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Material demand and sustainability challenges of key infrastructures in emerging energy and digital technologies under the low-carbon transition

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Chapter 6

General discussion

6.1 Revisiting the research questions

The transition to a low-carbon and digitally connected society is reshaping how energy is produced, transported, consumed, and stored. It is also fundamentally altering the physical infrastructure that underpins modern life, from power grids and mobility systems to hydrogen supply chains and data centers. While these developments hold great promise for decarbonization and technological progress, they also introduce substantial and often overlooked material resource challenges. As infrastructures scale, so too does the demand for critical and strategic materials, raising concerns about supply security, environmental impacts, and long-term sustainability¹⁻⁴.

This thesis seeks to address the overarching research question: *How will the large-scale deployment of low-carbon and digital infrastructure systems affect future material demand and associated sustainability challenges?*

To answer this question, the thesis examines four parallel and interrelated sub-questions, each targeting a key infrastructure system that contributes to the material dynamics of a low-carbon and digitally connected future. Chapter 2 investigates the material implications of expanding electricity grids to support large-scale deployment of renewable energy. Chapter 3 examines how technological choices in low-carbon transport, specifically electric and hydrogen fuel cell vehicles, shape the demand for critical metals and influence upstream environmental impacts. Chapter 4 focuses on green hydrogen production, assessing how different electrolyzer technologies and material efficiency strategies affect long-term demand for key metals under multiple deployment scenarios. Finally, Chapter 5 explores the rapidly growing digital infrastructure sector by analyzing how the expansion of global data centers will impact future material use and related climate burdens.

The following sections revisit each research question in turn, drawing on the findings of Chapters 2 to 5. Together, they provide a sectoral and comparative perspective on how the material foundations of a low-carbon future may evolve, and what trade-offs and mitigation strategies may arise across different infrastructure domains. Section 6.1 summarizes the key results for each research question. Section 6.2 synthesizes broader cross-cutting insights across sectors. Section 6.3 critically reflects on the methodological choices and their associated limitations, and Section 6.4 outlines directions for future research.

RQ1. What are the material requirements for electricity networks under continued renewable energy expansion?

Chapter 2 addresses this question by presenting a dynamic, technology-specific assessment of global metal demand associated with electricity grid systems supporting wind and utility-scale solar PV deployment from 2021 to 2050. A dynamic material flow analysis (d-MFA) model was developed to estimate the annual inflow, stock accumulation, and outflow of copper, aluminum, and steel embedded in three grid technologies: onshore wind, offshore wind, and solar PV. The analysis integrates detailed engineering design parameters for power cables, substations, and transformers with capacity expansion projections, using the IEA Sustainable Development Scenario (SDS) as the baseline for energy transition.

Under the SDS, metal inflows increase significantly over time. In the 2046–2050 period, annual copper demand for these grid systems is projected to reach 11.4 Mt, which corresponds to approximately 11.4% of global copper production in 2020⁵. For aluminum and steel, the annual demands in the same period amount to 3.4 Mt and 9.0 Mt, respectively, representing about 1.0% and 0.1% of their respective 2020 global production levels^{6,7}. This indicates that while steel and aluminum demand remain modest in relative terms, copper demand is more material-intensive and warrants closer attention.

Cumulatively from 2021 to 2050, grid infrastructure for wind and solar deployment is projected to require 44 Mt of copper (49%), 33 Mt of steel (37%), and 17 Mt of aluminum (19%), amounting to a total of approximately 90 Mt. Among these, power cables dominate copper and aluminum use, accounting for 97% and 87% of their respective cumulative demands. In contrast, steel use is more evenly distributed across cables (55%) and substation transformers (34%).

Compared to other energy-related applications, the cumulative copper demand from renewable grid systems alone would represent approximately 12% to 18% of the total copper required for future energy technologies, vehicles, and appliances⁸. Similarly, the cumulative aluminum demand for solar PV grid systems would account for about 12% of the aluminum required for solar technologies in total. Furthermore, in 2050 the global power system is expected to require only 3 to 4.4 kt of neodymium and 3.7 to 14 kt of cobalt⁹. In comparison, the aluminum required by renewable grid systems alone would be hundreds of times greater than neodymium demand and tens of times greater than cobalt demand, highlighting the massive scale of bulk metal needs in energy infrastructure.

The study also explores the circularity potential. By 2050, grid decommissioning could yield 10 Mt of copper, 4 Mt of aluminum, and 8.4 Mt of steel. While these outflows are minimal before 2035, they increase rapidly thereafter. During the 2046–2050 period alone, over 40% of copper and aluminum demand could theoretically be met by recycled materials if full recovery were achieved. Over the entire period, secondary supply could offset 20% to 25% of the cumulative copper and aluminum demand under optimistic assumptions. However, actual recovery is likely to be significantly lower in practice. Although copper, aluminum, and steel are generally considered highly recyclable, this does not hold for transmission infrastructure supporting renewable projects, particularly submarine and underground cables. Unlike overhead lines, which are relatively easy to dismantle and recover, underground and subsea cables are commonly left in place after project decommissioning due to high removal costs and environmental concerns^{10,11}. Industry practices and legal frameworks for dismantling grid components remain unclear, in contrast to the established requirements for removing wind turbines and foundations¹². To unlock this secondary resource potential, regulatory standards and recovery systems for grid decommissioning need to be developed.

In summary, Chapter 2 demonstrates that developing electricity grid systems for wind and solar deployment will become an increasingly important driver of global metal demand, particularly for copper. While overall supply pressures appear manageable for steel and aluminum, copper emerges as a potential bottleneck, especially given its importance across multiple sectors. The study's analysis of end-of-life outflows further shows that secondary supply could offset a significant portion of future demand, although recovery will be constrained by technological and regulatory challenges. These results underline the need for proactive planning to ensure the long-term sustainability of grid infrastructure. In addition, under a more ambitious decarbonization pathway, such as the Net-Zero Emissions (NZE) scenario, total cumulative metal demand for renewable grid systems would nearly double to around 180 Mt by 2050. This reinforces the urgency of addressing copper-intensive grid expansion in high-renewable futures.

RQ2. How do different technology preferences for electric and hydrogen fuel cell vehicles affect long-term critical metal demand and environmental impacts?

Chapter 3 addresses this question using a scenario-based modeling framework that integrates dynamic material flow analysis (d-MFA) with prospective life cycle assessment (p-LCA). The analysis considers three deployment scenarios: a balanced scenario (S1), where battery electric vehicles (EVs) dominate light-duty vehicles (LDVs) and fuel cell vehicles (FCVs) are used for heavy-duty vehicles (HDVs); an FCV-

dominant scenario (S2); and a BEV-dominant scenario (S3), in which each technology is scaled across both vehicle segments. The environmental impact assessment focuses on material production only.

The results show that technology preferences substantially affect long-term demand for critical materials. Under the balanced S1 scenario, annual material demands by 2050 moderately increase compared to 2020 global production levels, with lithium reaching around 0.7 Mt (~8 times 2020 global production)¹³, nickel at approximately 0.7 Mt (~28% of 2020 global production)¹⁴, cobalt at 0.3 Mt (~1.8 times 2020 global production)¹⁵, manganese at around 0.3 Mt (~1% of 2020 global production)¹⁶, and platinum-group metals (PGMs) around 0.1 kt (~23% of 2020 global production)¹⁷. In contrast, the FCV-dominant S2 scenario significantly increases the demand for PGMs, with annual demand in 2050 reaching about 1.2 kt, approximately 2.7 times the global PGM production in 2020. Conversely, in the EV-dominant S3 scenario, lithium demand in 2050 rises sharply to approximately 1.5 Mt (~17 times the global lithium production in 2020), nickel to about 1.4 Mt (~56% of 2020 global production), and cobalt to roughly 0.7 Mt (~4.5 times). This sequential comparison underscores the distinct supply pressures associated with each technological pathway.

The p-LCA results further reveal that material production for EVs and FCVs entails distinct environmental burdens. Under the balanced S1 scenario, environmental impacts across all assessed categories remain moderate, avoiding the extremes observed in other scenarios. In the FCV-dominant S2 scenario, freshwater ecotoxicity (859.2 Mt 1,4-DCB-eq) and particulate matter formation (21.9 Mt PM₁₀-eq) significantly increase, reflecting the intensive environmental burdens associated with platinum mining and refining. Conversely, the EV-dominant S3 scenario leads to the highest cumulative greenhouse gas emissions (2,005.3 Mt CO₂-eq) and human toxicity potential (1,567.3 Mt 1,4-DCB-eq), primarily driven by energy- and emission-intensive battery metal supply chains.

These findings confirm the strategic relevance of the balanced deployment strategy modeled in S1. Allocating EVs to the LDV segment, where battery systems are more size- and cost-effective, and FCVs to HDV applications, where longer range and fast refueling are advantageous, can help mitigate both material supply constraints and environmental pressures. By distributing material demand more evenly across supply chains, this balanced approach may offer a more sustainable path toward transport decarbonization.

RQ3. How do electrolyzer technologies and material efficiency strategies shape global demand for critical metals under alternative hydrogen deployment scenarios?

Chapter 4 investigates this question through a dynamic, technology-differentiated material flow analysis applied to green hydrogen electrolyzer deployment. The model estimates demand for six critical metals—nickel, zirconium, platinum, iridium, lanthanum, and yttrium—across three technology types: alkaline (AEL), proton exchange membrane (PEM), and solid oxide electrolyzers (SOEC). Deployment projections are based on three widely used future scenarios from international institutes or corporate reports: Shell Sky 1.5, IEA Net Zero Emissions (NZE), and Deloitte Green Hydrogen, which collectively represent the lower, midrange, and upper bounds of anticipated global electrolysis capacity by 2050.

Across all hydrogen deployment scenarios, the future demand for electrolyzer metals is projected to rise steeply, driven by both the scale of deployment and the technology mix. By 2050, annual requirements increase by several orders of magnitude: nickel and zirconium (used primarily in AEL and SOEC) by 530–1,900 times, platinum and iridium (specific to PEM electrolyzers) by 920–3,300 times, and rare earths like lanthanum and yttrium (used in SOEC) by over 2,000–8,000 times. While nickel and zirconium demand remains within a manageable share of current global production, platinum-group metals—especially iridium—and yttrium pose serious supply risks due to extreme scarcity, limited recycling, and their status as by-products. These findings underscore that electrolyzer technologies, particularly PEM and SOEC, are not resource-neutral, and that their future deployment must be carefully aligned with long-term material availability.

To evaluate mitigation potential, the study assessed three material efficiency strategies: stack lifetime extension, reduction in material intensity (MI), and end-of-life (EoL) recycling. Among these, material intensity reduction emerges as the most impactful, cutting cumulative demand by up to 37% across all metals under the NZE scenario. Lifetime extension also proves highly effective, especially for PEM and SOEC, where short operating lives would otherwise trigger frequent replacements. Recycling plays a mixed role: it significantly reduces nickel and platinum demand (by 30–36% under ambitious assumptions), but contributes little to zirconium, yttrium, and iridium due to technical and economic barriers. When applied together, the three strategies can reduce total cumulative metal demand by 34–52% between 2020 and 2050, depending on the deployment scenario and electrolyzer mix.

Overall, the study confirms that electrolyzer technology choice is not resource-neutral and must be incorporated explicitly in hydrogen deployment planning. Material efficiency strategies, particularly those enacted early, can substantially reduce future critical metal pressures. Yet, without proactive measures, green hydrogen expansion risks exacerbating supply constraints and introducing new geopolitical dependencies into the energy transition.

RQ4. How will the global expansion of data center infrastructure affect material use and embedded climate impacts?

Chapter 5 addresses this question using the IMAGINE-DC framework (Integrated modeling of the product-Material-enerGy-emIssions Nexus associated with IT infrastructures in global data centers), which combines dynamic material flow analysis (DMFA) with prospective life cycle assessment (p-LCA). The model quantifies global material demand and material-related greenhouse gas (GHG) emissions from the production of servers, storage devices, and network switches, the core hardware infrastructure of data centers, under three Shared Socioeconomic Pathway (SSP) scenarios (SSP1, SSP2, SSP5) over the 2020–2035 period.

The results show that total material demand for data center IT infrastructure could range from 30.4 Mt (SSP1) to 70 Mt (SSP5) by 2035. In the SSP2 baseline scenario, cumulative demand reaches 46.1 Mt, with storage equipment contributing more than 75% of this total due to the exponential growth in global data volumes. Precious metals and rare earth elements are identified as particularly constrained: in 2035 alone, projected demand for ruthenium, palladium, and dysprosium could exceed 102%, 72%, and 35% of their respective 2019 global production levels^{18–20}. This intensity reflects the high material concentration of modern storage technologies and printed circuit boards¹.

Material-related GHG emissions, calculated from cradle to factory gate for 25 materials, are also projected to increase substantially. Cumulative emissions range from 236 Mt CO₂-eq (SSP1) to 615 Mt CO₂-eq (SSP5), with the SSP2 midpoint scenario producing 371 Mt CO₂-eq. Nearly 99% of these emissions stem from the primary production of metals, especially precious metals, which, despite representing less than 0.1% of total mass, account for nearly 19% of total material-related emissions.

Material efficiency (ME) strategies can substantially reduce the environmental impacts of data center infrastructure. In the SSP2 scenario, lifetime extension and lightweight design individually reduce cumulative material demand by 19 % and 18 %, and GHG emissions by 9 % and 22 %, respectively. Strategies such as increased reuse, collection,

and material recovery have smaller effects on total demand but reduce emissions by approximately 10 % by shifting supply from primary to secondary sources. When implemented in combination, all ME strategies together can reduce both cumulative material demand and associated emissions by 39 % by 2035.

Overall, Chapter 5 demonstrates that the rapid expansion of global data centers, if unmanaged, could significantly strain critical material supply chains and add hundreds of megatonnes of emissions from material production alone. However, the findings also suggest that targeted material efficiency strategies and technology shifts can meaningfully reduce both material pressures and upstream environmental burdens, reinforcing the importance of integrating material-focused interventions into digital sustainability strategies.

Overall RQ: How will the large-scale deployment of low-carbon and digital infrastructure systems affect future material demand and associated sustainability challenges?

This thesis set out to answer a central research question: How will the large-scale deployment of emerging low-carbon and digital infrastructure systems affect future material demand and associated sustainability challenges under different development scenarios? Drawing on the sectoral analyses and cross-cutting insights presented in previous chapters, this section brings together the key findings to directly address this question in an integrated manner.

First, the results confirm that infrastructure systems essential to the low-carbon transition, such as electricity networks, low-carbon transport, hydrogen production, and digital infrastructure, will collectively exert significant pressure on global material supply chains. Even under conservative deployment scenarios, cumulative demand for certain critical metals (e.g., copper, lithium, platinum, iridium, dysprosium) is projected to grow well beyond current production levels. These increases are not uniform across sectors or metals but instead reflect the specific material profiles of each technology. For instance, copper dominates grid infrastructure, lithium and cobalt are central to battery electric vehicles, while platinum-group metals are heavily concentrated in fuel cells and PEM electrolyzers. In the case of data centers, the high demand for rare earth elements stems from their use in key IT components such as storage devices and servers, which are essential to support the growing volume, speed, and complexity of digital services. Together, these sector-specific demands form a converging pattern: the energy transition is not only carbon-constrained but increasingly material-constrained.

Second, the specific deployment pathway, particularly the pace of infrastructure expansion and the choice of technology, plays a decisive role in shaping both the magnitude and composition of material demand. For example, in Chapter 2, when the expansion of grid infrastructure supporting wind and solar power is modeled under a more ambitious decarbonization scenario (IEA Net Zero Emissions), the total cumulative demand for copper, aluminum, and steel nearly doubles compared to the Sustainable Development Scenario. These findings underscore that faster deployment pathways significantly amplify resource pressures. Moreover, different technological choices can shift the demand burden between metals with very different supply risk profiles. For example, Chapter 4 shows that favoring PEM electrolyzers over alkaline systems greatly increases reliance on platinum and iridium, both of which face severe supply constraints. These cases demonstrate that decisions made today on technology adoption and deployment speed will lock in distinct material trajectories, and such trajectories may be difficult to reverse once infrastructure investment is committed.

Third, while material efficiency strategies can mitigate a significant share of future demand, especially over the medium and long term, they are not sufficient to eliminate sustainability risks on their own. In Chapter 4, combining lifetime extension, material intensity reduction, and recycling reduces cumulative metal demand for electrolyzers by up to 52%. Similarly, Chapter 5 shows that applying a full set of material efficiency strategies can reduce cumulative material demand and emissions in data centers by 39% by 2035 under the SSP2 scenario. However, the short-term effectiveness of such strategies varies across sectors. As demonstrated in Chapters 2 and 3, electricity grids and transport systems benefit more slowly from these measures, mainly due to long component lifespans and delayed stock turnover. In addition, as noted in Chapters 2 and 4, recycling plays a limited role in the early years of deployment, since most materials will only become available for recovery after 2035. These findings suggest that while material efficiency is essential, it must be complemented by upstream measures such as supply diversification, material substitution, and improved governance to ensure long-term sustainability.

Finally, the findings indicate that material-related sustainability challenges go well beyond supply risk. The extraction and processing of critical metals result in substantial upstream environmental impacts, including greenhouse gas emissions, toxicity, water use, and particulate pollution. These impacts vary markedly by metal and are often concentrated in a small number of producing countries. Chapter 5 shows that although precious metals make up less than 0.1% of the total mass in data center equipment, they account for nearly 19% of related greenhouse gas emissions due to energy-intensive

mining and refining. Likewise, Chapter 3 reveals that cobalt and platinum, while used in smaller quantities than lithium or nickel in electric vehicles, are major contributors to freshwater ecotoxicity and particulate emissions. These examples demonstrate that decarbonization can shift environmental burdens upstream. Addressing this trade-off requires integrating material and environmental dimensions across life cycle stages and infrastructure systems.

In sum, the thesis demonstrates that the large-scale deployment of low-carbon and digital infrastructure systems may reshape global material flows, exposing new potential resource constraints and environmental trade-offs. Meeting climate goals without transferring unsustainable burdens to material systems will require a more integrated approach to energy–material planning, informed by prospective, sector-specific evidence and cross-cutting strategies for material efficiency, circularity, and risk mitigation.

6.2 Cross-sectoral synthesis and broader insights

The main research question of this thesis asked how the large-scale expansion of low-carbon and digital infrastructure influences global material requirements and associated sustainability challenges across different development scenarios. The results presented in Chapters 2 to 5 collectively demonstrate that clean energy and digital transition entails a substantial increase in material demand, especially for critical and strategic metals. This increase is shaped not only by the total deployment scale but also by the speed of expansion, the underlying technological pathways, and the extent to which material efficiency strategies are implemented. Although each sector presents specific dynamics and challenges, several cross-cutting patterns and system-level insights emerge.

6.2.1 The low-carbon transition entails a shift from energy-intensive to material-intensive systems

Across all four sectors examined in this thesis, material requirements increase substantially as infrastructure systems scale to meet decarbonization targets. Under high-growth scenarios, the demand for key structural and functional metals, such as copper, nickel, and steel, rises by factors of five to twenty compared to 2020 levels. For certain critical elements such as platinum, iridium, and dysprosium, the projected increases are even more extreme, ranging from hundreds to thousands of times current demand. These trends signal not just quantitative intensification, but also a qualitative

shift in material dependency: from common industrial metals to high-risk, low-substitutability elements that are often geographically concentrated, environmentally burdensome to extract, and difficult to recycle at scale.

The electrification of transport, the deployment of electrolysis-based hydrogen production, and the global expansion of data infrastructure all require vast quantities of specialized materials embedded in relatively compact but high-performance systems. While these technologies contribute to significant reductions in operational carbon emissions, they simultaneously introduce new forms of upstream environmental burden and geopolitical risk tied to raw material supply. In this context, the sustainability challenge of the low-carbon transition is no longer confined to carbon mitigation alone.

This reflects a deeper structural shift: as societies decarbonize, they increasingly confront a new class of constraints, those rooted in the material intensities and resource risks of the very technologies enabling that transition. In short, the climate problem is not being solved in isolation but rather transformed into a broader issue of material sustainability and resource governance.

6.2.2 Material efficiency strategies offer meaningful but varied mitigation potential

While total material demand is substantial, all chapters show that upstream interventions can effectively moderate its scale. Material efficiency strategies such as extending product lifetime, reducing material intensity per unit of output, adopting lightweight designs, and improving collection and recovery have demonstrated tangible reductions in cumulative material requirements and associated emissions. For instance, in the case of data centers, the combination of lightweight server design and longer product life can reduce both metal demand and greenhouse gas emissions by nearly 40 percent. In hydrogen electrolysis systems, reducing the platinum and iridium content in PEM stacks while improving stack durability significantly flattens future demand curves. In other systems, like grid infrastructure and vehicles, improvements in material efficiency show stronger effects only in the long term, due to slower stock turnover. Notably, recycling is constrained in the near term across all systems because of the low availability of end-of-life components, meaning that secondary supply cannot offset the steep near-term increases in demand. These findings emphasize the importance of focusing on demand-side strategies in the next two decades, while enabling recycling to play a stronger role later in the century.

6.2.3 Deployment speed and technology choice critically shape sustainability outcomes

Material demand is not only driven by how much infrastructure is built, but also by how quickly it is deployed and what technologies are chosen. Faster deployment scenarios, such as those represented by SSP5 or Deloitte hydrogen projections, result in nonlinear accelerations in material use and emissions. These trajectories show that the temporal concentration of infrastructure growth significantly amplifies supply pressure. At the same time, different technological pathways result in divergent material profiles, even when they serve similar functions. For example, battery electric vehicles rely on lithium, cobalt, and nickel, while fuel cell vehicles shift the pressure to platinum-group metals. Similarly, PEM electrolyzers entail far higher iridium and platinum use than AEL or SOEC systems. In data storage, the replacement of HDDs with SSDs reduces rare earth demand but increases climate impacts due to chip manufacturing. These contrasts underscore that infrastructure choices are not neutral concerning materials. Technology selection implicitly defines future resource exposure and must therefore be assessed not only for performance or cost, but also for its material intensity and long-term sustainability implications.

6.2.4 Secondary supply will not scale fast enough to meet short-term demand

Although recycling and recovery are frequently discussed as essential to sustainable material management, the temporal dynamics of infrastructure deployment create a critical mismatch between when materials are needed and when they become available for reuse. Long component lifespans in power grids, vehicles, and electrolyzers mean that end-of-life flows remain negligible in the 2020s and only begin to rise meaningfully after 2035. In the case of global electricity grids, even under optimistic recycling scenarios, secondary copper can meet at most 15 percent of demand by 2050. For data centers, although reuse and recycling slightly improve supply structure, they do little to reduce climate impacts unless combined with upstream efficiency. Similarly, in electrolyzers, iridium and platinum recycling can only contribute substantially after long operational periods, and rare earth recovery remains technologically and economically limited. These patterns indicate that while circularity is essential in the long run, it cannot be relied upon to mitigate supply risks or environmental impacts in the crucial early decades of transition. Instead, strategies that reduce demand before products are even manufactured, such as lowering material intensity and extending lifetimes, must be prioritized now.

6.3 Critical Reflections and Limitations

6.3.1 Assumptions in dynamic material flow modeling

While this thesis offers quantitative insights into future material requirements and associated sustainability challenges across four key infrastructure systems, it is important to recognize the underlying methodological and empirical limitations. A key limitation across all four chapters relates to the assumptions embedded in dynamic material flow analysis (d-MFA). Parameters such as material intensity, product lifetimes, and stock turnover are central to future demand estimates but remain difficult to determine with high accuracy, especially for emerging technologies such as hydrogen electrolyzers or next-generation data center hardware. Many studies, including this one, assume constant material intensities over time, which may overestimate long-term demand by ignoring expected technological improvements. At the same time, lifetime assumptions often rely on limited empirical data, and fail to distinguish between economic, technical, and component-specific durations. These simplifications can introduce significant uncertainty into model outcomes, especially in early deployment phases where performance variability is high.

6.3.2 Sensitivity to future technology and behavioral dynamics

Several chapters do not fully capture the effects of technological innovation or behavioral adaptation on material demand. For instance, Chapter 3 models future vehicle stock and associated metal demand based on fixed battery sizes and fuel cell configurations, but does not account for advances in material substitution, downscaling, or evolving mobility patterns that may influence overall fleet size. Similarly, the hydrogen scenarios in Chapter 4 are based on broad deployment trajectories, yet omit possible breakthroughs in catalyst design, electrolyzer stack efficiency, or alternative hydrogen carriers. While scenario analysis offers a structured way to explore uncertainties, the outcomes remain sensitive to these evolving system characteristics.

6.3.3 Data availability and representativeness

An important constraint lies in the availability and representativeness of input data. Although efforts were made to use peer-reviewed literature, industry reports, and technical specifications, significant variation exists across data sources, especially regarding emerging materials such as rare earths or iridium. In some cases, proxy data or regional averages were applied to fill gaps. These assumptions, while necessary, may reduce the geographic or technological specificity of results. Moreover, the dynamic evolution of material composition, driven by changes in design, miniaturization, or regulation, is difficult to anticipate but may have substantial implications for future projections.

6.3.4 Limitations in system boundaries and life cycle assessment scope

Prospective life cycle assessment (p-LCA), as applied in this thesis, introduces limitations related to system boundaries and scope. Chapters 3 and 5 focus on upstream material production while excluding downstream phases such as product use or operation. For example, in the transport sector, use-phase energy emissions are not considered, limiting the ability to compare full life-cycle trade-offs between electric and fuel cell vehicles. In addition, supporting infrastructure (e.g., cooling systems in data centers, substations for electricity networks) is often excluded, and some chapters omit less prominent but environmentally relevant materials. While these boundary choices are necessary for tractability, they result in conservative estimates that may understate total impacts. The use of global or regional average values also masks national-level differences, which may be important for targeted policymaking.

6.3.5 Scenario dependence and uncertainty in future pathways

Scenario-based modeling enables exploration of long-term consequences, but results are inherently conditional. The scenarios used in this thesis, drawn from IEA, SSPs, and other sources—depend on assumed rates of deployment, technology diffusion, and policy commitment. Real-world outcomes may deviate substantially due to unforeseen political, economic, or technological shifts. For instance, the NZE and Deloitte hydrogen scenarios assume rapid scaling of electrolyzers and material efficiency measures that may prove unrealistic. Conversely, disruptive innovations such as new battery chemistries or digital efficiency gains could change material trajectories in ways not captured here. Therefore, these results should be interpreted not as forecasts, but as policy-relevant illustrations of what different choices may entail.

6.4 Future Research Directions

6.4.1 Improve empirical data quality and transparency for emerging and distributed infrastructures

Reliable empirical data on material composition and design parameters remains a fundamental prerequisite for accurate material demand modeling. While this thesis made extensive use of available literature, industry reports, and modeled assumptions, the results also revealed substantial data gaps, particularly in rapidly evolving or highly distributed infrastructures. For example, in Chapter 5, quantifying rare earth use in SSDs and precious metal content in servers was limited by a lack of publicly available and standardized device-level data. Similarly, in Chapters 3 and 4, estimates for platinum,

iridium, or zirconium intensity in fuel cell stacks and electrolyzer components often relied on single-source studies or aggregated assumptions, with limited verification across manufacturers or technology generations.

These data constraints are not unique to this study but reflect a broader challenge in prospective sustainability modeling, where technology frontiers shift faster than empirical characterization. To improve the robustness and reproducibility of future research, it is essential to invest in systematic data collection efforts that track evolving product designs across multiple supply chains and regions. In sectors such as digital infrastructure, where hardware is modular, diverse, and frequently updated, collaborative frameworks between academia, industry, and public agencies could help establish open-access material intensity databases. Initiatives such as product environmental passports, right-to-repair legislation, and enhanced material disclosure standards may also facilitate broader data transparency, especially for critical and hazardous components.

Beyond single-point estimates, future research should aim to capture the statistical variability and uncertainty ranges of key input parameters. Reporting mean values alone is insufficient, particularly when assessing future deployment on a global scale. Incorporating probability distributions, regional heterogeneity, and sensitivity bounds for material intensities, stack sizes, and component lifetimes would enable more informative scenario analysis and policy interpretation. This approach would also improve the compatibility of bottom-up material models with top-down energy and policy frameworks, where uncertainty propagation is increasingly emphasized.

6.4.2 Strengthen system-level modeling of design evolution and material substitution pathways

This thesis has already incorporated dynamic changes in material intensity and component lifetime in several chapters. For instance, the PEM stack material loading in Chapter 4 was modeled with time-dependent reductions under different technological learning and policy trajectories, while Chapter 5 included alternative hardware configurations and lifetime extension scenarios in data center equipment. However, the broader dynamics that shape these shifts, particularly across coupled infrastructure systems, remain an open area for further research.

One promising direction is to embed material substitution and design evolution within a system-level framework that links technical change to regulatory interventions, cost curves, and industrial scaling behavior. As observed in recent trends, shifts from cobalt-

rich to cobalt-free batteries, from HDD to SSD in data storage, or from noble-metal catalysts to base-metal alternatives in hydrogen production, are not only technology-driven but also policy- and supply-driven. Anticipating these shifts requires a more integrated representation of substitution pathways that responds to constraints, trade-offs, and market pressures in real time.

Future work could adopt multi-pathway substitution modeling, where technologies are not treated as fixed options but as evolving portfolios with diverging resource implications. This may involve scenario branching, probabilistic path weighting, or co-evolution models that track how cost, policy, and environmental impact jointly shape technology choice over time. Such approaches would better capture the non-linear, competitive, and policy-sensitive nature of infrastructure innovation and help material flow models stay aligned with real-world trajectories. Building on the dynamic formulations already applied in this thesis, further efforts can extend these mechanisms to cross-sectoral feedback and endogenous decision logic.

6.4.3 Integrate material demand modeling with energy–climate–technology policy systems

To effectively inform sustainability strategies, future material demand modeling must be better integrated with energy transition, climate mitigation, and technology deployment frameworks. While this thesis employs dynamic material flow analysis and prospective life cycle assessment to evaluate the physical implications of infrastructure expansion, it relies on externally defined energy or deployment scenarios derived from models such as the IEA’s NZE or the SSP framework. These scenarios offer useful baselines but do not reflect feedback between material constraints and energy system behavior, nor do they allow for the evaluation of resource feasibility and climate goals within the same analytical structure.

Coupling material demand models with energy–climate–technology models, such as integrated assessment models (IAMs), power system expansion tools, or hydrogen market simulations, would allow for a more complete exploration of system-level trade-offs. For example, if future copper availability were more tightly constrained than currently assumed, how would this affect the viability or optimal mix of wind energy deployment, data center expansion, or electrified transport? Conversely, if more aggressive decarbonization targets require accelerated infrastructure scaling, how would that interact with long-term supply constraints for iridium, platinum, or rare earth elements? At present, such cross-domain feedback is underrepresented in both material-centric and energy-centric modeling communities.

Advancing this integration will require methodological alignment across tools. Material flow models may need to adopt shared scenario frameworks or harmonize temporal and spatial resolution with IAMs. IAMs, in turn, may need to incorporate more granular resource modules, regionally resolved material supply chains, or criticality-informed constraints on technology diffusion. Initiatives to develop open-access, modular platforms could support this convergence and facilitate model co-development between researchers working on energy, materials, and sustainability policy. In the context of increasingly binding resource and climate limits, linking these domains will be essential to ensure that long-term energy and infrastructure transitions are both environmentally viable and physically achievable.

6.4.4 Expand modeling paradigms to include circularity, service-based transitions, and behavior change

Most material demand assessments, including those in this thesis, rely on stock-driven and product-centric modeling paradigms. These approaches are valuable for capturing large-scale infrastructure deployment and replacement dynamics, but they offer limited insight into how shifts in service delivery models, user behavior, and institutional change could alter material trajectories. As sustainability transitions increasingly call for not only technological change but also systemic demand-side interventions, future research should move beyond purely volumetric growth scenarios and consider how sufficiency, circularity, and behavioral shifts may reshape infrastructure needs.

One important avenue is the integration of circular economic strategies beyond end-of-life recycling. This includes modeling reuse, remanufacturing, modular design, and shared ownership as structural features of future systems. For instance, the reuse of server components in data centers or the redeployment of power cables from decommissioned wind farms could significantly delay primary material demand and reduce environmental burden. However, these pathways are rarely modeled quantitatively at scale, due to a lack of empirical data and standardized frameworks. Incorporating them into dynamic MFA would require new assumptions around collection rates, quality degradation, design compatibility, and user acceptance.

A second avenue involves shifting the unit of analysis from physical stocks to delivered services, such as mobility, data processing, or hydrogen provision. This would allow material intensity to be framed in terms of service units (e.g., passenger-kilometers, terabyte-months, or kilograms of hydrogen) and open the door to modeling scenarios that reduce material use through changes in consumption norms or system design. Examples include mobility-as-a-service platforms that reduce personal vehicle

ownership, server virtualization that minimizes hardware needs, or digital energy management systems that optimize electrolyzer use patterns.

Finally, incorporating behavioral and institutional dynamics, such as repair culture, product longevity expectations, or policy-driven sufficiency measures, would bring material modeling closer to real-world system transitions. These factors are often treated as exogenous or left implicit, but they play a decisive role in shaping infrastructure turnover, product replacement cycles, and design incentives. Future research can draw on insights from social practice theory, behavioral economics, and policy analysis to operationalize these variables within quantitative frameworks.

Together, these expanded paradigms would enable a more holistic assessment of how societies can meet infrastructure service needs within material and environmental boundaries, not only by substituting technologies or improving efficiency, but also by rethinking how services are provided, valued, and sustained.

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