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Metal requirements for road-based electromobility transitions in Sweden

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ABSTRACT

This research investigated the metal requirements for electrifying Swedish cars and heavy-duty trucks and refueling infrastructure. We assessed vehicle and infrastructure metal use given four cornerstone scenarios: battery electric vehicles and chargers, conductive and inductive electric road systems, and fuel-cell vehicles, besides an internal combustion engine scenario. Twenty-seven metals were evaluated. To our knowledge, this study presents a first attempt to develop a detailed inventory of prevailing and prospective charging infrastructures. Our study estimated total metal requirement at 7400–9600 kt and infrastructure share at 6%–25% (200–2400 kt). Infrastructure requires about 15% of gold, 30%–40% of silver and copper, and 40%–60% of molybdenum. Results revealed that the following metal flows contribute the most to long-term resource scarcities: rhodium in fossil-fueled vehicles; gold in electric vehicles; palladium and gold in conductive and copper and palladium in inductive electric road systems; as well as platinum in fuel cells.

1. Introduction

Current road transport network is heavily reliant on fossil fuels and responsible for 23% of the European Union's (EU) greenhouse gas (GHG) emissions (EEA, 2020; IEA, 2020). To fulfill its Paris Agreement obligations (UNFCC, 2021) and transform into a climate-neutral economy (EC, 2018), at least 60% (EAFO, 2017) and potentially up to 94% (TandE, 2018) of the EU's total GHG reduction by 2050 must come from the road transport sector. Large-scale adoption of battery electric (BEVs) and hydrogen fuel cell electric vehicles (FCVs) is therefore seen as central to road transport decarbonization (Mock, 2021).

Electromobility transitions pose new sustainability challenges, such as the need for charging with low carbon electricity and the likelihood of environmental "burden-shifting" from the tailpipe to raw material acquisition (Baars et al., 2020). Electrified powertrains (BEVs and FCVs) introduce new material flows, hitherto mild or absent in the supply chain of their fossil-fueled counterparts (de Koning et al., 2018; Hache et al., 2019). These are attributable to traction battery, permanent magnet synchronous motor (PMSM), and additional power electronics for charging and traction inverter. Previous literature covers lithium, cobalt, manganese, and nickel in traction lithium-ion batteries (LIB) (Helbig et al., 2018); gold, silver, and palladium for power electronics (EC, 2017a) and onboard electronic subsystems (Andersson et al., 2019); platinum in fuel cells (Hao, Han et al., 2019); and the rare earth elements (REE) neodymium and dysprosium in the PMSM (Alves Dias et al., 2020). Shifts in metal demand might extend to base metals as well. For example, a midsize BEV could contain 50% more aluminum (DuckerFrontier, 2019; Løvik, 2021) than a comparable internal combustion engine (ICE) vehicle.

1.1. Research gaps

First, there is the lack of a framework for a harmonized comparison of different vehicles for electromobility transitions. Second, metal requirements in previous literature are mostly passenger-car centric and heavy-duty electric trucks are scarcely addressed (Hao, H. et al., 2019). Third, emission benefits of BEVs and FCVs cited in regulatory (EAFO, 2017) and stakeholder assessments (ACEA, 2021a) are predicated upon the co-existence of essential infrastructure, such as chargers and hydrogen refueling stations (HRS), which are ignored or limited to steel alloys, copper, and aluminum in prior works for stationary (Bekel and Pauliuk, 2019; Lucas, 2012; Lucas et al., 2013; Mendoza et al., 2016; Nansai, 2001) and dynamic charging electric road system (ERS) (Balieu et al., 2019; Bi, 2018; Chen, 2020), and platinum for proton-exchange membrane (PEM) electrolyzer (Rasmussen, 2019; Reverdiau et al., 2021). A detailed evaluation of high-power stationary chargers is absent and the front-end transformer-power electronics interface (PEI) powering the HRS (NEL, 2021) is also often overlooked. About half-a-dozen

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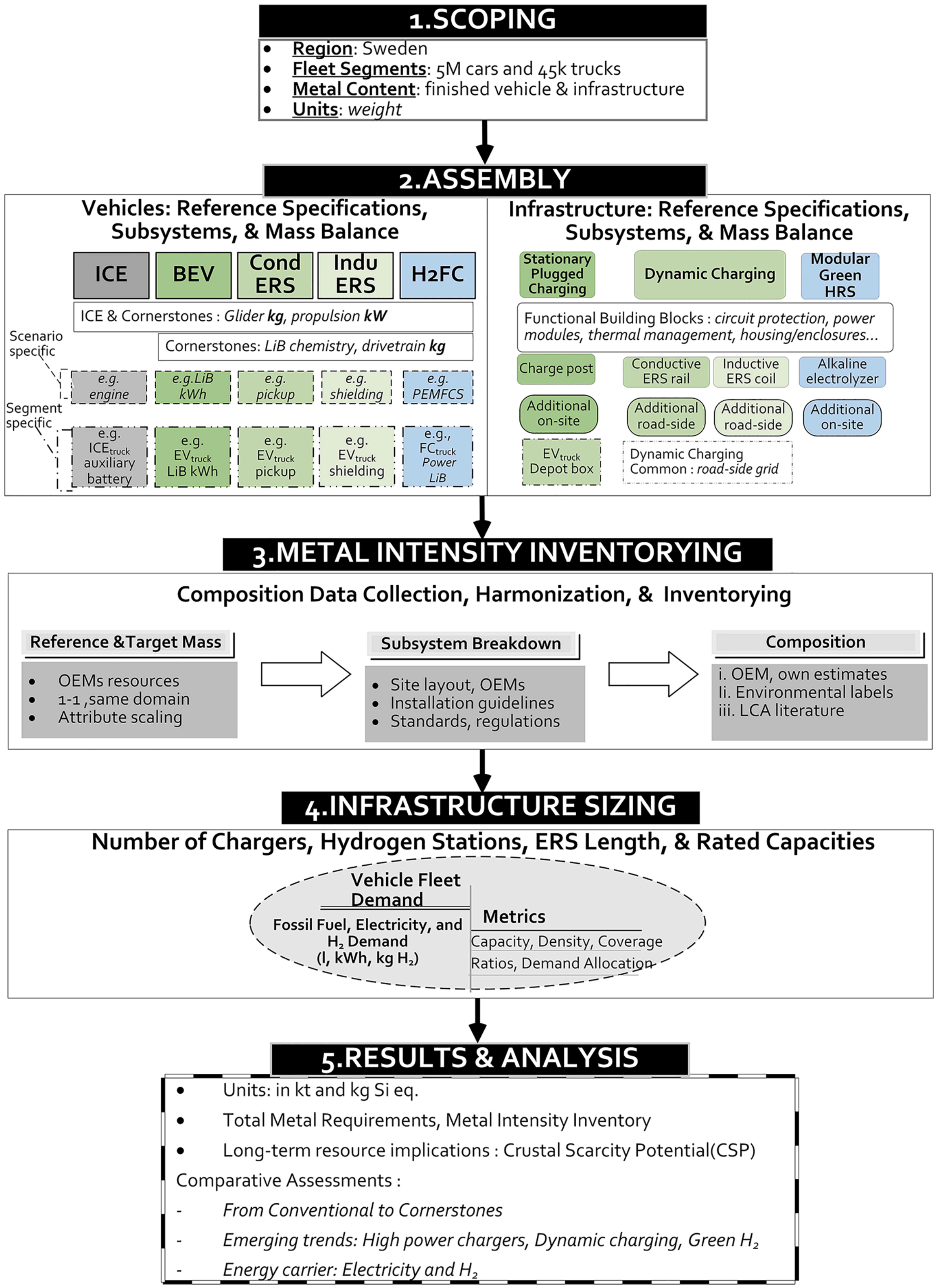

Fig. 1. Overall framework showing the five main steps of this study. Note: Common and specific scenario car and truck subsystems, and functional building blocks are particular to this study and not exhaustive. Conventional petrol/diesel refilling station is not shown for clarity.

critical raw materials (EC, 2020)—antimony, magnesium, platinum-group metals (PGMs), silicon, tantalum, and titanium—can be traced to just the PEI. Developing a methodology and a detailed metal intensity inventory to address these research gaps forms the sum and substance of this work.

1.2. Research questions

This study evaluates the total metal requirements and potential resource impacts of electrifying the Swedish light-duty passenger car and long-haul heavy-duty truck fleets. We use the "cornerstone

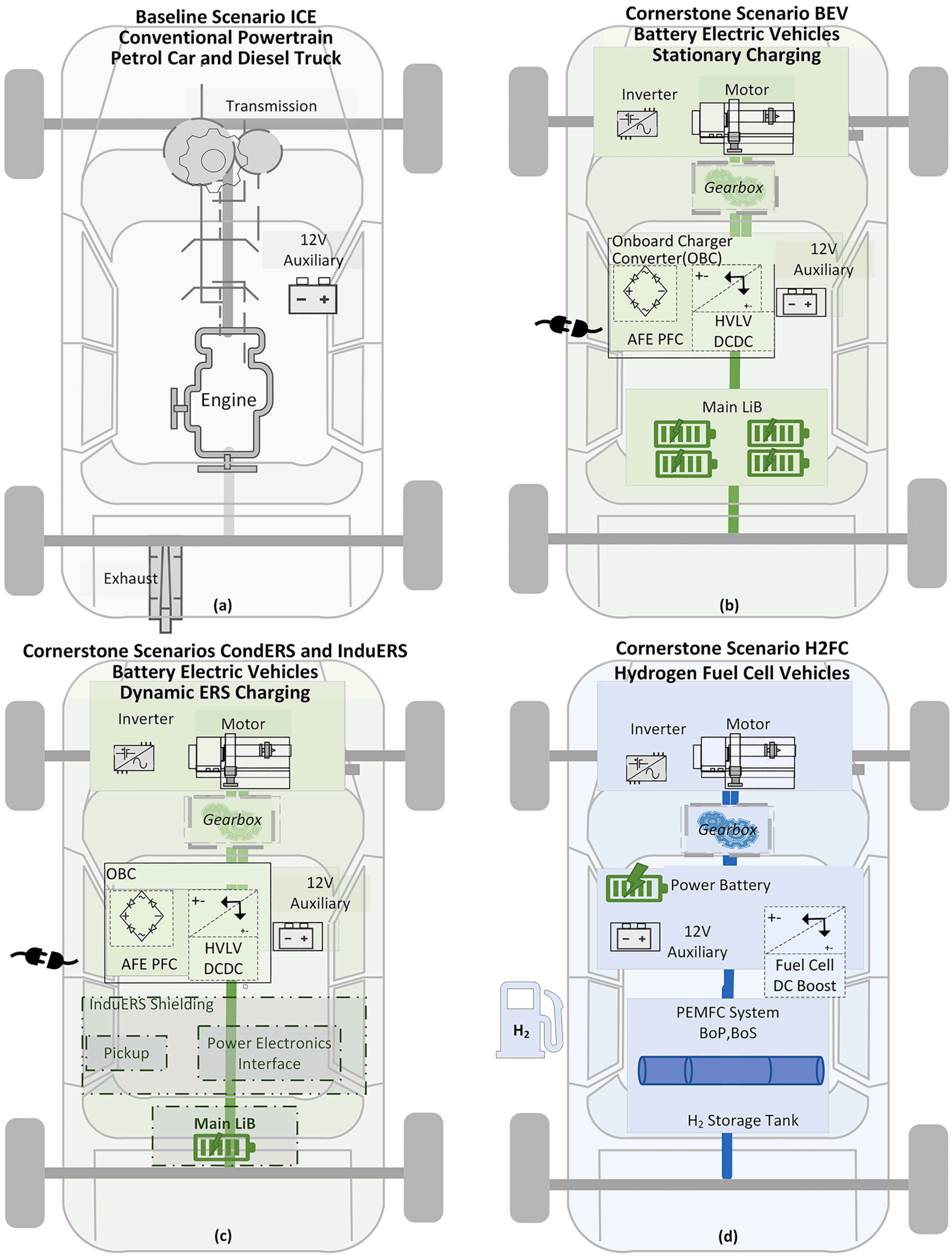

Fig. 2. Vehicle powertrain architecture and subsystems considered in this study. Note: Generic full-size sedan and long-haul truck glider common in all scenarios. Gearbox only for trucks. Pickup and the power electronics common to both CondERS and InduERS scenarios, and the latter includes additional Electromagnetic Interference (EMI) shielding. BoP/BoS—Balance of Plant/Stack; PEMFC—Proton Exchange Membrane Fuel Cell; OBC—Onboard Charger Converter includes AFE PFC—Active Front End Power Factor Correction and auxiliary High/Low Voltage DC to DC converter. Individual subsystem masses, specifications, parametric assumptions, and metal composition inventory for vehicles detailed in the supplemental information section S1.

scenarios" (Pesonen, 2000) approach and capture the demand for a range of metals from both vehicles and their recharging/refueling infrastructure. In the four considered cornerstone scenarios, 100% of all road-based transportation is electrified using the following technologies:

- BEV: Battery electric fleet (EV_{cars}, EV_{trucks}) with stationary and plugged-in charging infrastructure
- CondERS: Battery electric fleet with dynamic charging conductive ERS infrastructure

- InduERS: Battery electric fleet with dynamic charging contactless inductive ERS infrastructure
- H2FC: Hydrogen fuel cell electric fleet (FC_{cars}, FC_{trucks}) and modular infrastructure for green hydrogen

We consider a baseline scenario with only ICE vehicles, i.e., a fossil-fueled fleet and retail service station (ICE_{cars}, ICE_{trucks}). Our four research questions are:

(i) What are the total metal requirements in these cornerstone scenarios?
(ii) Which metals contribute decisively to variations in metal requirements across scenarios?
(iii) What is the relative importance of infrastructure's metal requirement?
(iv) What do these metal flows foretell about long-term resource challenges?

2. Methods and materials

The selected cornerstone scenarios are essentially *what-if* scenarios (Börjeson et al., 2006) answering what will happen to metal requirements in each case, if all road-based transportation in Sweden would be operated exclusively with one of these four respective technologies. These absolute scenarios are selected for illustrative purposes and are theoretically achievable but not necessarily likely to become realized. A broader objective of this study is to advance our knowledge of how different technical pathways for road transport decarbonization—powertrain options, supporting infrastructure, and energy supply, link to metal resource requirements, rather than predicting the trajectory of different pathways given a set of predetermined technology options. Hence, temporal aspects of attaining any one of the cornerstone scenarios, such as technological maturity, deployment timeline, diffusion rates, market share, and future performance improvements are not considered. The methodology does not factor endogenous inter- and intra-technology parametric dependencies. We limit our design space to the subset of factors central to our research questions—mass balances, material composition, powertrain architectures, and infrastructure choices.

Fig. 1 shows the five-step framework of our study. The *scoping* includes selecting the region of the study, vehicle fleet segments, baseline and future scenario powertrains and infrastructure, and material coverage. In line with the cornerstone scenario approach, we assume that the exemplar specifications characterize the entire fleet, albeit in a stylized manner. Essential subsystems following these specifications and their equivalent masses are combined to parameterize the complete vehicle and infrastructure in the *assembly* step. Material composition data is gathered and harmonized in the *inventorying* step. The *infrastructure sizing* step estimates the infrastructure necessary to meet the vehicle fleet's energy demand. Travel demand (vehicle-km) and fuel efficiency (L/100 km, kWh/km, kg H_2/km) are scenario independent and exogenous parameters. Finally, in *the results and analysis* step, we appraise metal requirement variations between cornerstone scenarios. We indicate possible supply constraints if these scenarios were actualized based on 2019–2021 global production data. Using a midpoint indicator from life cycle assessments, the Crustal Scarcity Potential (CSP) expressed as kg Si equivalents (kg Si Eq.) per kg metal (Arvidsson et al., 2020), we compare and contrast the long-term resource implications of cornerstone scenarios with the summed CSP of the baseline ICE scenario serving as the basis for normalizing the other scenarios' CSP.

This study covers Sweden's 5 million passenger cars and 45,000 long-haul trucks, which together account for ~90% of the entire stock of cars, buses, light lorries, heavy lorries, and buses (Trafikanalys, 2021a). The baseline scenario vehicle fleet contains only ICE petrol cars and diesel trucks. We limit cornerstone scenario vehicle technology mix to battery electric or fuel cell electric cars and trucks. Corresponding infrastructure options are petrol/diesel refilling station, stationary and plugged chargers, conductive and contactless dynamic ERS chargers, and modular green HRS. Metal requirements denote the metal content of the finished vehicle and infrastructure, including their constituent subsystems, components, or parts. The unit of analysis is metal mass. We estimated the demand for twenty-seven metals and the complete inventory is provided in the Supplemental Information (SI) file sections S1-S5. Results in Section 3 cover: base metals—aluminum, iron, and copper; alloying elements—chromium, manganese, magnesium, molybdenum, nickel, niobium, silicon, tantalum, titanium, and vanadium; drivetrain electrification related—dysprosium, neodymium, lithium, and cobalt; precious metals—gold, silver, and platinum group metals (PGMs)—palladium, platinum, and rhodium; and other metals—antimony, boron, lead, tin, and zinc. For completeness and simplicity, though a metalloid, antimony and boron are grouped with the other metals.

2.1. Vehicle subsystems modeling

The vehicle subsystems are illustrated in Fig. 2, showing the architectural differentiation between the ICE and other scenarios. Key design specifications of the glider and the best represented propulsion power are fixed. A 1200 kg glider fit for a full-size sedan with 120 kW/160 hp propulsion power is selected as the representative passenger car. A 40 t truck-trailer combination equipped with a 360 kW diesel engine characterizes the truck fleet. Auxiliary batteries in the ICE scenario are of lead-acid (PbA) type, whereas lithium-ion batteries (LIBs) of NMC622 type are included in the cornerstone scenarios for all other battery modeling (traction energy, power, auxiliary). The e-powertrain comprises LIBs, traction inverter and PMSM rated at 120 kW for cars (EV_{car}, FC_{car}) and 360 kW for trucks (EV_{truck}, FC_{truck}). The LIB is downsized by a factor of four in the CondERS and InduERS compared to the BEV scenario for both cars and trucks.

Essential subsystems for dynamic charging capability includes the pickup or current collector, PEI, and electromagnetic interference shielding (only for InduERS). The H2FC scenario (FC_{car}, FC_{truck}) covers the PEMFC stack, hydrogen tank, and power LIB. Auxiliary 12 V and onboard PEI (as onboard charger-converter in the BEV, CondERS, and InduERS scenarios, and FC boost converter in the H2FC scenario) are subsystems common across scenarios. Certain truck subsystems (e.g., InduERS pickup) are mass scaled variants of cars, and in other instances, primary original equipment manufacturer (OEM) sources are used for mass appropriation (e.g., the truck gearbox). Exemplar car and truck technical specifications, mass balances, and fleet attributes are presented in Table 1.

2.2. Infrastructure assembly

We selected cornerstone scenario infrastructures to reflect their current (SE, 2021a; Siemens, 2021a) and expected performance targets (H_2ME, 2020; Virta, 2021). Subsystems representing different sites (e.g., charging station), service providing equipment and its immediate proximity (e.g., charging post and power cabinet), upstream interface (e.g., grid connection), and other intermediaries essential for operational and compliance purposes, were determined from illustrative layouts (Black, 2017; NEL, 2021), standardized protocols (IEC, 2020; SIS, 2020), and OEM manuals (ABB, 2020b). Reference designs (TI, 2019), installation rules and procedures (IEC, 2018), and parts list (ABB, 2020a; Maximator, 2021a,b), are next collated to parse these subsystems into configurable building blocks. These are further organized by their functional purpose and associated with their composition data from the best represented Environmental Product Declaration (EPD) or Product Environmental Profile (PEP). Fig. 3 provides a schematic overview of the cornerstone infrastructures.

The BEV scenario considers seven stationary and plugged chargers Four EV_{car} chargers:

Table 1
Technical specifications, mass balances, and modeling assumptions for (a) passenger cars and (b) long-haul trucks. Note: Individual subsystem masses, specifications, parametric assumptions, and metal composition inventories are presented in Section S1 of the supplemental information.

(a) PASSENGER CAR- VEHICLE SUBSYSTEMS

Subsystems	Key specifications	ICE Petrol	BEV	CondERS	InduERS	H2FC	References
Full size sedan glider	1500-1600 kg kerb	1200		1200			Løvik (2021). Glider and engine rating based on 2015-2020 average Swedish car put on market (Diaz et al., 2021)
Engine (115 kg), exhaust (60 kg)	1.5-2 l, 120 kW, ~7 kg/kW	175					Comparable T3 platform B3154T7/B3154T2 engine (Volvo, 2020)
Transmission	6-speed	140					Major OEM supplier of 6-speed/250 Nm (Aisin, 2020) Automated manual transmission (AMT), composition from Ortego et al. (2018)
Auxiliary 12/24 V battery	PbA (ICE), rest NMC 622	20		4			12 V 70 Ah, lead-acid (PbA) Varta Silver Dynamic AGM (Varta, 2021b), 50% Pb (Banner, 2021) for conventional powertrains. Auxiliary LIB weight from Ohmmu (2021)
Traction LIB	BEV 60/15 kWh ERS		440	110			LIB NMC622 composition from Dai et al. (2019); Nelson (2018). For all NMC622, BMS 2.5 wt % of pack and BoM from (NXP, 2020). Pack weight from Cleantechnica (2018); UBS (2018)
Motor (53 kg) inverter (11 kg)	1 × 120 kW			64			Nordelöf et al. (2018); Nordelöf et al. (2019)
Integrated charger-converter	22 kW OBC 400/12-24 V,1.5 kW			17			Power electronic interface composition in SI section S1. Specifications and weights from Ovartech (2021).
Dynamic ERS vehicle assembly (VA)	Pickup, PEI, and shielding			20	100		ERS detailed in Tables S5-S6. Weights based on Swedish ERS pilots (Olsson, 2013a, O. b), OEM catalog (IPT Primove, 2021), and prototype (Bosshard, 2015)
PEMFCS	120 kW stack, 0.3 g/kW Pt					175	1 × 120 kW stack, 83 kg PEMFCS, and 92 kg vehicle balance-of-plant (BoP) (Miotti et al., 2015; Notter et al., 2015). Vehicle BoP includes air, water, heat, fuel management, control electronics, wiring, and other auxiliaries. Control electronics components from James et al. (2021); Thompson et al. (2018). Pt loading for cars 0.2-0.4 g/kW (Deloitte, 2020; Kongkanand, 2019; Reverdiau et al., 2021)
H_2 Tank	5.6 kg, 5.3 wt %, Type-IV					106	650 km range (Toyota, 2021a)
FC Boost converter	13 l volume, 650 V output					25	Toyota (2021b)
Power LIB	310 V, 4 Ah, 1.25 kWh					45	
Vehicle weight	Assembled	1535	1725	1415	1495	1620	
Metal weight	In scope	1525	1545	1358	1437	1400	
Metal fraction (MF) %		99%	89%	96%	96%	86%	
Car fleet size				5,000,000			Trafikanalys (2021b)
Driving distances				30 km/day, 11000 km/year			28-32 km (Hiselius and Rosqvist, 2018; Liu et al., 2015)
Fuel efficiency/100 km		5 l		23 kWh		0.84 kg	Fleet average estimates (5 l/100 km) (Diaz et al., 2021; Meszler, 2018); 0.15-0.31 kWh/km (EVDatabase, 2020); 0.008-0.0089 kg H_2/km at combined speeds (Toyota, 2021a)
Total annual demand		2.7 Bl		12.65 TWh		462 kt	

(b) LONG HAUL TRUCKS - VEHICLE SUBSYSTEMS

Subsystems	**Key specifications**	**ICE Diesel**	**BEV**	**CondERS**	**InduERS**	**H2FC**	**References**
Long-haul tractor-trailer glider	40 t GVW, 25 t payload	5100		5100			Glider mass and composition OEM confidential. Represents the 5-LH subgroup which accounts for ~60% of all registered trucks regulated under the emission standards (Ragon and Rodríguez, 2021).
Engine (1100 kg) exhaust (130 kg)	13-14 l, 360 kW, ~3 kg/kW	1230					Engine mass adapted from Volvo's FH series long-haul truck D13K500 engine and exhaust (Volvo, 2017, 2021).
Transmission	12-speed ICE, 4-speed rest	370		200			12-speed AMT gearbox AT2412F/AT2612F (278 kg) plus ~100 kg clutch (Volvo, 2016a,b,c). Composition from Wolff et al. (2020). Cornerstone scenarios gearbox from Eaton (2021), 65% 18CrNiMo6-7 and rest 35% aluminium (Rodrigues, 2018).
Auxiliary twin 24 V battery	PbA in ICE, rest LIB	100		35			Auxiliary battery twin 24V 180-225Ah rating PbA (Scania, 2021a,b). Varta Promotive EFB(Varta, 2021a), 50% Pb (Banner, 2021). Equivalent rated LIB weighs 35 kg.
Traction LIB	BEV 600/150 kWh ERS		4000	1000			4 t LIB (Hall, 2019; TandE, 2020). 600 kWh LIB weighs 3 t plus 30% for module and pack assembly. Downsizing LIB and other ERS subsystems detailed in Tables S5-S6.
Motor (155 kg) inverter (30 kg)	2 × 180 kW			185			Nordelöf et al. (2018); Nordelöf et al. (2019)
Integrated onboard charger-converter	44 kW OBC 750/12-48 V 3 kW			60			Mass scaled from cars
Dynamic ERS vehicle assembly (VA)	PEI, pickup, and shielding			100	600		CondERS and InduERS VA of cars mass-scaled by 5x and 6x for trucks, respectively.
PEMFCS	3 × 120 kW, 0.75 g/kW Pt					525	3 × 120 kW stack scaled from cars. Platinum loading for trucks 2-4 x of that of cars (Cullen et al., 2021; James et al., 2018), 3 x selected
H_2 Tank	40 kg, 5.3 by wt%					765	Average of N and M series EC79/HGV2 customized for Scania long-haul trucks mass-scaled for 40 kg (Hexagon, 2021)
FC Boost converter	3, 1 x per stack					75	3 x, 1 per stack, mass scaled from cars
Power LIB						135	
Vehicle weight	Assembled	6800	9580	6700	7180	7020	
Metal weight	In scope	4884	6370	4629	5100	4356	
Metal fraction (MF) %		72%	66%	69%	71%	62%	
Truck fleet size				45,000			Trafikanalys (2021b). ~84500 trucks (> 3.5 t) in-use, 53% of which are long-hauls (Maria et al., 2021).
Driving distances				450 km/day, 100000 km/year			Trafikverket (2021a, 2021c)
Fuel efficiency/100 km		33 l		125 kWh		8 kg	Fleet average estimates (33 l/100km). (Diaz et al., 2021; Meszler, 2018); 1.0-1.5 kWh/km (Nashed, 2019; Wilkins, 2020). 1.25 kWh/km (125 kWh/100 km selected)
Total annual demand		4.2 Bl		18 TWh		822 kt	

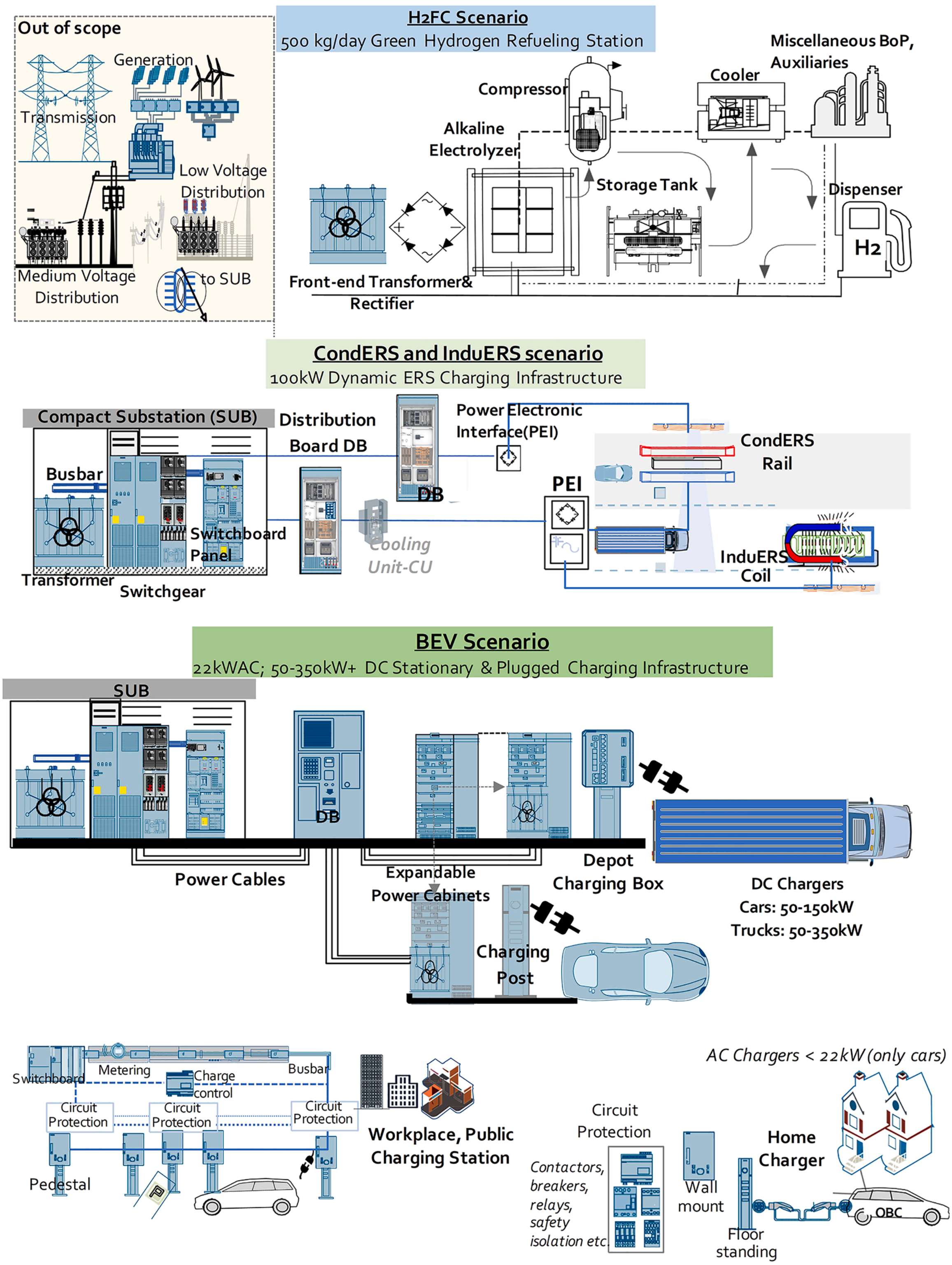

Fig. 3. Schematic representation of cornerstone scenario infrastructures. Note: Individual subsystem masses, specifications, parametric assumptions, required infrastructure, and metal composition inventory detailed in the supplemental information Sections S2–S6. Technical symbol libraries adapted from (Siemens, 2021b).

i Floor-standing 3–11 kW AC home charger
ii Workplace, or public charging station with five 22 kW AC chargers and 2 plugs per charger
iii A 50 kW DC fast charger (DC50)
iv High Power 150 kW DC charger (HPC150)

Three EV_{truck} chargers:

i Depot charger rated 50 kW (Depot50)
ii High power destination charger rated 150 kW (DEST150)
iii Ultra-fast highway corridor 350 kW charger (UFCCORR350)

Home charger metal requirements cover the charge dispenser, a charging cable, circuit protection components for compliance, and a charging controller (IEC, 2018; SE, 2021b). Public charging station metal requirements include busbars, switchboard, metering, charging station load management, and necessary circuit protection for charging multiple vehicles, besides the charge post and charging cable. Facilitating high-power charging entails local distribution network retrofitting and or reinforcing (WEF, 2021). Power distribution boards (ABB, 2021), power cabinets (Siemens, 2020), and compact substation (SUB) (ABB, 2018) containing grid interfacing switchgear, transformer, switching board, and busbars are prominent real-world use cases. Metal intensity inventory incorporates these practicalities to the best extent possible.

CondERS and InduERS design is based on ERS OEMs (Elways, 2021; IPT Primove, 2021), ERS pilots (Olsson, 2013a, b), and reports (Trafikverket, 2020). Metals needed to install CondERS and InduERS dynamic chargers encloses the entire ground assembly inclusive of cables and key grid-interfacing subsystems vital for "charging-while-driving": SUB, distribution board (DB) with power supply, monitoring, switching, and circuit protection devices, and CondERS rail/InduERS coil. Both dynamic charging infrastructures are rated 1 MW/e-km (ERS electrified km) charging up to 100 kW along 100 m sections.

In the H2FC scenario, HRS is represented by a modular 500 kg green H_2/day produced onsite via renewable alkaline electrolysis (AEL), including the dispenser. We chose this as it is affirmed in Sweden's National Climate Plans (FCH JU, 2020) and the EU's 2030 H_2 research agenda (H2EU, 2020). The LCI data from Burkhardt et al. (2016) is expanded by adding the metal content of front-end transformer-rectifier key for operating the HRS (NEL, 2021).

The BEV scenario EV_{car} fleet needs 4.5 million charge points — 4 million private overnight home chargers assuming 80% of users have access (Sunnerstedt et al., 2018); 415,000 public charging points (83, 000 public/workplace stations); 50,000 DC50; and 27,000 HPC150 chargers. The BEV scenario EV_{truck} fleet requires are 45,000 Depot50, 18,000 DEST150, and 9000 UFCCORR350 chargers. Vehicle to charger ratios are calculated from current installations (EAFO, 2021; NOBIL, 2021), regulatory guidelines (EC, 2021), stakeholder recommendations (ACEA, 2021b; Trafikverket, 2021a, b), and literature (Funke, 2019; IEA, 2018; Plötz et al., 2021). CondERS and InduERS scenario infrastructure includes 7200 e-km dynamic charging capable ERS (SI section S4) and BEV scenario private chargers per the current ERS techno-economic feasibility and pilot studies in Germany and Sweden (Trafikverket, 2020). Green HRS in the H2FC scenario reflects EC recommendations, pilot data (H_2ME, 2020), and foresight exercises (DeloitteandBallard, 2020; H2EU, 2020). The number of HRS needed (~2800) echoes the existing number of retail petrol/diesel service stations (Statista, 2021).

3. Results

We structured our results and analysis as follows. The broad contours of metal requirements in the baseline ICE and cornerstone scenarios are first established. Second, metal demand differences and the relative contribution from vehicles and infrastructure are then investigated. Third, we compare and contrast the near and long-term impacts of the total metal requirements using the average 2019–2021 global production data and the CSPs. Lastly, we summarize the results of the sensitivity analysis.

Fig. 4a depicts the total metal requirement by vehicle and infrastructure in each scenario. Metal demand for H2FC is the highest (9600 kt), followed by BEV (~8700 kt), ICE (8100 kt), InduERS (7900 kt), and CondERS (7400 kt). Vehicle fleets account for 97% of the total metal demand in the ICE (7800 kt), 93% in the BEV (8000 kt), CondERS (7000 kt), and InduERS (7400 kt), and 75% in the H2FC (7200 kt) scenarios. Stationary and plugged BEV charging infrastructures require ~7% (650 kt) of total BEV metals, marginally higher than the respective shares (6%) of CondERS (415 kt) and InduERS (480 kt) dynamic charging infrastructures. By virtue of fleet size difference (5000,000 cars and 45,000 trucks), trucks and their infrastructure combined account for 3–6% (240–540 kt) of total metal demand across all scenarios. It is worth emphasizing that truck infrastructure plays a comparable or even slightly bigger role in relation to the truck fleet by accounting for 43%–53% of the combined vehicle and infrastructure metal requirements for trucks.

The infrastructure share of total metals is highest in H2FC (2400 kt, 25% share) and lowest for the baseline ICE (220 kt, 3% share). Fig. 4b shows the shift in metal use from ICE to cornerstone scenarios (Δ metal demand in kt). Compared to ICE, BEV and H2FC metal requirements increase by 600 kt and 1500 kt, whereas it reduces by 640 kt and 160 kt in the CondERS and InduERS scenarios. Below, we probe the specifics of these metal flows required for replacing 1600 kt ICE engine and powertrain components (1200 kt iron, 220 kt aluminum, 70 kt magnesium, and 60 kt chromium), as well as its iron and ferro-alloy dominant infrastructure.

3.1. Differences between ice and cornerstone scenarios

3.1.1. Iron, aluminum, and copper

Iron demand is highest in the H2FC scenario (~7200 kt), about 10% more than the ICE scenario (~6600 kt). The BEV, CondERS, and InduERS scenarios' iron requirements are comparable (5500–5600 kt). Total demand for iron reduces by 1000 kt (15%) relative to ICE in all cornerstone scenarios, except in H2FC, where it increases by 600 kt. While the vehicle fleet's iron demand decreases by 900–1050 kt, infrastructure iron requirements increases by 40 kt in CondERS and InduERS, 200 kt in BEV, and 1400 kt in H2FC scenarios.

Aluminum requirement is highest in the BEV (1600 kt, followed by the InduERS (~1400 kt), CondERS (~1150 kt), and lowest in the ICE scenario (~1000 kt). The LIB housing requires 150–600 kt depending on battery size. Motor casings, truck gearbox, and onboard PEI heat sinks and enclosure together need 170 kt, and 770 kt aluminum is in the common glider. In the CondERS and InduERS scenarios, dynamic charging ERS vehicle assembly requires 17 kt and 250 kt aluminum, respectively. The EMI shield is one of the main reasons for the divergence in aluminum demand between an InduERS (1370 kt) and CondERS (1160 kt) scenario. Approximately 90 kt aluminum in the H2FC scenario is for the PEMFC stack BoP. Major infrastructure sources for aluminum requirement are road-bound aluminum-alloy rail in the CondERS (30 kt), substation (3–6 kt), and off-board PEI (11–22kt). Infrastructure's overall share of aluminum requirement is negligible (15–55 kt, 1%–3%).

The four cornerstone scenarios require 4–6 times more copper than the ICE (about 110 kt), the highest being for the InduERS (660 kt), which is slightly more than the BEV (645 kt). The CondERS and H2FC scenarios' copper demand is comparable (400–420 kt). The bulk of the vehicle's copper demand in the BEV scenario is from the LIB (300 kt), and motor winding and onboard PEI (30 kt each). Downsizing to 25% of BEV batteries reduces copper for LIB to 75 kt, while dynamic charging ERS vehicle-assembly adds 61 kt and 296 kt of copper in a CondERS and InduERS scenarios, respectively. Infrastructure accounts for ~30% of total copper in all cornerstone scenarios. Power cables (100 kt), transformers (25 kt), busbar and charge-post (17 kt each) are major infrastructure subsystems that increase copper demand. Close to 40 kt copper in the InduERS primary/transmitter coil and 100 kt copper for PEMFCS BoP, including wiring, are other causes for increasing copper demand.

For the sake of completeness, it should also be mentioned that both aluminum and copper occur as alloying elements in steel, but this constitutes a very minor share of their total mass contribution.

3.1.2. Alloying elements

Demand for certain metals used in alloys follows the overall trends in vehicle and infrastructure iron and aluminum demand. Engine and

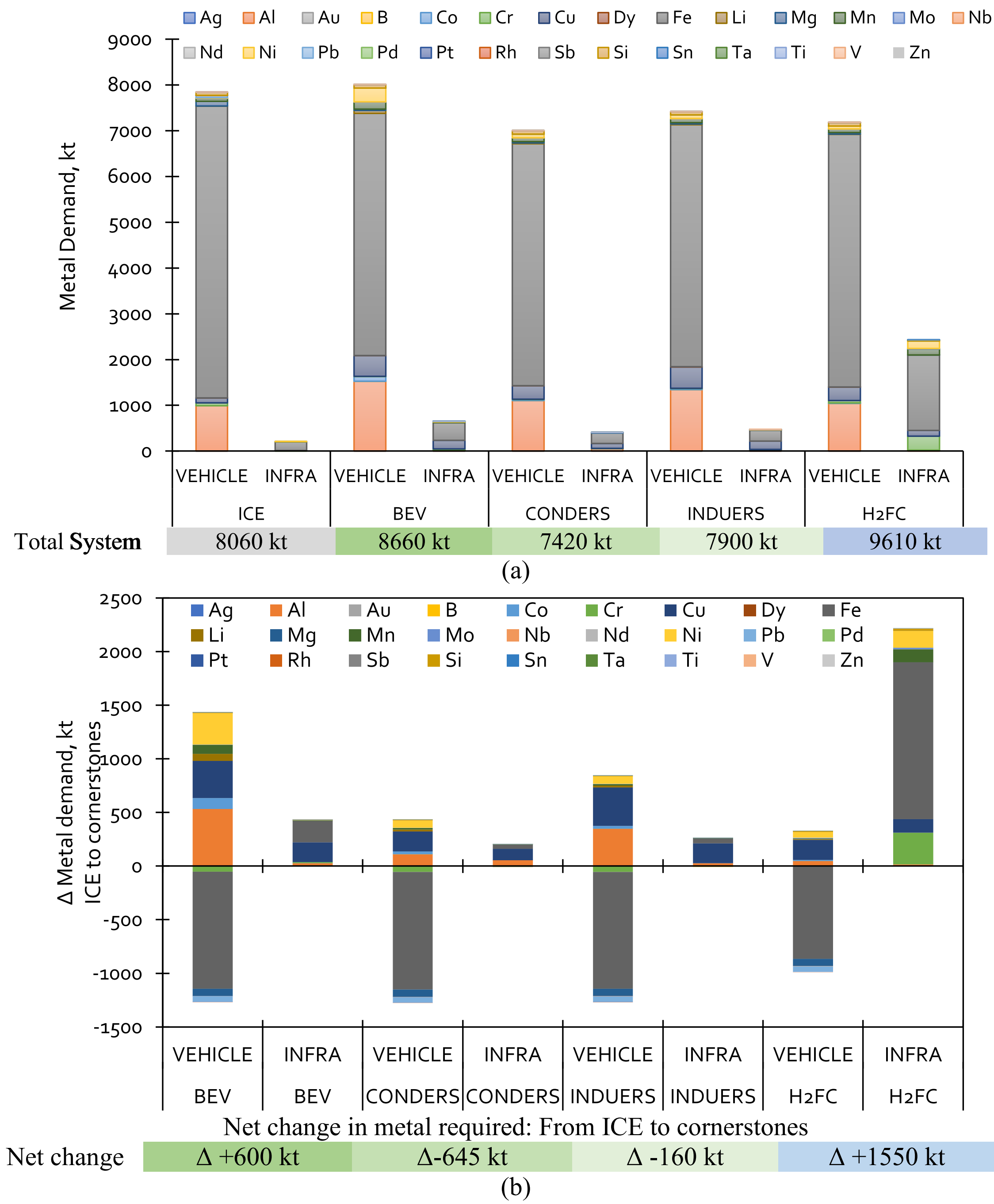

Fig. 4. (a) Total metal required; (b) ICE to cornerstone metal demand shifts.

powertrain components (~1.5 kt) dominate total niobium and titanium (~2 kt) of an ICE scenario. The generic glider's 30 kt magnesium, 36 t vanadium, 450 t zinc, 680 t niobium, ~2 kt molybdenum, 65 kt silicon is common to all scenarios. Glider forms at least 90% of the total vanadium, niobium, and silicon demand. Infrastructure contributes to nearly two-thirds of the total molybdenum required in a BEV or a H2FC scenario, which is twice as much as that of the CondERS or InduERS scenarios. About 35–50% of titanium, and 70%–85% of chromium are present in all cornerstone scenario infrastructures. Ferro-alloy demand for BEV infrastructure is ~15 kt (9 kt chromium, and 2–3 kt each of molybdenum and silicon) and ~320 kt in a H2FC scenario (290 kt chromium, 12 kt molybdenum, and 20 kt silicon).

3.1.3. Lithium, cobalt, manganese, and nickel

Car and truck NMC622 LIB in a BEV scenario require 65 kt lithium and 100 kt cobalt. Traction LIB downsizing reduces CondERS and InduERS scenario lithium and cobalt demand to 16 kt and 25 kt. As the LIB is needed for power applications, demand for lithium (7 kt) and cobalt (10 kt) is lowest in an H2FC scenario. Share of total manganese required by the LIB is 5% in the H2FC (10 kt out of ~200 kt), ~25% in both CondERS and InduERS (24 kt out of ~87 kt), and 60% in the BEV (95 kt out of 160 kt) scenarios. Traction LIB nickel demand in a BEV (300 kt) and both CondERS and InduERS scenarios (~78 kt) alone contribute to 95% of total nickel required in their respective scenarios. Other notable subsystems that need manganese and nickel, mostly as a constituent of different steel alloys include—55 kt manganese in the generic

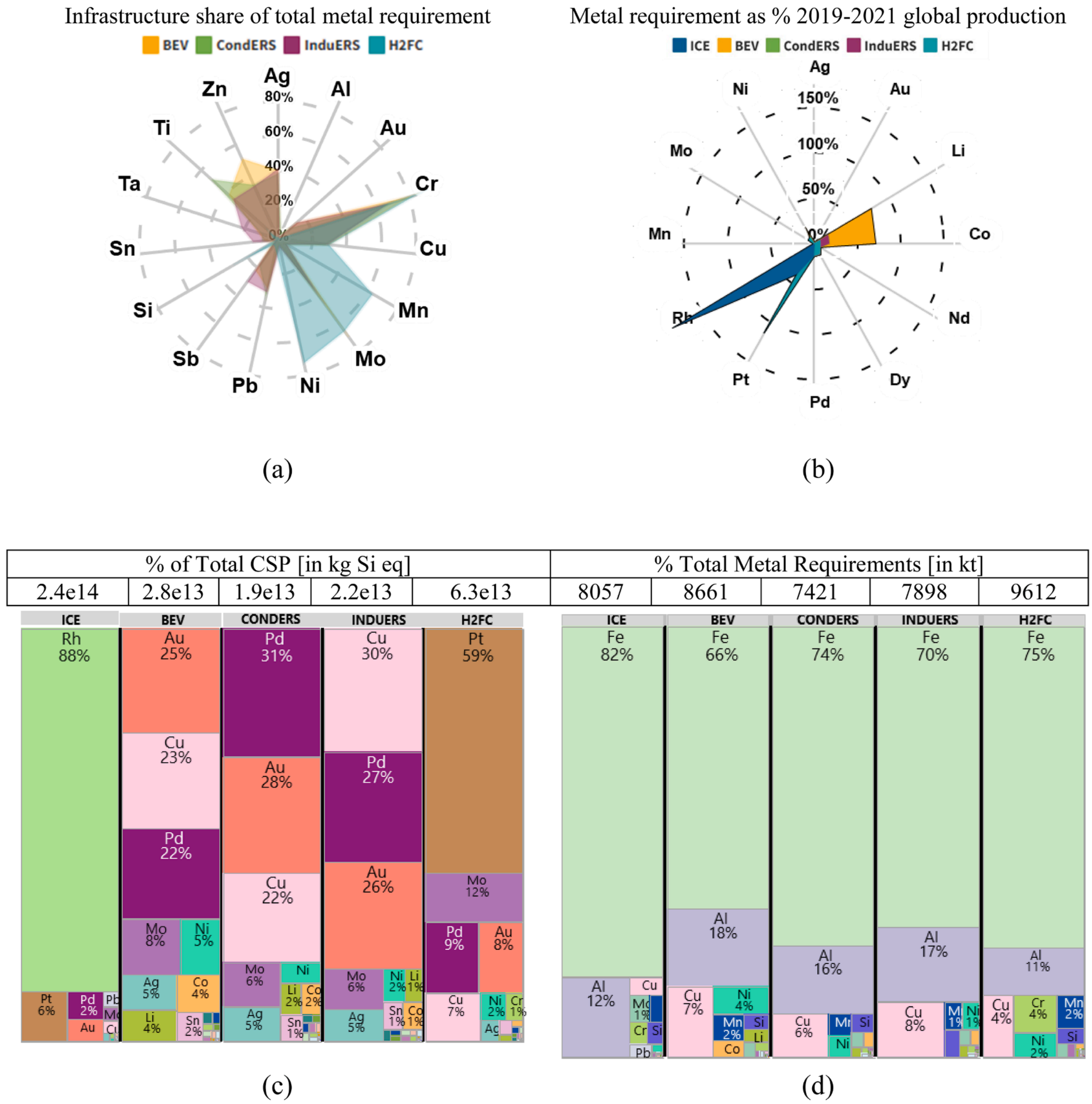

Fig. 5. Contextualizing the short- and long-term implications of metal requirements embodied in the ICE and cornerstone scenarios: (a) Infrastructure's share of total metal requirement; (b) metal demand as% of average global production 2019–2021; (c) share of long-term CSP; (d) share of total metal required.

glider, ~5–10 kt manganese and nickel in the BEV, CondERS, and InduERS infrastructure subsystems (enclosure, internal components, and substation), and ~125 kt manganese and ~165 kt nickel for the HRS (compressor, electrolyzer, storage).

3.1.4. *Precious metals and platinum group metals*

Nearly 15 t of silver and 61 t of gold are innate to the common glider across all scenarios. The increase in silver and gold compared to the ICE in the BEV scenario is 210 t and 17 t, respectively. The corresponding increases in CondERS scenarios are 130 t silver and 9 t gold and 150 t silver and 11 t gold in the InduERS scenario. As shown in Table S14 in the SI, the InduERS road-side grid and power supply need additional subsystems for contactless charging compared to CondERS. Road-side PEI of InduERS weighs five times that of CondERS PEI for the same charging power, which explains the slightly higher silver and gold requirement in InduERS, compared to the CondERS scenario. Except the H2FC scenario (12% total silver and gold), all cornerstone scenario infrastructures demand 35% of total silver and 10%–15% of total gold. The H2FC scenario requires 120 t silver and 2 t gold.

The auto-catalyst in the ICE fleet requires 31 t palladium, 72 t platinum, and 45 t rhodium. The H2FC scenario requires nearly three times more platinum (200 t) compared to the ICE. Onboard PEI and LIB BMS require slightly more palladium than the ICE in the BEV (32 t), and a comparable amount in the CondERS, InduERS, and H2FC scenarios. Infrastructure share of total palladium requirement is less than 0.4% on average across all cornerstone scenarios.

3.1.5. *Rare earth elements*

As the exemplar propulsion power is fixed (Table 1), traction motor REE requirement is same in all cornerstone scenarios: 340 t dysprosium and 2.3 kt neodymium. Demand for REE is dominated by the PMSM roughly accounting for 90% of total neodymium (2.6 kt) and 99% of dysprosium (345 t). The baseline scenario requires only 10%–15% (36 t dysprosium and 320 t neodymium) of cornerstone scenario's REE demand.

3.1.6. *Other metals*

All cornerstone scenarios require 77 t boron for PMSM. About 50 kt lead in the ICE scenario's lead-acid battery is uniformly avoided in all cornerstone scenarios. From 0.23 kt in the ICE engine and powertrain, the requirement for tin rises to almost 1.5 kt in the cornerstone scenarios, 80%–90% of which due to the on and off-board PEI. On and off-board PEI is also the major source of antimony (25–50 t) and tantalum (15–20 t) in the cornerstone scenarios. Enclosures, compact substation, and PEI add the most to cornerstone scenario zinc use of 2–5 kt.

3.2. Infrastructure share of total metal requirements

Fig. 5a provides a more detailed understanding of the infrastructure's contribution to the total metal requirements. Infrastructure requires roughly 110–190 kt copper (30% of total), 190–270 t silver (40% of total), 2–4 t gold (10%–15% of total), 30–40 t antimony (20%–30% of total), and 1.3–2.5 kt zinc (35%–50% of total) is required for BEV, CondERS, and InduERS scenarios. The H2FC scenario stands out in absolute and share of total nickel, molybdenum, manganese, and chromium, in various steel alloys for the HRS.

3.3. Short-term supply constraints

Using the average 2019–2021 global production as a reference, Fig. 5b displays the subset of metals with possible near-term supply constraints. Rhodium demand for exhaust catalyst in the ICE scenario (45 t) and platinum as PEMFC catalyst (197 t) in the H2FC scenario exceeds their global production of 25 t and 190 t Although the palladium requirement across all scenarios is less than 15% of global production (230 t), all cornerstone scenarios require comparable or slightly more than the palladium in the ICE scenario (31 t). The requirement of neodymium (2.3 kt) and dysprosium (340 t) for the traction motors is roughly 8% and 15% of their respective global production (28 kt and 2.5 kt, respectively). Lithium (65 kt) and cobalt (100 kt) requirement in the BEV scenario is about 70% of global production of 85 kt and 145 kt, respectively, which reduces to about 20% in the CondERS and InduERS.

3.4. Long-term scarcity

Fig. 5c-d shows the individual metal's share of the total CSP, and metal required. Overall, the ICE has the largest resource impact measured in terms of CSP (in kg Si eq) followed by the H2FC, BEV, InduERS, and CondERS scenarios. Infrastructure's share of total CSP is about 18% in the BEV, InduERS, and CondERS, and 12% in the H2FC, and the lowest in ICE at ~1%. Gold, silver, palladium, platinum, rhodium, copper, and select ferro-alloys (molybdenum, nickel), dominate the landscape of long-term CSP in all scenarios. Contrasting their absolute and relative share across and within scenarios reveals interesting trends that stress the implications of different powertrain and infrastructure choices on long-term resource impacts. The CSP of platinum (~4e13 kg Si eq.) alone in the H2FC is nearly twice as that of silver, gold, copper, and molybdenum combined, in the BEV, CondERS, and InduERS scenarios (1.2–1.7e13 kg Si eq.). These four metals together account for only 16% of H2FC scenario's total CSP but 80%–90% of BEV, CondERS, and InduERS scenarios. Another common theme between H2FC and ICE scenarios besides posing near-term supply challenges is that platinum group metals dictate their long-term resource impacts–platinum in H2FC (60% of total CSP) and rhodium in the ICE (88% of total CSP, 2e14 kg Si eq.), underscoring the importance of low or PGM-loading free catalysts (Pivovar, 2019) or highly efficient catalyst recycling at end of life.

Required and differential demand patterns prior discussed for copper, gold, silver, palladium, nickel, and molybdenum in the cornerstone scenarios extend to absolute resource impacts as CSP is a function of metal mass. However, a slight distinction can be seen if we inspect their relative scenario-specific shares. For example, gold, copper, and palladium are the top three contributors to BEV's total CSP whereas it is palladium, gold, and copper in the CondERS, and copper, palladium, and gold in the InduERS.

It can be noted that the long-term scarcity impact of nickel and molybdenum (~1.5–2e12 kg Si eq.) is 2–3 times as lithium and cobalt (6e11 kg Si eq) in CondERS and InduERS scenarios. Even in the larger battery equipped BEV scenario which requires the most lithium (~66 kt) and cobalt (~100 kt), absolute CSP of nickel and molybdenum (~4e12 kg Si eq.) is almost twice as that of as lithium and cobalt (2.3e12 kg Si eq.). In the power LIB equipped H2FC scenario, nickel and molybdenum imposes nearly 90% of lithium and cobalt's crustal scarcities. Infrastructure's demand for molybdenum is 35%–40% of total metals in CondERS and InduERS and ~ 60% in BEV and H2FC scenarios being primary reasons for the aforementioned observations.

3.5. Sensitivity analysis

We investigate the robustness of our results by varying certain parameters that are uncertain and influences the overall analysis. While the cornerstone scenarios provided an insight into the metal demand, the sensitivity analysis further considers variations in specific subsystems and metal flows of interest. We selected traction LiB chemistry and size, charging infrastructure capacity, and platinum loading for conducting the sensitivity analysis. For the purposes of parity, tractability, and facilitating further interpretation, the sensitivity analysis is tailored to a specific cornerstone scenario. Leveraging the insights from Sections 3.1-3.4., we prioritized a subset of metals based on salient contributions by weight or CSP . The results of the sensitivity analysis are summarized below and shown in Fig. 6a-c.

3.5.1. Impact of different LIB chemistries (BEV_811, BEV_955, and BEV_LFP)

We selected NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), NMC955 ($LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$), and LFP ($LiFePO_4$) as possible future alternatives to NMC622 in line with the low- and cobalt-free LIB technology developments (Liu et al., 2021; Xu et al., 2022). Compared to the cornerstone scenario NMC622, NMC811 requires roughly half of cobalt and manganese (~50 kt each) which reduces further to ~25% in the case of NMC955 (Fig. 6a). The LFP option entirely avoids 100 kt each of cobalt and manganese and 300 kt nickel required for the NMC622. Lithium demand is comparable across all three NMC-based chemistries (60 kt–65 kt). In all the three NMC-type traction LIBs, lithium, cobalt, nickel, and manganese together contribute to ~15% of total CSP possibly indicating scarcity burden shifting away particularly from cobalt to nickel in pursuit of nickel-rich low-cobalt NMC-type LIBs.

3.5.2. Battery size and charging power (BEV_2x_xFC)

Bigger batteries and expanding the network of high power chargers are potential solutions to range anxiety and reducing charging times, the latter being more important for long-haul trucks given their mission profiles (Speth and Funke, 2021). To capture this evolving interplay between battery sizes, installed charging infrastructure capacity and design recommendations (Plötz, 2021; Sauter, 2021), we doubled the traction LIB capacity (to 120 kWh for cars and 1200 kWh for trucks), increased the charging power of public DC fast chargers for cars, and included additional truck specific charger options >500 kW and MW-scale chargers (SI section S7).

Compared to the cornerstone BEV scenario, total metal requirements increase by ~20% (~1720–1470 kt from vehicles and 250 kt due to infrastructure) to ~10,400 kt and total CSP increases by 60% (4.5e13 kg Si eq.). Cobalt (200 kt) and lithium (130 kt) demand doubles, exceeding average global production by ~40%–50%; and nickel demand also doubles to 620 kt. The BEV_2x_xFC requires 50% more copper (1000 kt); 40%–50% more silver (380 t) and gold (43 t); twice as much palladium (63 t); and 60% more manganese (260 kt) compared to the cornerstone BEV scenario. These aforementioned nine metals account for almost 99% of the of BEV_2x_xFC total CSP (Fig. 6b).

3.5.3. Dynamic charging ERS capacity expansion (CondERS_2x and InduERS_2x)

This maximalist case assumes that the length of dynamic charging capable ERS approaches Sweden's rail network length of ~16,000 km

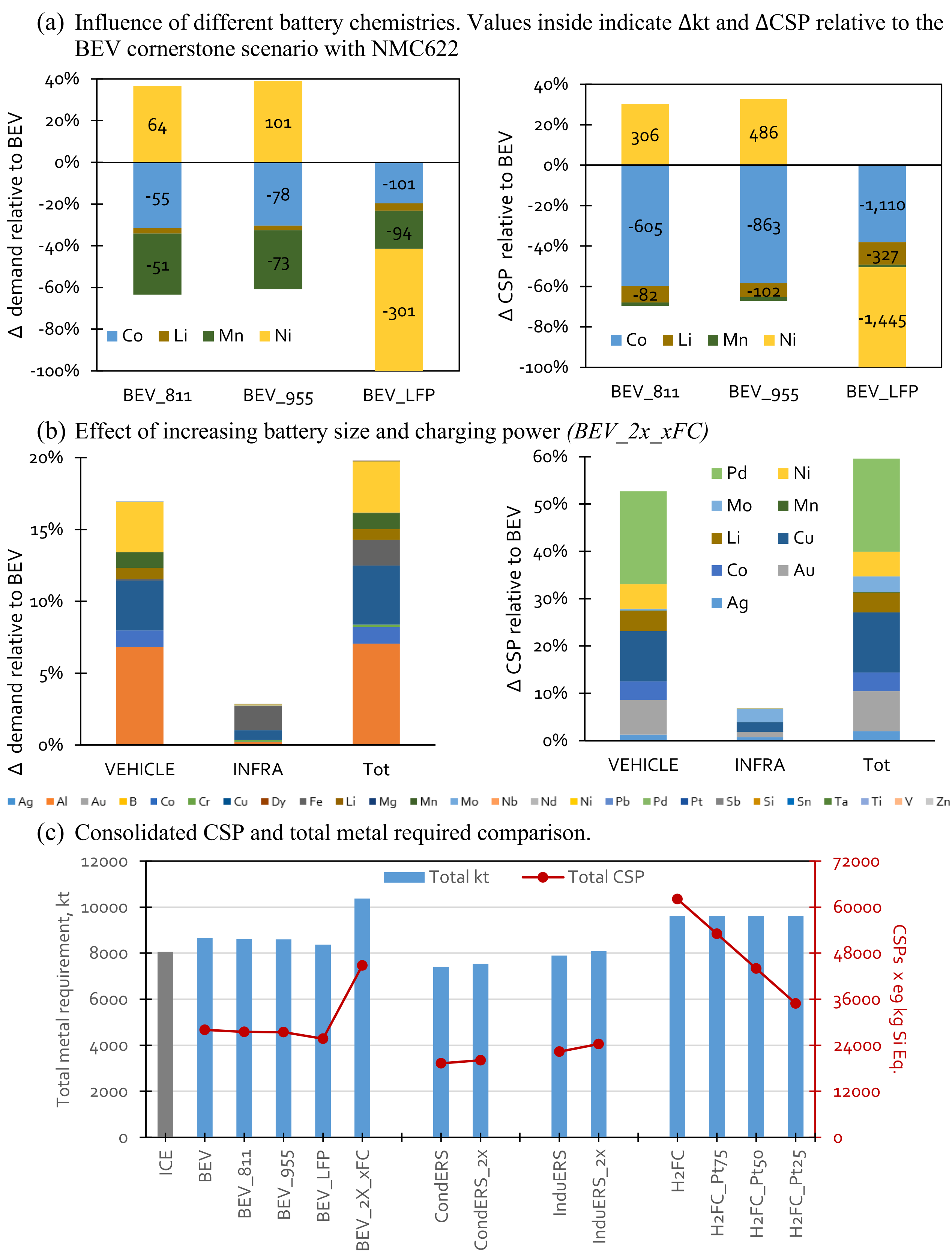

Fig. 6. Sensitivity analysis results. Note: Only a subset of metals shown because of their salient contributions by weight or CSPs.

(Trafikverket, 2022). Doubling the ERS length from 7200 e-km to 14, 400 e-km increases CondERS_2x and InduERS_2x infrastructure metal required by 130 kt and 190 kt respectively. Copper accounts for 40% (50 kt) of CondERS_2x and nearly two-thirds (~130 kt) of InduERS_2x incremental demand. This is mainly driven by copper needed for the supporting grid infrastructure powering the ERS such as power cables, power modules, transformer, substation, and electrical protection devices—45 kt in CondERS_2x and 90 kt in InduERS_2x. Though conductive and inductive dynamic charging ERS differ in operating principle, relative advantages, and practical installation considerations (Oluf et al., 2018), from a metal demand perspective, copper plays a prominent role regardless (Watari et al., 2022).

3.5.4. Platinum loading of PEMFCS (H2FC_75Pt, H2FC_50Pt, H2FC_25Pt)

Since platinum is the single biggest contributor to CSPs (~60% for H2FC) after rhodium (~90% for ICE) across all cornerstone scenarios, we explored the influence on the total CSP from decreasing fuel cell catalyst platinum loading to 75%, 50%, and 25% of its original value. In terms of g/kW, this translates to 0.23, 0.15, and 0.05 from 0.3 g/kW for cars; and 0.56, 0.38, and 0.18 from 0.75 g/kW for trucks in the H2FC cornerstone scenario. Correspondingly, total platinum reduces to 143 t, 95 t, and 48 t from ~200 t in the H2FC cornerstone scenario. Platinum content estimated for the three lower platinum loading cases vary between 6 and 28 g/car and 65–200 g/truck accounting for 55%–85% of total CSP. The total CSP with the lowest platinum loading (H2FC_25Pt) is 3.5e13 kg Si eq., which is still higher than the CSP of the other cornerstone scenarios. Even the extreme case of platinum free PEMFCS has a higher CSP (2.6e13 kg Si Eq) than the CondERS and InduERS cornerstone scenarios, in addition to requiring 20–30% more metals. It is interesting to note the near-equivalent scarcity burdens of BEV_2x_xFC (4.5e13 kg Si eq.) and H2FC_50Pt (4.4e13 kg Si eq.), which is pertinent for assessing the relative benefits of battery-based vs fuel-cell pathways for trucks.

4. Discussion

Transforming the ICE scenario to any of the cornerstone scenarios reduces iron while increasing aluminum, copper, lithium, cobalt, nickel, manganese, REE, gold, silver, and palladium demand.

Battery and PEI strongly influence vehicle fleet's aluminum demand in all cornerstone scenarios. Besides light-weighting trends, housings, enclosures, and heat dissipations structures in the LIB, motor, and power-modules are the major causes for incremental aluminum demand, with a negligible contribution from the infrastructure.

Multiple subsystems require copper and precious metals, illustrated by how the vehicle copper, silver, and gold requirements are associated with the battery size in the BEV, dynamic charging ERS vehicle assembly in the CondERS and InduERS scenarios, and the fuel-cell boost converter in the H2FC scenario. Infrastructure related copper, silver, and gold requirements are a function of charging power, number of power conversion stages, design configuration (stationary and plugged, rail-bound conductive, or contactless ERS), and interoperability of car and truck infrastructures. Despite replacing the fossil-fueled engine, exhaust, and powertrain components, demand for palladium is relatively unchanged or increases slightly in the cornerstone scenarios due to in-vehicle and off-board power modules.

Demand for rhodium in the ICE scenario catalysts and platinum in fuel cells in the H2FC scenario exceed current yearly global production and dominate their respective scenario's CSP. While this could indicate near-term supply challenges for platinum if a rapid expansion of fuel cell vehicles would take place, it also points to quickly falling demand for rhodium if ICE vehicles become phased out. The resource impacts of copper, palladium, gold, and silver are clearly evidenced in the CSPs of BEV, CondERS, and InduERS scenarios. Their distribution between vehicle fleet and infrastructure shows the relative importance of including the infrastructure in metal requirement assessments of low-carbon road transport transitions.

The sensitivity analysis highlighted a shuffling of scarcity burden between lithium, cobalt, and manganese, collectively redirecting to nickel in prospective nickel-rich and low-cobalt traction LIBs, while the NMC-free option LFP showed a reduction in scarcity impacts for all these metals. The combined effect of increasing the battery sizes and installed charging capacity reveals two coupled trends. First, technology-driven solutions towards higher power and faster charging increase infrastructure's share of copper, silver, gold, and select ferro-alloys. Second, larger demand for battery-specific metals such as lithium, cobalt, nickel, and manganese correlates with increases in palladium and gold for on- and off-board PEI and electronics like BMS. The undue influence of platinum demand on CSP is reflected in the PEMFCS catalyst loading sensitivity analysis, highlighting the importance of reducing the platinum content.

This study's outcomes offer opportunities for targeted intervention, informed decision making, and investigative research at various nodes along the raw material supply chain and emerging trends in vehicle design and infrastructure technologies.

Key strategies for reducing primary metal demand and mining efforts could include (EC, 2017b): widespread adoption of circularity concepts—lifetime extension, reduction, remanufacturing, and recycling. These measures have major ramifications for OEMs, material suppliers, governmental agencies, network operators, and infrastructure developers. The perceptible shift in profile, intensity, and quantity of metals, from the ICE to the cornerstone scenarios, also suggest the need for a more developed and dedicated recycling procedures, where recovering metals back with sufficient purity for recycling in identical or equivalent applications, becomes the industrial norm (Andersson et al., 2017) . Other measures include increased utilization of charging infrastructures by promoting standardization, flexibility, and inter-operability.

4.1. Study limitations

Assumptions necessitated by the methodology about homogenous car and truck fleets, powertrain specifications, battery chemistry and sizes, infrastructure choices, and subsystems modeled, is one of the limitations of this study. The authors acknowledge that the stylized vehicles with pre-determined infrastructure choices are just some out of a large number of possible outcomes for future electromobility. This variation is partly considered through the sensitivity analysis, but this still only covers a share of all potential outcomes.

Inventory data availability, quality, harmonization, and exhaustiveness is intrinsic to any large-scale data collection exercise from diverse data sources at varying resolutions applies to this study as well. The primary data collected, and the comprehensive inventory were developed based on EPDs of various products manufactured in the EU published within the past five years and verified by independent third parties. Wherever possible, equivalent category inventory from the scientific literature, manufacturers, own estimates, extrapolation, averaging of multiple data sources if available, and attribute-based scaling were utilized to fill data gaps.

We selected the "cornerstone scenarios" approach over predictive and normative approaches, as it best fits the fundamental nature of our inquiry regarding future resource requirements of fossil-free transport. Accuracy of the analytical framework in relation to current real-world implementation, and the temporal evolution of most likely candidates of future vehicle and infrastructure technologies, has not been the focus of this work.

Future expansions on this work could consider multiple reference vehicles and infrastructure based on market share and diffusion trends, temporal dynamics of metal flows, and probabilistic parameters for uncertainty analysis.

5. Conclusions

This study evaluated the metal requirements for electrifying the Swedish vehicle fleet of 5000,000 cars and 45,000 long-haul trucks, including their infrastructure from the vantage point of four cornerstone scenarios and an ICE baseline scenario. The metal requirement is highest for H2FC (9600 kt), followed by BEV (8700 kt), ICE (8100 kt), InduERS (7900 kt), and CondERS (7400 kt) scenarios. We developed a detailed metal intensity inventory of a portfolio of current and future charging infrastructures and expanded the coverage of HRS metal composition. This facilitated uncovering new insights on metal demand by scope (vehicles or infrastructure) and segment (car or truck), undiscussed in prior studies. Compared to the ICE scenario, demand for battery metals (lithium and cobalt) increase and iron and lead requirements are notably reduced in the cornerstone scenarios. Several metals also have notable shares (>10%) from the scenarios' infrastructures, including copper, silver, gold, antinomy, and zinc in the BEV, CondERS, and InduERS, as well as nickel, molybdenum, manganese, and chromium in the H2FC scenarios. The findings thus clearly demonstrate the value of considering infrastructure's metal content in metal demand assessments of electromobility transitions. The granularity of the inventory helps trace increased demand for low-volume metals that still may pose relatively more significant long-term scarcity challenges, such as gold, platinum, and palladium.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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