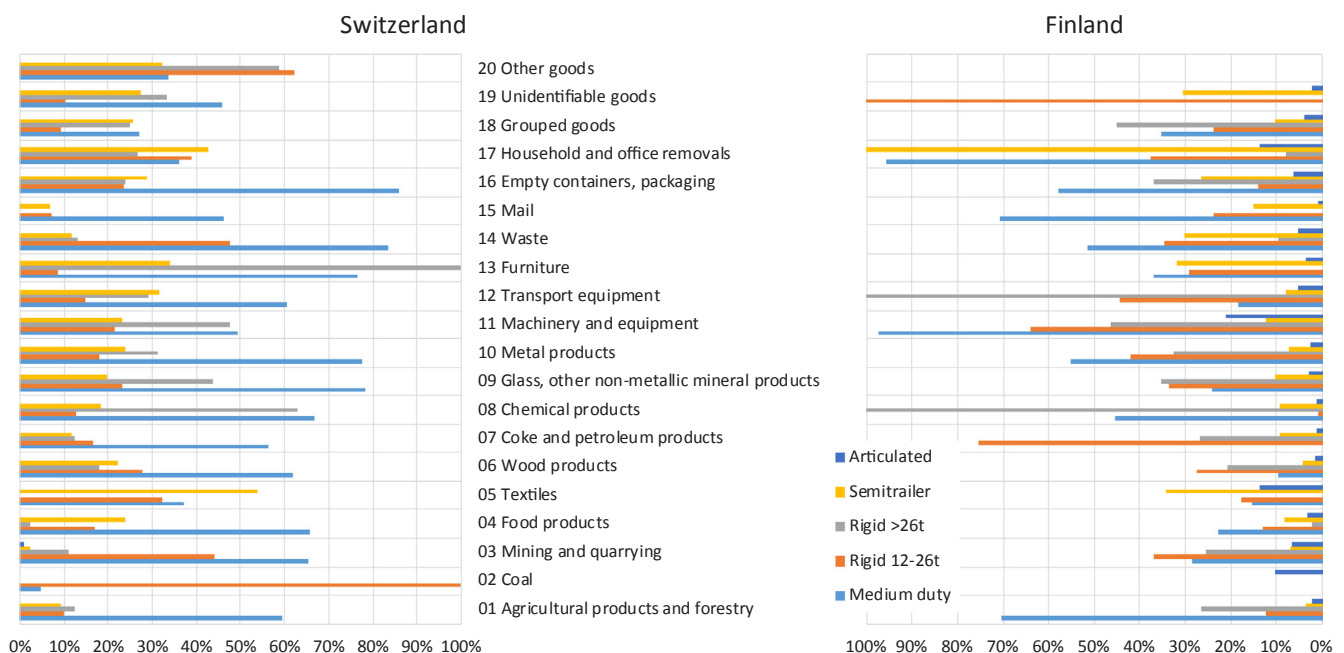


Fig. 8. Electrification potential as % of tkm by commodity and truck type in the current technology scenario.

Table 4
Market potential for electric truck in the scenarios.

		Electric truck market (trucks)				
		Annual mileage (km)	Current technology	Improved vehicles	Improved vehicles and charging	Towards full electrification
Switzerland	Medium duty	45,875	1956	2346	2346	2393
	Rigid 12–26 t	70,016	3237	7490	7490	9173
	Rigid > 26 t	66,995	1114	2835	2835	3741
	Semitrailer	102,363	1497	3514	3968	4208
	Articulated	75,842	1	6	6	6
	Total		7804	16,191	16,645	19,521
	Overnight charging power (MW)		390	810	2497	2928
Finland	Medium duty	57,546	3732	4263	4263	4414
	Rigid 12–26 t	60,385	1549	3217	3217	3624
	Rigid > 26 t	52,823	668	1268	1268	1614
	Semitrailer	140,119	282	740	947	1371
	Articulated	158,046	460	1160	1539	2487
	Total		6691	10,650	11,235	13,509
	Overnight charging power (MW)		335	532	1685	2026

larger trucks, if the battery capacities would be improved from current electric trucks.

Calculating the number of electric trucks enables us to also estimate the maximum charging power required for overnight charging, assuming that all electric trucks would be charged at the same time with the 50 or 150 kW charging power. In Switzerland the required power would be 390–2900 MW depending on the scenario, while in Finland the power would be 340–2000 MW. In Switzerland the electricity load from charging electric trucks would have been 8–57% [37] and in Finland 4–21% [38] of the average electricity load in 2016. Such additional load is not trivial and should be taken into account in planning electricity generation and grid in the future. Implications for local grid may be dramatic, especially as most of the overnight charging is likely to take place in depots which tend to cluster in certain logistics areas, e.g. around the Ring road III around Helsinki in Finland [39]. However, further analysis of implications to local grid would require detailed spatial analysis and routing of the trips in the data, which is beyond the scope of this study. It should also be noted that the 2000 MW load in Finland in the towards full electrification scenario would only cover 35% of the total haulage and majority of haulage should be covered with trucks using biodiesel or electrified roads, if freight transport should be decarbonized as the GHG reduction targets require.

5. Discussion

Six hypotheses were stated at the beginning of this study and answered in the analysis. The First hypothesis claimed that useful and comparable analysis between countries on the potential of electric trucks is possible using the data from continuous road freight transport surveys. The methodology developed in this study proved that this hypothesis is true for Switzerland and Finland. Furthermore, similar analysis should be possible in all the countries which gather data from road freight transport following the EU regulation 70/2012 [30]. This study is the first to present comparable international comparison on the electrification potential of electric trucks between two countries as previous research have focused on a single country or geographic area.

The Second hypothesis stated that electric trucks could perform majority of freight transport in Switzerland, but only a small share in Finland due to the extensive use of truck-trailer combinations with gross vehicle weight (GVW) of up to 76t for long distance transport. The first part of the hypothesis is not true, as with the current technology scenario only 18% of haulage could be performed with electric trucks, although the share increases to over 50% in the improved vehicles scenario. As for the second part of the hypothesis, the share of truck mileage, haulage and CO₂ emissions that could be covered by electric trucks is in fact low in Finland compared to Switzerland. The

differences between countries are small in the scenarios with low capacity batteries, but greatly increases in scenarios with high battery capacities. This was found out to be due to the extensive use of heavy truck-trailer combination in Finland.

Hypothesis three stated that availability of fast recharging infrastructure has a major effect on the potential of electric trucks. Overall, the effect of on-road recharging time is significant, as the electrification potential doubles compared to only overnight recharging for most truck types in both current technology scenario and towards full electrification scenario when charging time reaches 2 or 2.5 h. Hence, hypothesis H3 is found to be true. Furthermore, overnight charging using fast charging infrastructure is also a prerequisite for using electric semi-trailers and articulated trucks that have a battery capacity of 400–800 kWh depending on the scenario. Hence, this analysis confirms the importance on fast recharging (or in their case battery swapping) highlighted by Cabukoglu et al. [21], although the electrification potential with just overnight charging was shown to be larger in this analysis than in theirs. This is because the battery capacity was not as limited as it was in their study due to limiting battery capacity according to the fuel tank volume. Fast recharging of such large batteries will require careful planning of infrastructure [40].

The fourth hypothesis claimed that improvements are needed to the electric grid because of the charging needs of electric trucks. It was clearly seen that a definitive answer to this hypothesis would require spatial analysis and routing of the trips reported in the dataset used in this study. While such analysis was beyond the scope of this study, it can be said based on the market potential calculation that electric trucks are likely to have large impact on local grids near logistics centres and rest stations along major roads. Furthermore, the effect of charging batteries of electric trucks on the peak electricity load is likely to be significantly larger than the effect of electrifying trucks with electrified road systems [18,19].

Hypothesis five stated that there are major differences in the potential of electric trucks with different commodities. The study showed that this is true, as within both countries the electrification potential varies considerably between commodities, although in Finland more so than in Switzerland. Especially in the towards full electrification scenario the differences in electrification potential between commodities seem to diminish, while in Finland the differences remain. With a few commodities the electrification potential is similar in both countries, but generally there is a wide gap in electrification potential between countries at commodity level.

The sixth hypothesis said that certain electric truck types can be identified to have commercial potential with certain types of freight transport operations based. This hypothesis was found to be true as the commodities which are constrained by payload volume rather than

weight and are to large extent carried using medium duty or < 26t rigid trucks trucks seem to provide high potential for electrification even with the current technology scenario.

6. Conclusions

This study has shown that electric trucks are already a viable solution for a large share of road freight haulage with medium duty trucks. Improvements to battery capacity and recharging infrastructure may also make electric trucks a viable option for heavy duty rigid trucks and semitrailers. However, electrification of heavy articulated truck-trailer combinations through batteries seems unlikely as the potential remains at a low level even with high battery capacity. Hence, as much as 71% of Swiss road freight transport may be electrified using battery electric trucks, but due to the use of long and heavy truck-trailer combinations, Finland has very limited potential of using battery electric trucks. With the foreseeable battery technology, electrification using electrified roads seems to be the solution in Finland, or reducing emissions through substituting biofuels for diesel. Policymakers may use the results of this study as an overview on the greenhouse gas mitigation potential of battery electric trucks.

Electrification potential may be increased through certain policy measures, such as exempting battery electric trucks from the maximum gross vehicle weight limits, or allowing a 5% increase in gross vehicle weight, which would already enable most of the electrification potential. In addition, development of recharging infrastructure is a prerequisite for electrification of trucks. The policy measures used to promote passenger car charging could be used as a benchmark to promote truck charging. Future research should also include comparison between the alternate ways of electrifying road freight transport, i.e. batteries with charging, batteries with battery swapping and electrified road systems.

Electrification of trucks will have a significant effect on the electricity grid, especially near rest stations and logistics centres, due to high required charging power. There might be dozens of trucks charging simultaneously at the busiest charging stations, which would require charging power of tens of megawatts. Hence, routing-based analysis of the potential of electric trucks would be needed to map the most important charging stations. In order to further analyze the effects on the electricity grid, a spatial analysis by routing the trips reported in the datasets used in this study could be carried out.

This study presented the first analysis on the potential of battery electric trucks on the commodity-level. The results may help fleet managers to make informed investment decisions on the types of freight transport operations most suitable for electrification. Further research using data from several years and routing the operations would enable more detailed analysis on commodity-level.

Further research including international comparison of additional countries could be carried out using the methodology developed in this study. Similar data as used in this study should be available in the European countries and the detailed description of research process of this study can be used as a guideline for future analyses.

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